Evaluación de la sostenibilidad ambiental de la producción citrícola en el Uruguay mediante análisis de ciclo de vida

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Aprobación Universitat Politècnica de València

NEUS SANJUÁN PELLICER, CATEDRÁTICA DE UNIVERSIDAD DEL DEPARTAMENTO DE TECNOLOGÍA DE ALIMENTOS DE LA UNIVERSITAT POLITÈCNICA DE VALÈNCIA, Y **JOANNA LADO LINDNER**, INVESTIGADORA PRINCIPAL DEL INSTITUTO NACIONAL DE INVESTIGACIÓN AGROPECUARIA E INTEGRANTE DEL COLEGIO DE POSGRADO DE FACULTAD DE AGRONOMÍA, UNIVERSIDAD DE LA REPÚBLICA

CERTIFICAN:

Que la memoria titulada *Evaluación de la sostenibilidad ambiental de la producción citrícola en el Uruguay mediante análisis de ciclo de vida*, presentada por **María Inés Cabot Lujambio** para aspirar al grado de doctora en Ciencia, Tecnología y Gestión Alimentaria, cumple las condiciones adecuadas para su aceptación como tesis doctoral, por lo que

AUTORIZAN: a la interesada a su presentación en el Departamento de Tecnología de Alimentos de la Universitat Politècnica de València.

Y para que conste a los efectos oportunos, presentamos la referida memoria firmando el presente certificado en Valencia y Salto, 2023.

Fdo. Neus Sanjuán Pellicer

Fdo. Joanna Lado Lindner

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Tesis aprobada por el tribunal integrado por (título, nombre), (título, nombre) y (título, nombre) el (día) de (mes) de (año). Autora: María Inés Cabot Lujambio. Directora: Neus Sanjuán Pellicer. Codirectora: Joanna Lado Lindner.

«Only those who will risk going too far

can possibly find out how far one can go.»

T. S. ELLIOT

Agradecimientos

La presente tesis es el resultado de una serie de casualidades y causalidades, motivada por entender e intentar cambiar (aunque sea un poquito) el mundo en el que vivimos. Muchas personas fueron parte de esta aventura, y el interlineado es 1,5, ¡así que mejor empiezo a agradecer ya!

En primer lugar, a mis tutoras Neus y Joanna, dos pilares para mí durante la realización de este doctorado. Ambas profesionales brillantes, pero por sobre todo excelentes personas. Quisiera agradecer a Neus por enseñarme a investigar, por ayudarme a ordenar las ideas y prepararme para jugar en las grandes ligas. Y a Joa, gracias por además ser mi psicóloga, mi RR. PP., y sobre todo por haber sido la primera persona que creyó en mí. Gracias por tu mentalidad positiva siempre y por haber contestado ese mail allá por 2018. Sin vos no existiría esta tesis, y te voy a estar agradecida siempre.

Un especial agradecimiento a UPEFRUY por haberme compartido sus datos. A todos los productores citrícolas y viveristas uruguayos a los que he molestado con preguntas durante estos cuatro años. Especialmente a Gustavo, Cristina, Gladiana, Martín, Gonzalo, Michel, Yoana, Yamandú… Gracias también al Instituto Nacional de Investigación Agropecuaria y especialmente a Daniel Vázquez por su apoyo. También a la Agencia Nacional de Investigación e Innovación y a la Comisión Académica de Posgrado por las becas que me permitieron realizar y culminar el doctorado.

Agradezco también a los investigadores que estuvieron involucrados en la realización de la tesis; Gabi, otra de las grandes responsables de que esta tesis tuviese lugar, Matías, excelente resumidor de conocimientos en audios de 5 minutos, Inma y Javier. Gracias también a Almudena y Giuliana por su apoyo y palabras de aliento siempre.

Al *ASPA team* por haberme hecho sentir tan cómoda durante estos años, en especial a Bea, Vir, Ángela y a mis *Latin LCAs*; Nelson, una gran persona que me ha ayudado en muchos momentos, y Coronita, mi compañero de despacho *for ever* y gran gran amigo. Gracias por hacerme sentir como en casa.

Gracias a mis amigos en Uruguay por la paciencia, por haber aguantado semanas con mensajes sin contestar y por todo su cariño aún a la distancia. A Bel, Carlita, Matías, Gastón, Cin, Julio, Lu, Flo, Isa y a Berita, a quien las coincidencias de vida la hicieron ser una de las primeras personas que lean esta tesis, siendo casualmente una de las primeras personas que me enseñaron el verdadero significado de la palabra amistad.

Gracias a mi familia; mamá, papá y el gordi, sin ustedes no sería quien soy hoy, ni hubiese llegado tan lejos. Gracias por haberme apoyado en todas mis locuras (incluida esta). Gracias a mi tía Gaby, a Luli y a Magda, tres mujeres valientes a quienes admiro y quiero mucho. Gracias a mi abuela Chula, quien llegó a verme empezar con este sueño, y a quien siempre le tendré reservado un lugar especial en mi corazón.

Por último, gracias a mi gran compañero de aventuras, Ivan. No me podía haber imaginado a nadie mejor con quien transitar estos años. Gracias por tu dulzura, por tu apoyo, por tus chistes (malos), por tus platos (estrella Michelin), por tu amor y por tu paciencia. Gracias por hacerme la vida más fácil, especialmente cuando se ha puesto más desafiante.

Y finalmente (ahora sí), gracias al destino que está escrito y al que nos animamos a escribir nosotros.

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Resumen

Los cítricos son el cultivo frutícola más importante de Uruguay en términos de producción, superficie y aporte económico. Considerando la gran contribución de los sistemas agroalimentarios a los impactos ambientales, evaluar aquellos asociados a la producción citrícola en el país cobra gran relevancia para transitar hacia sistemas alimentarios sostenibles. En esta línea, el objetivo de la presente tesis es evaluar estos impactos ambientales mediante la utilización del análisis de ciclo de vida (ACV) y estudiar aspectos metodológicos clave de su aplicación a la producción citrícola. Se lleva a cabo una revisón crítica de la literatura de ACV de cítricos y se desarrollan cuatro casos de estudio en establecimientos representativos de la región, en concreto, la producción de limones, mandarinas y naranjas, y la producción de plantones en vivero. Los impactos se evalúan de la cuna hasta la puerta del establecimiento, usando unidades funcionales tanto de masa como de área y datos primarios correspondientes a varias temporadas de cultivo. Los principales puntos críticos ambientales detectados son las emisiones de campo producto de la aplicación de fertilizantes, la irrigación, y la producción de óxidos de cobre. Desde el punto de vista metodológico, se destaca la importancia de usar distintas unidades funcionales y de abordar la variabilidad temporal y la especificidad según el sitio de los datos de inventario, así como de usar métodos de caracterización de impactos regionalizados. Se observa que la contribución de las primeras etapas del cultivo al impacto ambiental de la producción citrícola es baja.

Palabras clave: análisis de ciclo de vida; impacto ambiental; frutas cítricas; sostenibilidad agrícola; cultivo perenne; ciclo de cultivo

Summary - Assessment of the environmental sustainability of citrus production in Uruguay using life cycle analysis

Citrus is the most important fruit crop in Uruguay in terms of production, area, and economy. Considering the great contribution of agri-food systems to environmental impacts, evaluating those associated with citrus production in the country becomes highly relevant to move towards sustainable food systems. In this line, the goal of this dissertation is to evaluate these environmental impacts using life cycle assessment (LCA) and to study key methodological aspects of its application to citrus production. Literature on citrus LCA is critically reviewed and four case studies are developed in representative agricultural holdings of the region, specifically, the production of lemons, mandarins and oranges, and the production of seedlings in nurseries. Impacts are assessed from cradle to gate, using both mass and area functional units and primary data for several growing seasons. The main environmental hotspots detected are on-field emissions from fertiliser application, irrigation, and copper oxides production. As to methodology, the relevance of using different functional units and addressing temporal variability and site-specificity of inventory data is highlighted, as well as using regionalised impact characterisation methods. It is observed that the contribution of the first stages of the crop to the environmental impacts of citrus production is low.

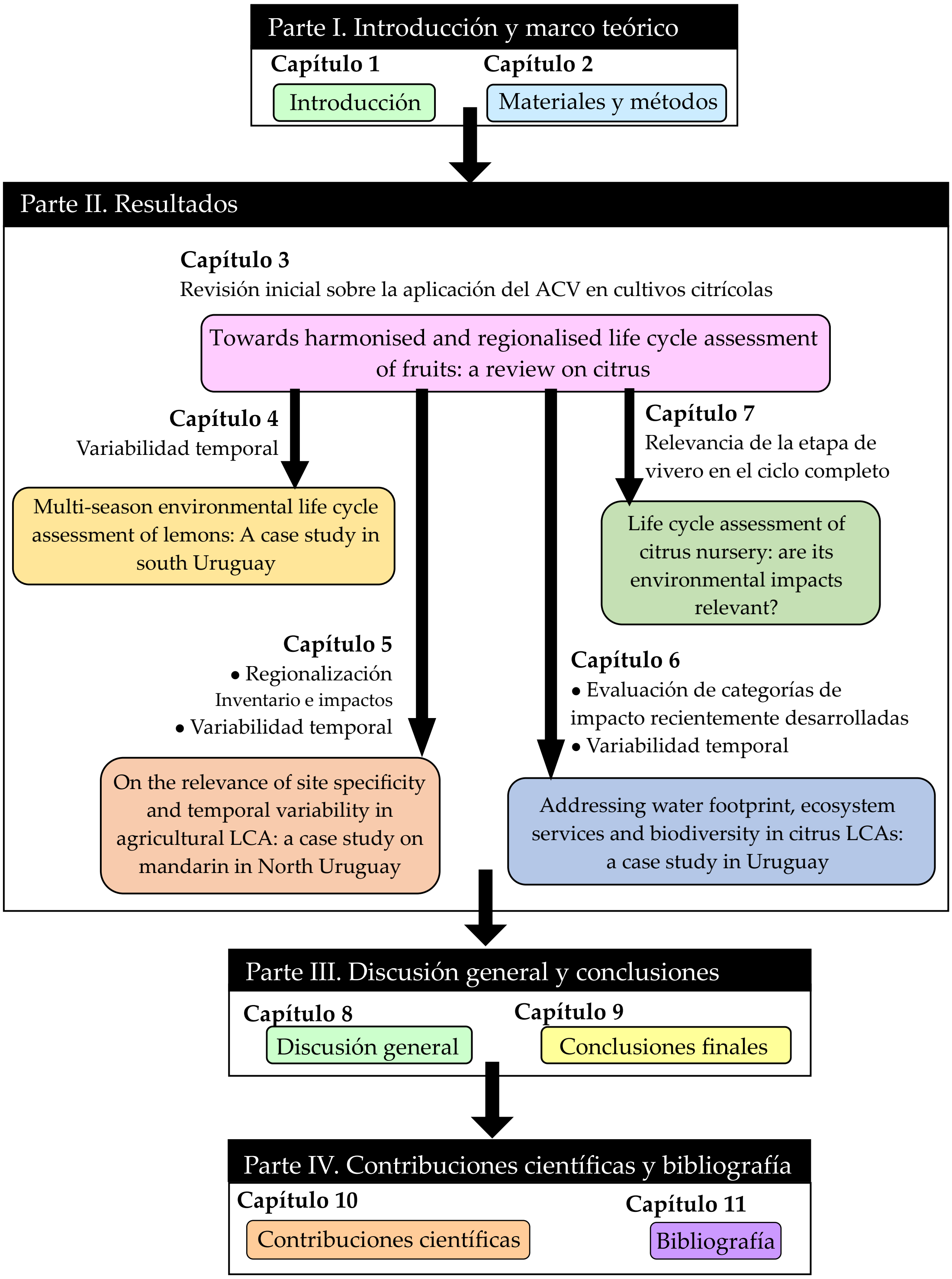
Keywords: life cycle assessment; environmental impacts; citrus fruits; agricultural sustainability; perennial crop; crop cycle

Resum - Avaluació de la sostenibilitat ambiental de la producció citrícola a l'Uruguai utilitzant l'anàlisi de cicle de vida

Els cítrics són el cultiu de fruita més important de l'Uruguai en termes de producció, superfície i aportació econòmica. Considerant la gran contribució dels sistemes agroalimentaris als impactes ambientals, avaluar aquells associats a la producció citrícola del país cobra gran rellevància per a transitar cap a sistemes alimentaris sostenibles. En aquesta línia, l'objectiu de la present tesi és avaluar aquests impactes ambientals utilitzant l'anàlisi de cicle de vida (ACV) i estudiar aspectes metodològics claus de la seua aplicació a la producció citrícola. Es fa una revisió crítica de la literatura d'ACV de cítrics i es desenvolupen quatre casos d'estudi en explotacions representatives de la regió, en concret, la producció de llimes, mandarines i taronges, i la producció de plançons en viver. Els impactes s'avaluen del bressol fins a la porta de l'establiment, usant unitats funcionals tant de massa com d'àrea i dades primàries corresponents a diverses temporades de cultiu. Els principals punts crítics ambientals detectats són les emissions de camp, producte de l'aplicació de fertilitzants, la irrigació, i la producció d'òxids de coure. Des del punt de vista metodològic, es destaca la importància d'usar diferents unitats funcionals i d'abordar la variabilitat temporal i els aspectes lloc-específics de les dades d'inventari, així com d'usar mètodes de caracterització d'impactes regionalitzats. S'observa que la contribució de les primeres etapes del cultiu a l'impacte ambiental de la producció citrícola és baixa.

Paraules clau: anàlisi de cicle de vida; impacte ambiental; fruites cítriques; sostenibilitat agrícola; cultiu perenne; cicle de cultiu

Estructura de la tesis



Parte I. Introducción y marco teórico

La parte I de la tesis está compuesta por dos capítulos. El **capítulo 1** (Introducción) se divide en dos grandes bloques, el referente a la sostenibilidad ambiental agrícola y el referente a la producción citrícola. En el primer bloque se presenta una visión general de la importancia de la agricultura en el mundo, los problemas ambientales que genera y la relevancia que adquiere la agricultura sostenible. En esta línea, se presentan las principales políticas de sostenibilidad propuestas en los últimos años tanto en el ámbito global como específico, dando especial relevancia a las políticas europeas y estadounidenses, dado que son los principales importadores de cítricos uruguayos, y a las del propio país de estudio, Uruguay. Por último, se destaca la utilidad de incorporar el pensamiento de ciclo de vida a la toma de decisiones y se hace un breve repaso de los avances en la principal herramienta de medida del impacto ambiental de un producto, el análisis de ciclo de vida (ACV). Además, se comentan los aspectos metodológicos en los que se debería profundizar para mejorar su aplicación a la producción citrícola, así como su utilidad en el desarrollo de ecoetiquetas. En el segundo bloque del capítulo se desarrolla la importancia de los cítricos como producto, su relevancia en el comercio mundial, y se profundiza en el rol clave de los productores del hemisferio sur en el mercado citrícola internacional. Finalmente, se presenta la motivación de la tesis y se enumeran sus objetivos. El **capítulo 2** (Materiales y métodos) describe la metodología aplicada, el análisis de ciclo de vida, detallando las fases que lo componen, a la vez que se comentan las principales decisiones metodológicas tomadas para la realización de la tesis. Por último, se describen los sistemas estudiados, haciendo una breve descripción de las principales prácticas agrícolas llevadas a cabo en cada uno de ellos.

Parte II. Resultados

La parte II se compone de cinco capítulos: uno de revisión de los últimos avances de la investigación de ACV en frutas cítricas y cuatro que ahondan en los aspectos metodológicos a mejorar detectados en la revisión mediante el desarrollo de casos de estudio. Concretamente, se aborda la variabilidad temporal de los datos de inventario y cómo afecta a los impactos ambientales, la representatividad regional del inventario, en especial de las emisiones en el campo, y de los impactos ambientales, la evaluación de categorías de impacto recientemente desarrolladas y de especial relevancia en los ACV agrícolas, y la importancia de la etapa de vivero citrícola en los impactos totales del ciclo productivo. Así, la parte II queda estructurada de la siguiente forma:

Capítulo 3 (*Towards harmonised and regionalised life cycle assessment of fruits: a review on citrus*). En él se hace una revisión descriptiva, crítica y actualizada de los últimos avances de la investigación de ACV en cítricos. Se identifican las principales decisiones metodológicas para la implementación de la metodología en los estudios revisados y se proponen recomendaciones para una aplicación armonizada del ACV en cítricos, además de identificar las áreas que merecen más investigación, que dan lugar a los siguientes capítulos.

En el **capítulo 4** (*Multi-season environmental life cycle assessment of lemons: A case study in south Uruguay*) se presenta la evaluación del impacto ambiental de la producción de limones en el sur de Uruguay, se estudia la variabilidad temporal de los impactos contemplando cuatro temporadas de cultivo y se sugieren alternativas de mejora para los puntos críticos detectados.

En el **capítulo 5** (*On the relevance of site specificity and temporal variability in agricultural LCA: a case study on mandarin in North Uruguay*) se evalúan los impactos ambientales de la producción de mandarinas en el norte de Uruguay. Se estudia la variabilidad temporal de los impactos tomando para ello datos de seis temporadas de cultivo y se analiza el efecto de la utilización de modelos específicos del sitio para la estimación de las emisiones nitrogenadas derivadas de la aplicación de fertilizantes y de métodos específicos del sitio para la cuantificación de los impactos ambientales.

En el **capítulo 6** (*Addressing water footprint, ecosystem services and biodiversity in citrus LCAs: a case study in Uruguay*) se realiza una evaluación ambiental de la producción de naranjas en el norte de Uruguay poniendo el foco en categorías de impacto no evaluadas previamente en cultivos citrícolas, considerando seis temporadas de cultivo.

El **capítulo 7** (*Life cycle assessment of citrus nursery: are its environmental impacts relevant?*) presenta la evaluación del impacto ambiental de la producción citrícola en vivero, estableciendo un valor de referencia para este proceso. Asimismo, se evalúa la relevancia de los impactos ambientales de esta etapa respecto a los de la totalidad del ciclo citrícola y propone alternativas para su reducción a partir de los puntos críticos detectados.

Parte III. Discusión general y conclusiones finales

La parte III incluye el **capítulo 8** (*Discusión general*) y el **capítulo 9** (*Conclusiones finales*).

Parte VI. Discusión general y conclusiones finales

La parte IV incluye el **capítulo 10** (*Contribuciones científicas*) y el **capítulo 11** (*Bibliografía*).

Parte I. Introducción y marco teórico

1. INTRODUCCIÓN

En el **capítulo 1** se destaca la importancia de la agricultura en el ámbito mundial y se hace una introducción a los problemas ambientales con los que se enfrenta actualmente, lo cual repercute en una preocupación manifiesta por parte de consumidores y políticos. Esto se evidencia en las políticas ambientales surgidas en los últimos años. Se da un papel preponderante al análisis de los objetivos de desarrollo sostenible (ODS) propuestos por las Naciones Unidas, ya que varios de ellos presentan vinculación directa con los impactos generados por la agricultura. Asimismo, se estudian las principales políticas ambientales europeas y estadounidenses (principales países importadores de cítricos uruguayos), así como las uruguayas. También se analiza brevemente la evolución de la medición de la sostenibilidad ambiental, haciendo referencia al pensamiento de ciclo de vida y a la importancia de la metodología de análisis de ciclo de vida, destacando su contribución al desarrollo de ecoetiquetas ambientales. Por último, se aborda la importancia de la citricultura, tanto en el ámbito mundial como regional y del país, de manera de entender la relevancia que adquiere el estudio de los impactos ambientales asociados.

De esta manera, el capítulo se estructura de la siguiente forma:

- Importancia de la sostenibilidad ambiental en la agricultura
- Importancia de la citricultura
- Motivación de la tesis
- Objetivos de la tesis

1.1. IMPORTANCIA DE LA SOSTENIBILIDAD AMBIENTAL EN LA AGRICULTURA

El sector agrícola juega un papel estratégico en cuanto a la disponibilidad de alimentos y el logro de la seguridad alimentaria y nutricional (Wegren y Elvestad, 2018, Otsuka, 2013, Smutka et al., 2015, 2009). Asimismo, según el Banco Mundial (BM) es el principal sector económico en muchos países y la principal fuente de alimentos y de ingresos de aquellos que viven en la pobreza extrema (BM, 2023a). También es esencial para el crecimiento económico; en 2021 representó el 4 % del producto interno bruto (PIB) del mundo y, puntualmente, el 7 % del PIB del Uruguay (BM, 2023b). Asimismo, tiene un impacto mucho mayor en la reducción de la pobreza y la mejora de la seguridad alimentaria que otros sectores de la economía (Majid, 2004, Irz et al., 2001), ya que su crecimiento es entre dos y cuatro veces más eficaz para incrementar los ingresos de las personas más pobres (BM, 2023a).

Según las cifras publicadas por la Organización de las Naciones Unidas para la Alimentación y la Agricultura (ONUAA, en inglés FAO), en 2021 la población mundial alcanzó los 7890 millones de personas (ONUAA, 2023a), llegó a superar los 8000 millones en 2022 (El Mundo, 2022) y se prevé que alcance los 9700 millones en 2050 (ONUAA, 2021a). Esto conlleva un aumento de la demanda de alimentos, para lo cual será necesario aumentar la producción agrícola. En Asia meridional y África subsahariana, la producción deberá aumentar un 112 % y en el resto del mundo por lo menos un 30 % (ONUAA, 2021a). Paradójicamente, la capacidad mundial de producción de alimentos no es la principal limitante, sino el agotamiento de los recursos. Las prácticas intensivas e industrializadas de producción de alimentos, que se han desarrollado para satisfacer la demanda mundial, dañan cada vez más el medioambiente y podrían provocar una catástrofe ecológica a escala local o incluso mundial (Nellemann et al., 2009, Hazell y Wood, 2008). De esta manera, se vuelve imperiosa la necesidad de contar con una agricultura más productiva y eficiente en el uso de los recursos, que aumente la disponibilidad de alimentos y contribuya a la seguridad alimentaria mundial, al mismo tiempo que preserve los recursos naturales y la biodiversidad.

En esta línea surgen los conceptos de agricultura y alimentación sostenibles, propuestos por la ONUAA (ONUAA, 2023b). Se basan en un manejo de los recursos naturales que permita mantener las funciones ecosistémicas suficientes para sostener las necesidades humanas actuales y futuras y, al mismo tiempo, garantizar la rentabilidad, la salud ambiental y la equidad social y económica. De esta forma, la alimentación y la agricultura sostenibles contribuyen a los cuatro pilares de la seguridad alimentaria (disponibilidad, acceso, utilización y estabilidad) y a las tres dimensiones de la sostenibilidad (ambiental, social y económica).

1.1.1. Principales problemas ambientales que genera la agricultura

La agricultura genera la mayor parte de las presiones sobre los suelos y los recursos hídricos del mundo, las cuales producen una serie de externalidades que afectan también a otros sectores (ONUAA, 2021a).

El uso de agua asociado a la agricultura es elevado, presentando un aumento histórico desde aproximadamente 500 $km^3 \cdot año^{-1}$ consumidos en el 1900 hasta valores de casi 3000 $km^3 \cdot año^{-1}$ en 2017 (ONUAA, 2020). Esto puede causar presiones ambientales significativas en regiones con estrés hídrico, como se refleja en el aumento del nivel de estrés hídrico mundial, el cual fue de 12,97 % en 2015 y llegó al 13,07 % en 2020 (ONUAA, 2023a). A escala mundial, la agricultura representa el 72 % de todas las extracciones de aguas superficiales y subterráneas. Puntualmente, las extracciones de aguas subterráneas para la agricultura de regadío representan más del 30 % de las extracciones agrícolas de agua dulce y siguen creciendo en torno a un 2,2 % anual (ONUAA, 2021a).

La agricultura no solo usa el agua como insumo, sino que también contribuye a contaminar ríos, lagos y océanos. El uso de fertilizantes por superficie cultivada ha aumentado históricamente. Entre ellos, el uso de nitrógeno aumentó de 8,5 $kg \cdot ha^{-1}$ en 1961 a 72,9 $kg \cdot ha^{-1}$ en 2020 y el uso de P_2O_5 de 8,0 $kg \cdot ha^{-1}$ en 1961 a 30,9 $kg \cdot ha^{-1}$ en 2020 (ONUAA, 2023a). En este sentido, las estimaciones indican que la agricultura es responsable del 38 % de las entradas totales de fósforo a las masas de agua debidas al uso antropogénico y del 78 % de la eutrofización mundial de los océanos y el agua dulce (ONUAA, 2021a, Poore y Nemecek, 2018). En 2020 se utilizaron más de 2,6 millones de toneladas de pesticidas con fines agrícolas, lo que supone un aumento de 1,2 $kg \cdot ha^{-1}$ en 1990 a 1,8 $kg \cdot ha^{-1}$ en 2020 (ONUAA, 2023a). Estos pesticidas contaminan los recursos hídricos con carcinógenos y otras sustancias tóxicas que afectan tanto la salud humana como la de los ecosistemas (Mateo-Sagasta et al., 2017). En este sentido, se puede destacar que el 74,8 % del suelo agrícola mundial (aproximadamente 28,8 millones de km^2) se encuentra en riesgo de contaminación por pesticidas (Tang et al., 2021).

La agricultura es también un impulsor crucial del cambio climático. Históricamente, las emisiones de gases de efecto invernadero de la agricultura aumentaron de $3{,}26 \cdot 10^6$ mil toneladas de CO_2 equivalentes en 1961 a $5{,}95 \cdot 10^6$ mil toneladas de CO_2 equivalentes en 2019 (ONUAA, 2023a). Ese mismo año, el 31 % de las emisiones antrópicas mundiales procedían de los sistemas agroalimentarios, contribuyendo con el 78 % de las emisiones de N_2O, el 53 % de las emisiones de CH_4 y el 21 % de las emisiones de CO_2 (ONUAA, 2021a). La etapa de producción primaria es la que más aporta, con aproximadamente el 41 % de las emisiones, seguida de los procesos anteriores y posteriores con el 35 % y el cambio en el uso del suelo con el 24 % (ONUAA, 2021a).

Asimismo, el uso intensivo del suelo para el cultivo genera un gran impacto en el medioambiente. La mitad de la tierra habitable del mundo se utiliza para la agricultura (Ritchie, 2019) y, en concreto, la agricultura de regadío ocupa el 20 % de las tierras cultivadas (ONUAA, 2021a). Actualmente, el 44 % de la superficie de cultivo de regadío se ve afectada por la degradación del suelo provocada por el ser humano y el 18 % se encuentra deteriorada debido al empeoramiento de su estado biofísico (ONUAA, 2021a). Por último, cabe destacar también que la agricultura es el principal impulsor de la reducción de la biodiversidad mundial (Ritchie, 2019), debido principalmente a la pérdida de bosques y tierras silvestres destinadas al cultivo.

1.1.2. Políticas de sostenibilidad ambiental agroalimentaria

Los impactos ambientales antes mencionados han captado la atención de políticos y otros tomadores de decisión. En consecuencia, durante los últimos años han aumentado las iniciativas ambientales dirigidas hacia el sector agroalimentario. Entre otras, destacan los objetivos de desarrollo sostenible (ODS), propuestos por la Organización de las Naciones Unidas (ONU), que comprenden 17 objetivos con metas específicas para alcanzarlos (ONU, 2023a). Vale mencionar también el Pacto Verde Europeo (PVE) propuesto por la Comisión Europea (CE), el cual engloba programas clave para el sector agrícola como la «Estrategia de la Granja a la Mesa» (CE, 2023a). En el caso de

Estados Unidos, destacan las leyes y regulaciones dirigidas a la producción de cultivos propuestas por la Agencia de Protección Ambiental de Estados Unidos (EPA) y el Departamento de Agricultura de los Estados Unidos (USDA). Por último, en Uruguay han surgido diversas iniciativas ambientales dentro de las que destacan el Plan Nacional de Adaptación a la Variabilidad y el Cambio Climático para el Sector Agropecuario de Uruguay (PNA-Agro), publicado por el Ministerio de Ganadería, Agricultura y Pesca (MGAP) y el Sistema Nacional de Respuesta al Cambio Climático y Variabilidad (SNRCC) (MGAP y SNRCC, 2019), entre otros.

(i) Objetivos de desarrollo sostenible (ODS)

Los objetivos de desarrollo sostenible (ODS) se definen como un llamamiento universal a la acción para luchar contra la pobreza, cuidar el planeta y disminuir las desigualdades en el mundo (ONU, 2023b). De esta forma, los 17 objetivos propuestos abarcan aspectos sociales, económicos y ambientales, y 6 de ellos se encuentran intrínsecamente ligados con la agricultura (fig. 1.1.).

Fig. 1.1. Objetivos de desarrollo sostenible propuestos por las Naciones Unidas, destacando con color aquellos relacionados con la agricultura. Fuente: adaptado de ONU (2023b)

Dentro del ODS número 2, «hambre cero», destaca la meta 2.4, que trata sobre la implementación sistemas de producción de alimentos sostenibles y prácticas agrícolas resilientes. Como indicador se propone cuantificar la proporción de superficie agrícola dedicada a la agricultura sostenible y para ello se proponen 11 subindicadores que brindan los requisitos mínimos para alcanzarla (Gennari y Navarro, 2019). El ODS 3, que trata sobre «buena salud y bienestar», presenta un vínculo tanto positivo como negativo con la producción agrícola. Su vínculo es positivo desde la perspectiva de que el aumento de la productividad agrícola puede mejorar la nutrición, el acceso a los alimentos y a los recursos económicos, lo que favorece la salud. Pero, a su vez, los cambios ambientales y de hábitat inducidos por la actividad agrícola pueden conducir a cambios en los ecosistemas que intensifiquen el contagio de enfermedades transmisibles o incluso causar daños directos a los trabajadores agrícolas (Howden-Chapman et al., 2017). La vinculación del ODS 6, «agua limpia y saneamiento», con la agricultura es evidente, dada la estrecha interacción entre ambos, como se mencionó con anterioridad. Puntualmente, las metas 6.3 y 6.4 hablan de mejorar la calidad del agua y reducir su escasez. Para la primera destaca el indicador 6.3.2, que cuantifica la proporción de masas de agua con buena calidad ambiental, y, para la segunda, el indicador 6.4.2, que trata sobre la cuantificación del nivel de estrés hídrico, medido como la extracción de agua dulce en función del total de agua dulce disponible (ONU, 2023c). Debido a su ubicación al inicio de la cadena alimentaria, la agricultura tiene un papel clave en el ODS 12, «consumo y producción responsables», en especial en las metas 12.2 y 12.4; en la primera, ya que trata sobre la gestión sostenible y el uso eficiente de los recursos naturales, y en la segunda, puesto que se refiere a la reducción de la liberación de productos químicos y desechos al aire, agua y suelo (ONU, 2023d). El ODS 13, «acción climática», trata sobre la necesidad de tomar medidas urgentes para combatir el cambio climático y sus impactos. La agricultura es un impulsor crucial del cambio climático, pero también es uno de los sectores más afectados por él. Los efectos del cambio climático en los cultivos son evidentes en varias regiones del mundo, siendo los impactos negativos más comunes que los positivos (Porter et al., 2015). Por este motivo adquiere especial importancia el indicador 13.2.2, «emisiones totales de gases de efecto invernadero por año», el cual permite monitorear el progreso hacia una agricultura climáticamente más sostenible. Por último, el ODS 15, «la vida en la tierra», abarca varios aspectos vinculados con la producción agrícola. En primer lugar, la meta 15.1, que aborda el uso sostenible de los ecosistemas terrestres y de agua dulce continentales y sus servicios. También el indicador 15.3.1, ya que propone medir la proporción de tierra degradada en función de la superficie total de tierra, dando cuenta así de los impactos sobre el suelo. Y, finalmente, la meta 15.5, que aborda la pérdida de biodiversidad (ONU, 2023e).

(ii) Pacto Verde Europeo (PVE)

El Pacto Verde Europeo (PVE) constituye una estrategia de crecimiento sostenible e integrador de la Unión Europea (UE). Sus principales objetivos se centran en eliminar la producción neta de gases de efecto invernadero para 2050, que el crecimiento económico se disocie del uso de recursos y que, en esta transición, no existan personas ni países relegados (CE, 2023b). En concreto, comprende diversas iniciativas y objetivos para los distintos sectores de la economía. En lo que concierne a la agricultura, se recomiendan una serie de medidas y políticas, dentro de las que se encuentra la llamada «Estrategia de la Granja a la Mesa», cuyo objetivo principal es aumentar la sostenibilidad de la cadena alimentaria de la UE y lograr un sistema alimentario justo, saludable y respetuoso con el medioambiente (CE, 2023a). Esta estrategia se compone de varios pilares (fig. 1.2.), de los cuales el más estrechamente vinculado con la producción agrícola es el de garantizar la producción sostenible de alimentos. Una herramienta fundamental para la concreción de dicha estrategia es la Política Agrícola Común (PAC), la cual cuenta con una última reforma en vigor para los años 2023-2027 (CE, 2023c) donde se plantean diez objetivos principales (CE, 2023d) que se desglosan en objetivos específicos por país (CE, 2023e) y se apoyan en un conjunto de indicadores (CE, 2023f) que se supervisan a través de informes de rendimiento anuales y semestrales.

Fig. 1.2. Los cuatro pilares de la «Estrategia de la Granja a la Mesa». Fuente: adaptado de CE (2023a).

(iii) Leyes y regulaciones en Estados Unidos (EPA-USDA)

La EPA cuenta con una serie de leyes y reglamentos vinculados con la producción de cultivos (EPA, 2023). Estas tratan principalmente sobre el manejo de los pesticidas (uso, almacenamiento y disposición), pero abordan también aspectos como la contaminación del aire, agua y suelos.

Por su parte, en los últimos años, el USDA ha puesto el foco en el cambio climático. En esta línea, ofrece programas y servicios voluntarios para promover el secuestro de carbono, la reducción de las emisiones de gases de efecto invernadero y la mitigación de los impactos del cambio climático (USDA, 2023a). Dentro de ellos se ofrecen herramientas y se abordan tópicos clave como el manejo de nutrientes (USDA, 2023b), la cantidad y calidad del agua (USDA, 2023c, 2023d) y la salud del suelo (USDA, 2023e), entre otros.

(iv) Políticas de sostenibilidad ambiental en el Uruguay

En Uruguay existen diversas iniciativas con el objetivo de lidiar con los impactos ambientales asociados a la producción agropecuaria (fig. 1.3.). Entre ellas destaca el Plan Nacional de Adaptación a la Variabilidad y el Cambio Climático para el Sector Agropecuario de Uruguay (PNA-Agro) (MGAP y SNRCC, 2019), propuesto por el Ministerio de Ganadería, Agricultura y Pesca (MGAP) y el Sistema Nacional de Respuesta al Cambio Climático y Variabilidad (SNRCC). Este plantea diversos objetivos dentro de los que se encuentran promover acciones para desarrollar y adoptar sistemas de producción menos vulnerables a los impactos de la variabilidad y el cambio climático y conservar los agroecosistemas y sus servicios. Para ello se propone un plan de acción a 2025 que contiene 66 medidas de adaptación priorizadas por los actores vinculados al sector agropecuario.

Fig. 1.3. Principales políticas de sostenibilidad ambiental del Uruguay

Asimismo, el país cuenta con otros planes de relevancia en la materia, como son el Plan Nacional Ambiental para el Desarrollo Sostenible, publicado por el Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente (MVOTMA) y el Sistema Nacional Ambiental (SNA) (MVOTMA y SNA, 2019), el Plan Nacional de Aguas (MVOTMA, 2017) y la Estrategia Nacional de Biodiversidad 2016-2020 propuesta por el MVOTMA y el Ministerio de Relaciones Exteriores (MRE) (MVOTMA y MRE, 2016), entre otros. De igual modo, desde el año 2017, el país presenta los informes nacionales voluntarios de los ODS (Presidencia de la República Oriental del Uruguay, 2017, 2018, 2019, 2021, 2022) (fig. 1.4.).

Fig. 1.4. Informes nacionales voluntarios de los ODS de Uruguay en el período 2017-2022

1.1.3. Medición de la sostenibilidad ambiental

El pensamiento de ciclo de vida (PCV, LCT en inglés) constituye un marco multidimensional que pretende alcanzar soluciones eficaces para la mejora integral de la sostenibilidad de productos, procesos y sistemas, ya que va más allá del enfoque tradicional en el sitio de producción e incluye los impactos ambientales, sociales y económicos de un producto durante todo su ciclo de vida (Iniciativa del Ciclo de Vida, 2023, Mazzi, 2019). En esta línea, el análisis de ciclo de vida es actualmente la herramienta operativa más importante del pensamiento de ciclo de vida (Mazzi, 2019) y representa «el mejor marco para evaluar los impactos ambientales potenciales de los productos» (CE, 2003). Permite evaluar cuantitativamente los impactos ambientales de los bienes y procesos desde la cuna hasta la tumba, modelando las relaciones de causa-efecto en el medioambiente y, por lo tanto, ayudando a comprender las consecuencias ambientales de las acciones humanas. Posee cuatro características que lo convierten en una herramienta completa y sólida: adopta una perspectiva de ciclo de vida, cubre una amplia gama de problemas ambientales, es cuantitativo y tiene base científica (Bjørn et al., 2018b). A su vez, es una importante herramienta de apoyo a la toma de decisiones que, entre otras funciones, permite a las empresas comparar y optimizar el desempeño ambiental de los productos, así como diseñar políticas para el consumo y la producción sostenibles por parte de las autoridades (Mazzi, 2019).

La medición de la sostenibilidad ambiental con perspectiva de ciclo de vida no es nueva. Podría considerarse que el primer estudio orientado al ciclo de vida se presentó en 1963, estudiando los requerimientos energéticos para la producción de químicos (Boustead, 2003). Más adelante, en los años 70, se publicó el primer estudio de ACV público y revisado por pares, que trataba sobre empaques (Hunt et al., 1974). En los 80 se lanzaron los dos primeros softwares comerciales para ACV (GaBi en 1989 y SimaPro en 1990). En los años 90, el enfoque del ciclo de vida tuvo un auge; la Sociedad de Toxicología y Química Ambiental (SETAC) acuñó el término «análisis de ciclo de vida» (SETAC, 1993) y la Organización Internacional de Normalización (ISO) publicó los primeros estándares para armonizar las prácticas del ciclo de vida (ISO, 1997, Fava et al., 1991). Al mismo tiempo, diferentes instituciones desarrollaron bases de datos de inventarios del ciclo de vida y nuevas metodologías de evaluación de impacto, incluidas las llamadas evaluaciones de causa-efecto-daño (Bjørn et al., 2018a). En los 2000 se reconoció el ACV como una herramienta basada en la ciencia de utilidad para cambiar el modelo de desarrollo insostenible (ONU, 2002). También se lanzó la Iniciativa del Ciclo de Vida, enfocada en la difusión de las prácticas del ciclo de vida en todo el mundo (Iniciativa del Ciclo de Vida, 2002). En el contexto europeo, el PCV recibió un fuerte impulso por parte de la llamada Política Integrada de Producto (CE, 2003), que respalda instrumentos políticos como el etiquetado ambiental, la compra pública ecológica y la integración de aspectos ambientales en el desarrollo de estándares. En el siglo XXI, los enfoques metodológicos de PCV han mejorado: se han revisado los estándares internacionales de ACV (ISO, 2006a, 2006b), se ha comenzado a aplicar el PCV gradualmente en diversos sectores, y se ha integrado con otras herramientas de apoyo a la decisión.

Es de destacar también el uso de las ecoetiquetas para comunicar los resultados de ACV ambientales a los consumidores, las cuales, como cita el

Programa de las Naciones Unidas para el Medio Ambiente (PNUMA), constituyen una guía fácil para identificar productos más amigables con el medioambiente (PNUMA, 2011).

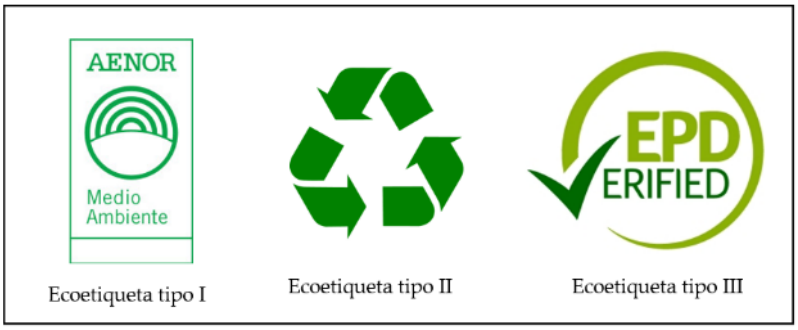


Fig. 1.5. Ejemplos de ecoetiquetas tipo I, tipo II y tipo III. Fuente: elaboración propia

En el ámbito internacional, los esquemas de etiquetado se clasifican en tres tipologías, I, II y III (fig. 1.5.), para las cuales existen normas específicas. El etiquetado ambiental tipo I, basado en la norma ISO 14024 (ISO, 2018), es un esquema que otorga una marca o un logotipo basado en el cumplimiento de un conjunto de criterios ambientales. La declaración ambiental tipo II es una afirmación declarada por los fabricantes con base en la normativa ISO 14021 (ISO, 2021, 2016). Por último, las declaraciones ambientales de tipo III, tienen como base la ISO 14025 (ISO, 2006c) y presentan información ambiental sobre el ciclo de vida de un producto con el objetivo de permitir comparaciones entre bienes con la misma función. Estas están destinadas a ser utilizadas en la comunicación de empresa a empresa, pero también han sido reconocidas por varios sectores como una interfaz importante entre la empresa y el consumidor (PNUMA, 2011). Estas declaraciones pueden tener varios nombres, dentro de las que destacan las declaraciones ambientales de producto (EPD por su sigla en inglés), las cuales han mostrado un fuerte aumento en los últimos años

(PNUMA, 2011). Las EPD se crean con base en un conjunto de reglas específicas, denominadas reglas de categoría de producto (RCP, en inglés PCR), que identifican y describen el proceso de elaboración de una EPD para que sea comparable y verificable (Butt et al., 2015). En relación con la presente tesis, destaca la publicación de las PCR para frutas y nueces (EPD, 2019).

El ACV se ha aplicado ampliamente y continúa aplicándose a la producción agrícola, con estudios que van desde cereales (Fallahpour et al., 2012, Blengini y Busto, 2009), hasta hortalizas (Abeliotis et al., 2013, Romero-Gámez et al., 2012, Torrellas et al., 2012) y frutas (Vázquez-Rowe et al., 2012, Milà I Canals et al., 2006). En cuanto a la producción citrícola, destacan los trabajos llevados a cabo en España (Martin-Gorriz et al., 2020, Ribal et al., 2019, 2017, 2011), Italia (Nicolo et al., 2017, Lo Giudice et al., 2013, Pergola et al., 2013) y Argentina (Machin Ferrero et al., 2022, 2021). Si bien estos estudios se han concretado con éxito, destaca la necesidad de mejorar y contemplar determinados aspectos metodológicos, como la representatividad temporal y espacial tanto del inventario como de la evaluación del impacto, la evaluación de nuevas categorías de impacto relevantes para los sistemas agrícolas, así como también la cuantificación de los impactos de las primeras etapas del cultivo que, para el caso de los cítricos comerciales, involucran una etapa en vivero.

1.2. IMPORTANCIA DE LA CITRICULTURA

Los frutos cítricos comerciales más importantes comprenden principalmente las especies de naranja dulce (*Citrus sinensis* Osbeck), mandarina (*Citrus reticulata* Blanco) y diferentes híbridos, limón (*Citrus limon*

(L) Burm.), pomelo (*Citrus paradisi* Macf. y *Citrus maxima* Burm.) y lima (*Citrus aurantifolia* Christm.), y conforman una parte significativa de la producción total de frutas en el mundo (Ladaniya, 2023). Los cítricos destacan por sus propiedades nutricionales, como su contenido de vitaminas B, C y provitamina A. Además, son fuente de minerales como el potasio, calcio, fósforo, magnesio o cobre, fibra dietética y fitoquímicos como los carotenoides, fenoles, flavonoides, cumarinas, limonoides, alcaloides y aceites esenciales (Ladaniya, 2023). Si bien su principal destino en el ámbito mundial es el consumo en fresco y la elaboración de jugos, los cítricos también se cultivan para la producción de aceites esenciales y ácido cítrico, mientras que a sus subproductos se les da varios usos, principalmente como alimento para animales (ONUAA, 2023c). Debido a su sabor característico y ampliamente aceptado por los consumidores, su accesibilidad desde el punto de vista económico y sus propiedades beneficiosas para la salud, los frutos cítricos son ampliamente consumidos mundialmente, lo que conlleva un elevado impacto económico tanto en países desarrollados como en desarrollo (Liu et al., 2012).

1.2.1. Producción citrícola en el mundo

Los cítricos constituyen unas de las principales frutas producidas y exportadas en el contexto mundial, con un intercambio anual de más de 17 millones y una producción total de casi 144 millones de toneladas en 2019 (ONUAA, 2021b), considerándose el frutal más importante en el mundo (Sidana et al., 2013, Liu et al., 2012). La naranja dulce es el cítrico más producido mundialmente (53 %), seguido por las mandarinas (26 %), los limones y las limas (14 %) y los pomelos (7 %) (ONUAA, 2021b). De la producción total de cítricos en el mundo, el 86 % se consume en fresco y el 14

% se procesa (Ladaniya, 2023). China y la UE son los principales productores citrícolas para consumo en fresco y en conjunto representan el 54 % de la producción. China destaca por su producción de mandarinas y la UE principalmente por su producción de naranjas y mandarinas (USDA, 2023f). En cuanto a la exportación de cítricos, Sudáfrica es el principal exportador mundial, con una participación del 24 % del total de cítricos exportados en el mundo, seguido de Turquía (18 %), principal exportador de mandarinas, y Egipto (16 %), destacando principalmente en la exportación de naranjas (USDA, 2023f). En 2021, el 1,1 % de la superficie mundial de cítricos se encontraba bajo manejo orgánico, concentrándose principalmente en Europa (48 %), debido a la alta producción orgánica en Italia y España, y en América Latina (29 %), como consecuencia de la producción orgánica en México y República Dominicana (Instituto de Investigación de Agricultura Ecológica, 2023).

1.2.2. El hemisferio sur y su rol en la citricultura mundial

Según cifras de la *World Citrus Organisation* (WCO), en 2022, los cítricos del hemisferio sur constituyeron un mercado de 3,8 millones de toneladas, representando el 27 % del comercio mundial de cítricos WCO, 2023). Según la misma fuente, los principales productos exportados son la naranja, constituyendo un 72 % del total de cítricos exportados desde el hemisferio sur, la mandarina un 14 % y el limón un 12 %. Los principales destinos son la UE y Reino Unido con un 35 % del mercado, Asia con un 21 % y América del Norte con un 19 %. El principal motor de crecimiento del mercado del hemisferio sur lo constituye Sudáfrica, con un 17 % de crecimiento medio en los últimos cinco años y 2,6 millones de toneladas exportadas en 2022 (WCO, 2023). Los productores citrícolas del hemisferio sur cuentan con una ventaja clave: debido a los períodos de cosecha, pueden proporcionar cítricos a los mercados del norte fuera de temporada, que son los principales importadores del mundo (Ladaniya, 2023, ONUAA, 2021b). En comparación con la producción del hemisferio norte, las tendencias de crecimiento son mayores para el hemisferio sur tanto para mandarinas, que crecieron un 10 % de media por año en los últimos 4 años (principalmente debido a su participación en el mercado de América del Norte), como para limones, con un crecimiento del 6 % en dicho período, debido a su presencia en el mercado de UE y Reino Unido (ProCitrus, 2023).

En cuanto a Latinoamérica, Brasil, Argentina y Perú, destacan como los principales productores citrícolas, sobresaliendo la producción de naranjas brasileras y peruanas, limones argentinos y mandarinas peruanas. En 2022, Brasil contó con una producción de más de 4,7 millones de toneladas de cítricos para consumo en fresco, Perú con más de 1,5 millones y Argentina con más de 1,2 millones (WCO, 2023). En cuanto a la exportación, los principales exportadores citrícolas latinoamericanos son Argentina, con más de 300 mil cítricos exportados en 2022, y Chile con más de 260 mil, seguidos de cerca por Perú, con más de 240 mil cítricos exportados en 2022, y un aumento significativo de sus exportaciones durante los últimos años (WCO, 2023).

En el 2022, Uruguay representó un 2,2 % de la producción citrícola latinoamericana para consumo en fresco y estuvo a cargo del 6,5 % de los cítricos exportados en la región (WCO, 2023). Los cítricos constituyen la fruta más producida y exportada del país (MGAP, 2022a), con una amplia oferta de variedades en función del momento del año. Según MGAP (2022b), la producción citrícola de la zafra 2021 fue estimada en 299 mil toneladas, de las cuales 40 % fueron de naranja, 33 % de mandarina y 26 % de limón. El principal destino de la producción citrícola uruguaya es la exportación como fruta fresca, que alcanzó el 46 % de la producción en 2021, y llegó al 55 % en el caso de la mandarina y al 52 % para la naranja. La producción comercial de cítricos en Uruguay se concentra en dos zonas: la zona norte (Salto, Paysandú y Artigas), que comprende el 91 % de la superficie total de cítricos y concentra especialmente la producción de naranjas, mandarinas y pomelos, y la zona sur (San José, Colonia, Canelones y Montevideo), donde adquiere relevancia el cultivo de limones, que alcanza el 32 % de la producción total del país. Los cítricos uruguayos se distinguen en el mundo por su gran calidad, la cual se debe, entre otros factores, a producciones que cumplen desde hace más de 20 años con certificaciones de tercera parte de estándares prestigiosos en el ámbito mundial, como GLOBALG.A.P. (GLOBALG.A.P., 2023), BRCGS-Brand Reputation through Compliance Global Standard (BRCGS, 2023) y HACCP-Análisis de Peligros y Puntos Críticos de Control (Alimentarius, 1969). A través de estas certificaciones nacionales e internacionales, las empresas se someten permanentemente a estrictos controles, de manera de alinear el desarrollo competitivo del sector con las metas del desarrollo sostenible (Quiñones, 2017). El sector citrícola ha sido declarado estratégico por el Gabinete Productivo del Uruguay debido a su trayectoria, siendo un sector consolidado, con un fuerte impacto desde el punto de vista social y que ha demostrado una enorme capacidad de adaptación a los cambios de la economía global (Caputi y Montes, 2010). Asimismo, es un rubro de gran importancia en cuanto a la generación de empleo directo e indirecto con alrededor de 15.000 trabajadores, contando con instancias de diálogo entre empresas y sindicatos del sector, dentro de las que destaca la Mesa de Diálogo

Sectorial de la Citricultura, que ha conllevado un fortalecimiento de los actores laborales, principalmente de los trabajadores (Quiñones, 2017).

1.3. MOTIVACIÓN DE LA TESIS

Ante un escenario mundial donde la agricultura es el principal generador de presiones ambientales sobre los recursos del planeta, teniendo en cuenta el papel preponderante de la producción citrícola en el mundo, su relevancia en Uruguay, así como el gran desarrollo de las regulaciones ambientales en los últimos años, se vuelve imperativa la cuantificación de los impactos ambientales asociados la producción citrícola. Por tanto, es fundamental conocer la situación actual en Uruguay y detectar los posibles puntos y propuestas de mejora con base en un análisis serio y minucioso. Teniendo en cuenta también las oportunidades metodológicas de mejora que presenta la aplicación del ACV a los cultivos agrícolas, y en especial a los perennes, es que se propone la presente tesis, motivada por las siguientes realidades:

- La agricultura representa el 72 % de las **extracciones de aguas** superficiales y subterráneas, es la causante del 78 % de la **eutrofización** mundial de los océanos y el agua dulce, del 31 % de las **emisiones antropogénicas** mundiales y de la **degradación** del 44 % **de las tierras** de cultivo de regadío, además de ser el principal impulsor de la **reducción de la biodiversidad** mundial.
- La **preocupación política** y la **demanda de los consumidores** de alimentos respetuosos con el medioambiente se encuentra en aumento. Evidencia de esto son iniciativas políticas como los **ODS** en el ámbito mundial, el **PVE** en Europa, el **PNA-Agro** en el país y las **ecoetiquetas** enfocadas hacia el consumidor.

- Los cítricos constituyen unas de las principales frutas producidas y exportadas en el mundo, siendo **la fruta más producida y exportada en el Uruguay**.
- **Los productores citrícolas del hemisferio sur son relevantes para la citricultura mundial**, ya que representan el 27 % del comercio mundial de cítricos en 2022 y proporcionan cítricos fuera de temporada a los mercados del norte, principales importadores en el contexto mundial.
- A pesar de la importancia que tiene esta fruta para el país, **no se han desarrollado estudios de ACV para la producción citrícola uruguaya**.
- **No existen datos ambientales específicos y cuantitativos** basados en datos primarios **sobre la producción de plantones citrícolas en viveros** a pesar de la relevancia que podría tener esta etapa debido al período de tiempo que abarca y el uso intensivo de insumos que puede conllevar.
- Dado que son metodologías de reciente desarrollo, no existen estudios publicados sobre la cuantificación de la **pérdida de biodiversidad**, la **pérdida de servicios ecosistémicos debido al uso del suelo** ni de la **huella hídrica integral de la producción citrícola** bajo una perspectiva de ciclo de vida.
- Las evaluaciones de **impacto ambiental de los sistemas agrarios son dependientes del sitio**, por lo cual el estudio de la influencia de la regionalización de inventarios e impactos ambientales adquiere relevancia.
- La producción agrícola es fuertemente dependiente de **los parámetros agroclimáticos**, por lo tanto, es necesario incorporar el estudio de la **variabilidad interanual en el análisis de los impactos**.

En esta línea, las hipótesis de partida de la presente tesis son las siguientes:

1. La aplicación de la metodología de ACV constituye una herramienta clave en la evaluación de la sostenibilidad ambiental de la producción citrícola del Uruguay, la cual puede mejorarse mediante la implementación de cambios en los procesos productivos.

2. Mediante una revisión descriptiva y crítica de la aplicación del ACV en cítricos se pueden detectar áreas de mejora metodológicas, que pueden ser abordadas mediante casos de estudio. A su vez, el desarrollo de estos casos de estudio permite seguir detectando nuevos aspectos a mejorar.

1.4. OBJETIVOS DE LA TESIS

El objetivo principal de la presente tesis es evaluar los impactos ambientales asociados a la producción citrícola del Uruguay con el fin de caracterizar dicha producción ambientalmente y estudiar aspectos metodológicos clave en la aplicación del ACV a la producción citrícola.

De esta manera, para alcanzar estos objetivos principales, se plantean diversos objetivos específicos:

1. Realizar una **revisión bibliográfica descriptiva y crítica sobre los últimos avances de la aplicación de ACV a la producción citrícola** con el objetivo de identificar aspectos metodológicos, puntos críticos del proceso productivo y necesidades de investigación, así como también proponer recomendaciones para la aplicación armonizada del ACV.
2. **Cuantificar** los **impactos ambientales** asociados a la **producción de limones, mandarinas y naranjas en Uruguay**, detectar los puntos críticos de impacto ambiental y proponer alternativas para la reducción de los impactos**.**

3. **Atender las principales áreas de mejora metodológica detectadas.** Concretamente, estudiar la variabilidad temporal de los impactos, la relevancia de la regionalización tanto de inventarios como de impactos ambientales, cuantificar los impactos asociados a las primeras etapas del cultivo y evaluar categorías de impacto poco analizadas en el ámbito agroalimentario.

2. MATERIALES Y MÉTODOS

El **capítulo 2** presenta una visión general de los aspectos metodológicos de la tesis. En primer lugar, se presenta la herramienta de evaluación de sostenibilidad ambiental aplicada en la tesis, el análisis de ciclo de vida (ACV), detallando todas sus fases, junto a los principales aspectos metodológicos abordados en la presente tesis. Posteriormente, se presentan de manera sucinta los sistemas de estudio evaluados; es decir, los campos y viveros citrícolas uruguayos que constituyen la base sobre la cual se desarrolla la tesis.

De esta forma, el capítulo queda estructurado de la siguiente manera:

- Análisis de ciclo de vida
- Sistemas de estudio

2.1. ANÁLISIS DE CICLO DE VIDA

La norma ISO 14040 (ISO, 2006a) define el ACV como la «recopilación y evaluación de entradas, salidas e impactos ambientales potenciales de un sistema de producto a través de su ciclo de vida», constituyendo una visión que busca evitar el desplazamiento de una carga ambiental potencial entre las etapas del ciclo de vida o los procesos individuales. El enfoque del ACV es ambiental, los aspectos e impactos económicos y sociales están fuera de su alcance, aunque se puede combinar con otras herramientas para desarrollar análisis más completos. A su vez, los impactos que evalúa el ACV son potenciales, es decir, no predice impactos ambientales absolutos y difiere de otras técnicas, como por ejemplo la evaluación del impacto ambiental, ya que constituye un enfoque relativo, basado en una unidad funcional. Asimismo, el ACV es una técnica iterativa y cada fase utiliza resultados de las otras.

2.1.1. Metodología

Los estudios de ACV se componen de cuatro fases. Estas son la definición del objetivo y el alcance de estudio, el análisis del inventario, la evaluación del impacto, y la interpretación (fig. 2.1.).

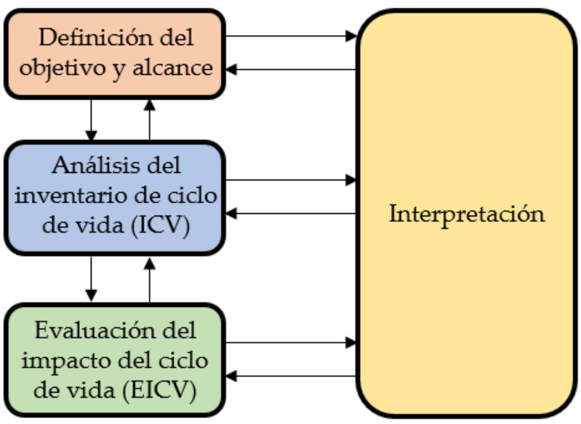


Fig. 2.1. Etapas del análisis de ciclo de vida. Fuente: ISO (2006a)

(i) Objetivo y alcance

La definición del objetivo del ACV comprende varios aspectos. En primer lugar, la definición de la aplicación prevista de los resultados. Implica también la identificación del público objetivo, ya que según a quién se dirija el estudio (p. ej.: si es para uso interno de la empresa, para divulgar externamente, si se trata de púbico especializado en el tema o no) se suelen requerir diferentes requisitos en el análisis. También se deben detallar las razones para llevar a cabo el estudio, identificando especialmente el contexto, el cual es clave para determinar los métodos más apropiados para el modelado (p. ej.: modelado atribucional o consecuente, enfoque por asignación o sustitución). Asimismo, se deben identificar las limitaciones en la aplicación de los resultados obtenidos, ya sea por la metodología utilizada, las hipótesis realizadas, o porque no se aborda la totalidad de los impactos involucrados en el proceso. Por último, en esta fase se debe establecer explícitamente si el estudio incluye una aserción comparativa destinada a ser divulgada al público, ya que en ese caso se debe cumplir con una serie de requisitos adicionales (CE, 2010).

El alcance abarca varios aspectos, entre los cuales destacan la definición del sistema y sus límites (procesos unitarios a ser incluidos en el sistema), así como la unidad funcional del estudio (unidad de referencia con base en la cual se relacionan las entradas y salidas), las categorías de impacto a evaluar y las metodologías a utilizar para dicha evaluación. Es importante que el alcance esté lo suficientemente bien definido para asegurar que la amplitud, profundidad y nivel de detalle del estudio sean compatibles y suficientes para alcanzar el objetivo establecido (ISO, 2006a). En el caso de los cítricos, el ciclo productivo se compone de cuatro etapas principales e inicia con la etapa de vivero, que suele durar algo más de dos años. Durante el tercer año, el árbol se trasplanta en el campo, donde inicia la etapa de baja producción, durante la cual inicialmente no produce cítricos por unos tres años para, posteriormente, comenzar a dar frutos de manera gradual por otros tres años. En el séptimo año, el árbol alcanza la etapa de plena producción, la cual tiene una duración aproximada de 20 años y el rendimiento del árbol es máximo. A esta etapa le sigue la fase de senescencia, en la que el rendimiento comienza a disminuir, aunque el árbol se suele renovar antes de que empiece, debido a razones económicas. Normalmente, las evaluaciones del impacto ambiental de la producción citrícola se centran en un año de plena producción, sin tener en cuenta el resto de las etapas productivas. Por ello, en el capítulo 7 de la presente tesis se estudia la relevancia de los impactos ambientales de las etapas de vivero y baja producción en el ciclo productivo citrícola, con el objetivo de entender si estos debieran considerarse y asignarse a los años de plena producción del árbol.

(ii) Análisis del inventario del ciclo de vida (ICV)

El análisis del inventario implica la recopilación de datos relevantes desde el punto de vista ambiental y los procedimientos de cálculo para cuantificar las entradas y salidas del sistema. Los datos que se recopilan en el ICV son principalmente las entradas de energía y materia prima, los productos, coproductos y residuos, y las emisiones al aire y vertidos al agua y suelo. Una vez recopilados los datos, se procede a la etapa de cálculo, que incluye la validación de los datos recopilados (p. ej.: mediante balances de materia) y su relación con los procesos unitarios y con el flujo de referencia de la unidad funcional. Por último, para los sistemas que den lugar a más de un producto o sistemas en los que se reciclen productos, se debe realizar una asignación de flujos (ISO, 2006a).

Al realizar un ICV es importante distinguir entre los procesos primarios y secundarios que componen el sistema de estudio, pues se modelizan de manera diferente. Los primarios se definen como aquellos que están bajo el control del responsable del proceso para el cual se lleva a cabo el ACV, mientras que los secundarios son aquellos en los que el responsable de la toma de decisiones no puede ejercer ninguna influencia o, en el mejor de los casos, puede ejercer influencia de forma indirecta (Frischknecht, 1998). En términos simples, los primeros son diseñados por quien lleva a cabo el estudio, mientras que los segundos se seleccionan de fuentes secundarias, comúnmente de bases de datos de referencia, los cuales, si procede, se adaptan a las condiciones del estudio (Kuczenski et al., 2018). En cuanto a los datos de los procesos primarios, su representatividad es un aspecto de vital importancia en los ACV agrícolas dada la alta variabilidad tanto de los parámetros climáticos como de las prácticas agrícolas, de ahí el interés de considerar varias temporadas de cultivo al recopilar los datos de inventario. Este aspecto se aborda en el capítulo 3, donde se hacen recomendaciones para la obtención de ACV más representativos y se contempla en los ACV realizados en los capítulos 4, 5, 6 y 7. Respecto a los datos secundarios, para el desarrollo de la presente tesis se han utilizado bases de datos con el objetivo de modelar el consumo de recursos y las emisiones de procesos como la producción fertilizantes y pesticidas, su transporte, el uso del tractor y de la bomba de riego, y la producción de estructuras del invernadero. Las bases de datos utilizadas fueron GaBi v.10 (Sphera Solutions GmbH, 2022), Ecoinvent 3.8. (Moreno Ruiz et al., 2021, Wernet et al., 2016) y Ecoinvent 3.9.1 (Fitzgerald y Sonderegger, 2022, Wernet et al., 2016).

Un aspecto metodológico de relevancia en los ICV agrícolas es el modelado de las emisiones de fertilizantes y pesticidas, así como la estimación del consumo de agua por el cultivo. Se trata de datos de especial relevancia dada su dependencia del sitio, además de la complejidad que implica su correcto modelado debido a la cantidad de parámetros que influyen en ellos. En este sentido, el Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) define distintos niveles de complejidad metodológica y requisitos de datos, siendo el nivel 1 el método básico, el nivel 2 el intermedio y el nivel 3 el más exigente. Los niveles 2 y 3 generalmente se consideran más precisos (IPCC, 2019). En esta línea, diversas guías se han desarrollado para ayudar a los practicantes en el modelado de las emisiones asociadas con la aplicación de fertilizantes, entre ellas las propuestas por el Programa Europeo de Seguimiento y Evaluación (EMEP) de la Agencia Europea de Medio Ambiente (EEA) (EMEP/EEA, 2019), las propuestas por Nemecek et al. (2019) y las propuetsas por el IPCC (IPCC, 2019, 2006), así como para las emisiones derivadas de la aplicación de pesticidas, como por ejemplo el PestLCI (Dijkman et al., 2012). A lo largo de la presente tesis se hace uso de todos ellos, a la vez que se realiza una comparación entre los resultados obtenidos para el modelado de las emisiones nitrogenadas, aplicando distintos niveles de complejidad metodológica. Otro dato de inventario a destacar en los ICV agrarios es el modelado del consumo de agua por parte del cultivo. Teniendo en cuenta que las normas ISO (ISO, 2014) definen el consumo de agua como «el agua extraída de una cuenca, pero no devuelta a ella», es importante que este parámetro no sea calculado simplemente como el agua irrigada. En este sentido, durante la tesis se utilizan diversos métodos de cálculo, como el balance de suelo en la zona radicular considerando la evapotranspiración en condiciones de estrés hídrico propuesto por Allen et al. (1998) o la suma de los valores de evaporación y absorción de agua del balance hídrico obtenido con el modelo LEACHM (Hutson y Wagenet, 1992).

(iii) Evaluación del impacto del ciclo de vida (EICV)

Esta fase tiene como propósito conocer y evaluar la magnitud y significancia de los impactos ambientales potenciales de un sistema. De esta manera, se asocian los datos de inventario con las categorías de impacto ambiental y sus respectivos indicadores. Además de la definición de las categorías de impacto, indicadores y modelos de caracterización, dentro de esta fase destacan dos pasos de especial relevancia: la clasificación y la caracterización (ISO, 2006a). La primera constituye la asignación de los resultados del inventario y responde a la pregunta «¿a qué categoría de impacto contribuye esta emisión?», y la segunda trata sobre el cálculo de los resultados del indicador de categoría y responde a la pregunta «¿en cuánto contribuye?». A lo largo de la presente tesis se evaluaron distintas categorías de impacto, tanto de punto medio (PM, *midpoint*, en inglés) como de punto final (PF, *endpoint*, en inglés). La diferencia entre categorías de impacto de PM y de PF viene dada por la vía de impacto, es decir, por la cadena causa-efecto del mecanismo ambiental evaluada. Según el *Manual ILCD* (CE, 2011), una categoría de impacto de PM proporciona indicadores para la comparación de intervenciones ambientales en la cadena causa-efecto entre las emisiones o consumo de recursos y el nivel de PF. Por su lado, las categorías de PF tienen en cuenta el efecto sobre un atributo o aspecto del entorno natural, las llamadas áreas de protección, en concreto la salud humana, los ecosistemas y los recursos, identificando un problema ambiental o motivo de preocupación (ISO, 2006a). En esta línea, los métodos de PF son modelos de caracterización que proporcionan indicadores para estas áreas de protección, o a un nivel cercano. En la tabla 2.1. se muestran las categorías de impacto evaluadas, especificando entre paréntesis si son de PM o de PF.

Tabla 2.1. Categorías de impacto evaluadas y métodos de evaluación de impacto utilizados en los distintos capítulos de la tesis

Categoría de impacto	Unidad	Método de evaluación del impacto	Capítulo 4	Capítulo 5	Capítulo 6	Capítulo 7
Cambio climático (PM)	kg CO_2 eq.	EN 15804 + A2	X	X		X
Agotamiento del ozono (PM)	kg CFC-11 eq.	EN 15804 + A2	X	X		X
Acidificación (PM)	Moles de H^+ eq.	EN 15804 + A2	X			X
Acidificación acuática (PM)	kg SO_2 eq.	Impact 2002 + v2.1		X		
		IMPACT World +		X		
Acidificación terrestre (PM)	kg SO_2 eq.	Impact 2002 + v2.1		X		
		IMPACT World+		X		
Eutrofización de agua dulce (PM)	kg P eq. kg PO_4 P-lim eq.	EN 15804 + A2	X	X	X	X
		IMPACT World+		X		
Eutrofización marina (PM)	kg N Eq.	EN 15804 + A2	X	X	X	X
	kg N N-lim eq.	IMPACT World+		X		
Eutrofización terrestre (PM)	Moles de N eq.	EN 15804 + A2 IMPACT World+	X	X		X
Formación de ozono fotoquímico, salud humana (PM)	kg NMVOC eq.	EN 15804 + A2	X	X		X
Uso de recursos, minerales y metales (PM)	kg Sb eq.	EN 15804 + A2	X	X		X
Uso de recursos, fósiles (PM)	MJ	EN 15804 + A2	X	X		X
Ecotoxicidad (PM)	CTUe (fracción de especies potencialmente afectada)	USEtox 2.12	X	X	X	X
Toxicidad humana, cáncer (PM)	CTUh (casos de enfermedad)	USEtox 2.12	X	X		X
Toxicidad humana, no canc. (PM)	CTUh (casos de enfermedad)	USEtox 2.12	X	X		X
Escasez de agua azul (PM)	m^3eq.	AWARE	X	X	X	X

Tabla 2.1. (cont.). Categorías de impacto evaluadas y métodos de evaluación de impacto utilizados en los distintos capítulos de la tesis

Categoría de impacto	Unidad	Método de evaluación del impacto	Capítulo 4	Capítulo 5	Capítulo 6	Capítulo 7
Daños a la salud humana debido al consumo de agua (PF)	DALY (años de vida ajustados por discapacidad)	LC-IMPACT 1.3			X	
Daños a los ecosistemas debido al consumo de agua (PF)	PDF (fracción potencialmente desaparecida)	LC-IMPACT 1.3			X	
Potencial de privación debido a la polución del agua (PM)	m^3	Pierrat et al. (2023)			X	
Potencial de erosión (PM)	kg	LANCA® v 2022.1			X	
Potencial de reducción de regeneración de aguas subterráneas (PM)	m^3	LANCA® v 2022.1			X	
Potencial de reducción de infiltración (PM)	m^3	LANCA® v 2022.1			X	
Potencial de Reducción de Filtración Fisicoquímica (PM)	mol	LANCA® v 2022.1			X	
Potencial de Reducción de Carbono Orgánico del Suelo (PM)	kg	LANCA® v 2022.1			X	
Pérdida de especies debido al uso de suelo (PF)	especies	ReCiPe 2016 v1.1 Chaudhary y Brooks (2018)			X	

Tabla 2.1. (cont.). Categorías de impacto evaluadas y métodos de evaluación de impacto utilizados en los distintos capítulos de la tesis

Categoría de impacto	Unidad	Método de evaluación del impacto	Capítulo 4	Capítulo 5	Capítulo 6	Capítulo 7
Pérdida de especies debido a la eutrofización marina (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies debido a la eutrofización del agua dulce (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies en ecosistemas de agua dulce debido al cambio climático (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies en ecosistemas terrestres debido al cambio climático (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies en ecosistemas de agua dulce debido al consumo de agua dulce (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies en ecosistemas terrestres debido al consumo de agua dulce (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies debido a la acidificación terrestre (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies debido a la formación de ozono fotoquímico (PF)	especies	ReCiPe 2016 v1.1			X	
Pérdida de especies debido al uso de la tierra (PF)	especies	ReCiPe 2016 v1.1			X	

Dentro de la EICV hay dos aspectos metodológicos que destacan en la evaluación de sistemas agrícolas, que son la regionalización de los impactos ambientales y la evaluación de categorías de impacto recientemente desarrolladas para su aplicación en ACV.

Como se ve en la tabla 2.1., en la EICV se pueden evaluar distintas categorías de impacto. Algunas de ellas, como el cambio climático, la destrucción del ozono estratosférico o el agotamiento de recursos abióticos, son categorías de impacto de efecto global y por ello son independientes del lugar de emisión o extracción. Pero otras, por ejemplo, la eutrofización o la acidificación, describen impactos que tienen efectos a escala regional o local y, por lo tanto, varían ampliamente según el lugar donde se llevan a cabo las prácticas agrícolas y las condiciones ambientales regionales o locales asociadas (Verones et al., 2020). Por este motivo, en los últimos años se han desarrollado metodologías de evaluación de impacto regionalizadas, como IMPACT World+ (Bulle et al., 2019) que permite la cuantificación de impactos de punto medio y punto final, o LC-IMPACT (Verones et al., 2020) para la cuantificación de impactos de punto final. Ambas metodologías presentan factores de caracterización de los impactos en diferentes ámbitos: global, continental, país y nativo. En la presente tesis se aplican metodologías regionalizadas para el cálculo de algunas categorías de impacto, tanto en el capítulo 5 como en el capítulo 6.

En cuanto a la evaluación de los impactos ambientales relacionados con la producción agrícola, hay categorías que tienen especial relevancia debido a su estrecha vinculación; entre ellas, las relacionadas con el uso del suelo y el uso del agua. Dado que son categorías que implican un alto grado de complejidad en su modelado debido a los procesos involucrados y su alta dependencia del sitio donde se lleva a cabo el proceso, su incorporación en los softwares comerciales de ACV es reciente. Estas se evalúan en el capítulo 6 de la presente tesis.

(iv) Interpretación del ciclo de vida

La fase de interpretación debe proporcionar resultados que sean coherentes con el objetivo y el alcance definidos, que aporten conclusiones, expliquen las limitaciones y proporcionen recomendaciones (ISO, 2006a). De esta forma, una correcta interpretación del ciclo de vida debe contemplar tres pasos (CE, 2010): primero, se identifican los aspectos relevantes, es decir, las etapas, procesos, flujos y categorías de impacto más importantes o las principales elecciones metodológicas que tienen el potencial de influir en la precisión de los resultados finales del ACV. Luego, se evalúan estos aspectos, lo cual implica la verificación de su integridad y consistencia y la verificación de la sensibilidad en combinación con análisis de escenarios y de incertidumbre. Finalmente, se identifican las limitaciones del estudio y los resultados de la evaluación se utilizan en la formulación de conclusiones y recomendaciones del estudio.

2.2. SISTEMAS DE ESTUDIO

Todos los casos de estudio abordados en la presente tesis se ubican en Uruguay, país de América del Sur, conformado por 19 entidades subnacionales de primer orden denominadas departamentos. Se encuentra situado en la parte oriental del Cono Sur y limita con Brasil por el noreste y con Argentina al oeste y suroeste. Ocupa una superficie de 176.215 km^2, contando en el 2021 con 3.426.260 de habitantes (BM, 2023c). El clima es subtropical húmedo, también conocido como pampeano, a excepción de una franja muy pequeña de clima oceánico en el sudeste. La temperatura media anual es de 17,5 ºC, variando desde unos 19 ºC en la zona noroeste hasta unos 16 ºC en la costa sureste. Las temperaturas más altas se presentan en enero y febrero, mientras que las más bajas son en junio y julio. Las lluvias son muy irregulares. Según el Instituto Uruguayo de Meteorología (INUMET) tienen su valor mínimo en el sur, sobre la costa, con casi 1000 mm, y su valor máximo en el norte, en la frontera con Brasil, con aproximadamente 1400 mm (INUMET, 2023), aunque presentan alta variabilidad, especialmente en los últimos años (Barreiro et al., 2019).

Para los sistemas estudiados en los capítulos 4, 5 y 6, las etapas consideradas en el ACV son la producción de fertilizantes y pesticidas, su transporte al campo y su aplicación, el uso de maquinaria para prácticas agrícolas (incluida la producción de combustible) y el riego (incluida la producción de electricidad para el bombeo), y se ilustran en la fig. 2.2.

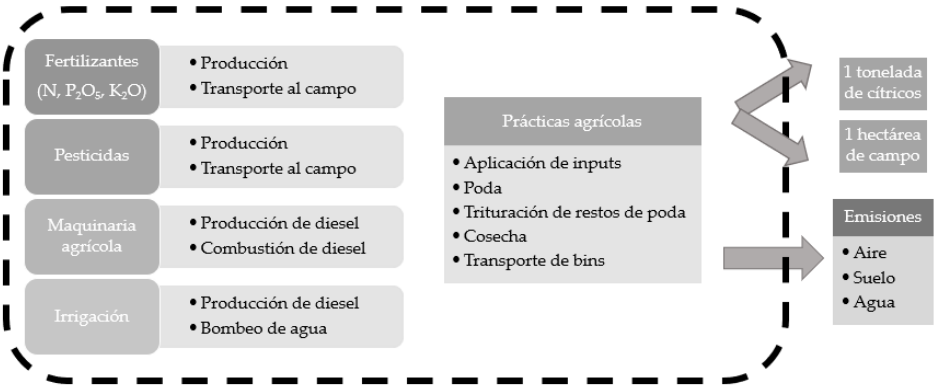


Fig. 2.2. Límites del sistema y etapas del ciclo de vida incluidas en los ACV presentados en los capítulos 4, 5 y 6 (adaptado de Cabot et al. (2023)).

Los meses de cultivo para las distintas variedades evaluadas se encuentran representados en la tabla 2.2.

Tabla 2.2. Meses de cultivo de las variedades de cítricos estudiados

<table>
<tr><th></th><th>E</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th></tr>
<tr><td rowspan="3">Año 1</td><td colspan="7"></td><td colspan="5">Limón Lisbon y Fino</td></tr>
<tr><td colspan="7"></td><td colspan="5">Mandarina Afourer</td></tr>
<tr><td colspan="9"></td><td colspan="3">Naranja Valencia</td></tr>
<tr><td rowspan="3">Año 2</td><td colspan="7">Limón Lisbon y Fino</td><td colspan="5"></td></tr>
<tr><td colspan="7">Mandarina Afourer</td><td colspan="5"></td></tr>
<tr><td colspan="9">Naranja Valencia</td><td colspan="3"></td></tr>
</table>

2.2.1. Campo en el sur para el cultivo de limón

El campo estudiado se encuentra ubicado en Kiyú, departamento de San José, al sur de Uruguay, región donde se concentra la producción de limones para consumo en fresco (fig. 2.3.). Tiene una superficie total de 244 ha, con cultivos de limón y mandarina y suelos dominantes de textura limoarcillosa (Brunosoles/Vertisoles), 10.8b según la clasificación CONEAT publicada por el Instituto Nacional de Investigación Agropecuaria (INIA) (INIA, 2023a). Para el período de estudio (2016-2020), la precipitación media anual fue de 1010 mm, la evapotranspiración potencial de 558 mm y la temperatura media de 17,0 ºC (INIA, 2023b). La temporada de cultivo tiene lugar de agosto a julio (tabla 2.2.), mes en el que los limones se cosechan manualmente. Se fertiliza de septiembre a diciembre mayormente mediante fertiirrigación. La aplicación de pesticidas se realiza vía foliar de septiembre a noviembre, excepto el óxido cuproso, cuya aplicación se extiende hasta mayo. El riego se realiza por goteo de septiembre a marzo mediante una bomba eléctrica alimentada desde un pozo subterráneo de aproximadamente 30 m de profundidad.

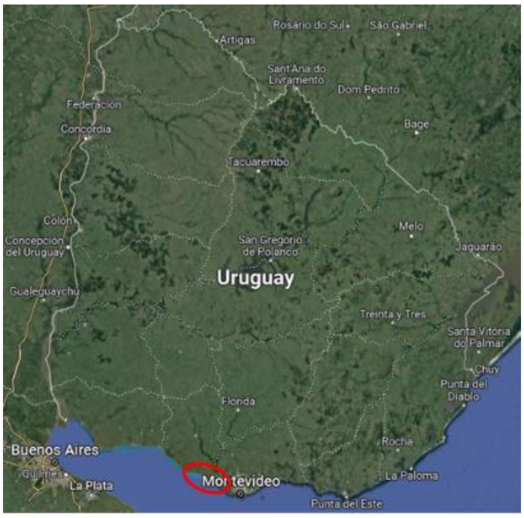


Fig. 2.3. Ubicación del campo de estudio productor de limones

2.2.2. Campo en el norte para el cultivo de mandarina y naranja

El campo estudiado se encuentra ubicado en Quebracho, departamento de Paysandú, al noroeste de Uruguay, región donde se concentra la producción de mandarinas y naranjas (fig. 2.4.). Cuenta con una superficie total de 272 ha, con plantaciones de estas especies. Los suelos dominantes son Planosoles/Argisoles y tienen texturas desde francolimosas a francoarenosas, 9.3 según la clasificación CONEAT (INIA, 2023a). Para el período de estudio (2016-2022), la precipitación media anual fue de 1348.9 mm, la evapotranspiración potencial de 1113 mm y la temperatura media de 19,6 ºC (INIA, 2023b). La temporada de cultivo tiene lugar de agosto a julio para las mandarinas Afourer y de octubre a septiembre para las naranjas Valencia (tabla 2.2.). La cosecha se realiza manualmente para ambas especies. La fertilización se lleva a cabo de septiembre a marzo para mandarinas y de octubre a marzo para naranjas vía fertiirrigación, aplicación foliar y aplicación directa al suelo. La aplicación de pesticidas se lleva a cabo durante todo el año vía foliar para combatir diferentes plagas, principalmente antracnosis, melanosis, sarna, ácaros, minador de los cítricos y cochinilla. El riego se realiza por goteo de septiembre a febrero para mandarinas y de octubre a abril para naranjas mediante una bomba eléctrica alimentada desde un lago.

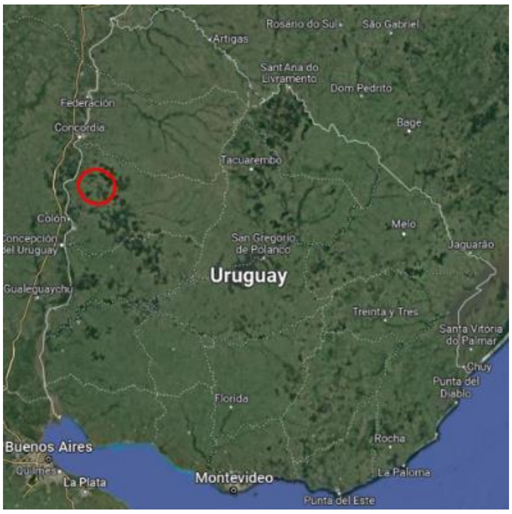


Fig. 2.4. Ubicación del campo de estudio productor de mandarinas y naranjas

2.2.3. Vivero para limones y mandarinas

El vivero estudiado se encuentra ubicado en Rodríguez, departamento de San José, al sur de Uruguay, región donde se concentran los viveros citrícolas del país. Está compuesto por 31 invernaderos multitúnel formados por 2 túneles con aberturas de ventilación lateral y frontal superior y una antecámara de doble puerta. Cada invernadero tiene un área de aproximadamente 450 m^2 y cuenta con un marco de acero galvanizado, paredes y techos de nylon de 150 μm y piso de piedras trituradas. El proceso productivo consta de diferentes pasos que duran hasta 28-32 meses (tabla 2.3.). Las etapas consideradas en el ACV son la producción y el transporte de insumos y sustratos, las operaciones agrícolas, el riego, la producción de infraestructura y las emisiones en el campo.

Tabla 2.3. Etapas en la producción de plantones en vivero

	E	F	M	A	M	J	J	A	S	O	N	D
Año 1					(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)-(2)
Año 2	(1)-(2)	(2)	(2)-(3)	(2)-(3)	(2)-(3)	(2)	(2)	(2)	(2) -(4)	(2)-(4)	(2) -(4)	(2)
Año 3	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)	(2)-(5)	(2)-(5)	(2)-(5)	(2)-(5)

(1) cultivo en semillero; (2) cultivo en maceta; (3) injerto de otoño; (4) injerto de primavera; (5) salida de las plantas al campo

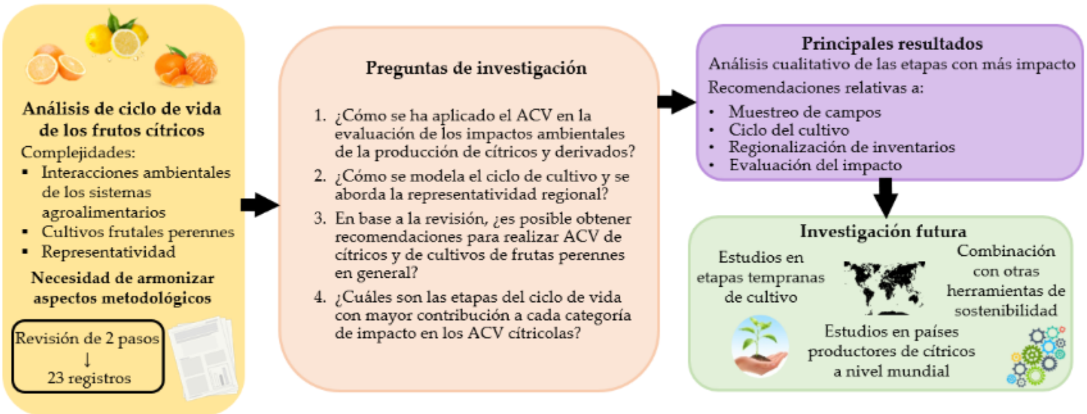
Parte II. Resultados

El **capítulo 3** se basa en el siguiente artículo:

Cabot MI, Lado J, Clemente G, Sanjuán N. 2022. Towards harmonised and regionalised life cycle assessment of fruits: A review on citrus fruit. Sustainable Production and Consumption, 33. https://doi.org/10.1016/j.spc.2022.07.024

3. HACIA UNA EVALUACIÓN DEL CICLO DE VIDA DE FRUTAS ARMONIZADA Y REGIONALIZADA: UNA REVISIÓN EN CÍTRICOS

Resumen gráfico:



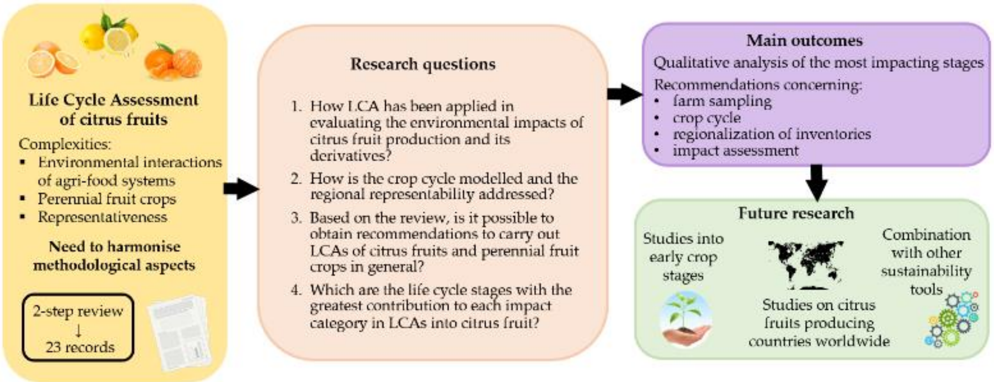
Resumen: El sector citrícola es relevante en el ámbito mundial. Teniendo en cuenta la gran contribución de los sistemas agroalimentarios a los impactos ambientales, evaluarlos y reducirlos puede generar una contribución positiva al medioambiente. El análisis del ciclo de vida (ACV) es una herramienta muy extendida que se utiliza para cuantificar las complejas interacciones ambientales de los sistemas agroalimentarios en general y de los cultivos de frutas perennes en particular. Sin embargo, ciertos aspectos metodológicos deben armonizarse para llevar a cabo ACV de frutas útiles y representativos. El objetivo de este estudio es proporcionar una revisión descriptiva y crítica actualizada de los últimos avances de la investigación de ACV en cítricos.

Nuestro objetivo es identificar las principales decisiones metodológicas, prestando especial atención a la modelización del ciclo de cultivo y la representatividad regional. Teniendo esto en cuenta, se proponen recomendaciones para una aplicación armonizada del ACV en cítricos, identificando áreas que merecen más investigación. También se identifican los puntos críticos principales del proceso productivo para comprender hacia dónde deben dirigirse los esfuerzos de mejora. Para ello se realizó una búsqueda bibliográfica en dos pasos y se obtuvo una muestra final de 23 estudios. La producción de pesticidas y fertilizantes junto con sus emisiones en el campo son los principales puntos críticos en los artículos revisados. En cuanto a las áreas donde se requiere más investigación, se detecta una falta de estudios sobre las primeras etapas de producción de cítricos. La representatividad del campo de estudio, tanto temporal como espacial, destaca como un tema crítico al evaluar la producción regional de frutas. Esto implica mejorar los inventarios del ciclo de vida mediante el uso de métodos específicos del sitio para estimar las emisiones de fertilizantes y plaguicidas, el desarrollo de conjuntos de datos regionalizados de insumos agrícolas y el fortalecimiento de los inventarios de agua. En cuanto a la evaluación de impactos, se debe fomentar la estimación tanto de la escasez de agua como de los impactos sobre la biodiversidad, junto con el uso de métodos de caracterización de impactos regionalizados. El desarrollo de estudios de ACV en países productores de cítricos fuera de la Unión Europea junto con el uso de otras herramientas de sostenibilidad puede servir de apoyo en el desarrollo de políticas ambientales. Los resultados de esta revisión pueden ser beneficiosos tanto para los profesionales de ACV como para los responsables de la toma de decisiones y allanar el camino para una producción de cítricos más responsable y sostenible.

Palabras clave: análisis de ciclo de vida; impacto medioambiental; frutas cítricas; ciclo de cultivo perenne; armonización; regionalización

3. TOWARDS HARMONISED AND REGIONALISED LIFE CYCLE ASSESSMENT OF FRUITS: A REVIEW ON CITRUS FRUIT

Graphical abstract:



Abstract: The citrus fruit sector is globally relevant. Considering the great contribution of agri-food systems to environmental impacts, assessing and reducing them can make a positive contribution to the environment. Life Cycle Assessment (LCA) is a widespread tool used to quantify the complex environmental interactions of agri-food systems in general and perennial fruit crops in particular. However, methodological aspects need to be harmonised to perform useful and representative LCAs on fruits. The goal of this study is to provide an updated descriptive and critical review of the state of the art of LCA research into citrus fruits. We aim to identify the main methodological decisions, paying special attention to crop cycle modelling and regional representability. Bearing this in mind, we propose recommendations for a harmonized application of LCA on citrus fruits, identifying areas worthy of further research. The main hotspots of the production process are also identified, to understand where improvement efforts should be directed to. To this end, a two-step search was carried out and a final sample of 23 records was obtained. The production of both pesticides and fertilizers together with their on-field emissions are the main hotspots in the reviewed articles. Regarding areas for further research, a lack of studies into the early stages of citrus fruit production is detected. Farm representativeness, both temporal and spatial, is highlighted as a critical issue when assessing regional fruit production. This implies improving life cycle inventories, namely by using site-specific methods to estimate fertiliser and pesticide emissions, developing regionalized datasets of agricultural inputs, and strengthening water inventories. As to the impact assessment, the estimation of both water scarcity and biodiversity impacts is encouraged, together with the use of regionalised impact characterisation methods. Boosting LCA studies on citrus fruits producing countries outside the European Union along with the use of other sustainability tools can support the development of environmental policies. The results of this review can be beneficial for both LCA practitioners and decision-makers, paving the way for a more responsible and sustainable citrus fruit production.

Keywords: Life Cycle Assessment; Environmental impact; Citrus fruits; Perennial crop cycle; Harmonisation; Regionalisation.

3.1. INTRODUCTION

Food production will need to increase by around 70% by 2050 to feed the projected population growth (Bell and Horvath, 2020). This increase in production is of great concern for both the authorities and the consumers themselves (UN, 2019). Ensuring food security requires fundamental changes in the way we produce and consume. In fact, United Nations Sustainable Development Goal number 12, "responsible production and consumption", seeks to create net gains from economic activities by reducing resource consumption, degradation, and pollution. It thus raises the need to adopt a systemic approach and achieve cooperation between participants in the supply chain, from the producer to the final consumer (UN, 2019). 'Business as usual' is no longer an option, hence, achieving a sustainable agriculture is an agreed and essential objective, which requires the application of methods to identify the environmental hotspots of agricultural processes and the implementation of techniques to improve their environmental performance (Nicoló et al., 2015). The agri-food sector is a relevant contributor to environmental impacts *via* resource depletion, land degradation, air emissions, or waste generation (Beccali et al., 2009) and, ironically, is both a significant contributor to climate change while simultaneously being affected by it (Thornton and Lipper, 2014). Therefore, there is a need to understand the interactions between food security and global environmental change (Ingram, 2012) to propose and adopt solutions toward a sustainable food system.

The global importance of the citrus fruit industry can be highlighted statistically; a total of 143,756 thousand tonnes of citrus fruits were produced in 2019, of which approximately 12% are exported. The main fresh citrus fruit producing region is Asia, accounting for 50% of global production, with China

(25%) and India (9.3%) in the lead. South America is relevant as well since is responsible for 19.3% of world production, with Brazil (13.7%) leading. This country additionally stands out for its high juice production, accounting for 1,317 thousand tonnes of frozen concentrated juice in 2020. Within Europe, the Mediterranean region is the main producer, where Spain, Egypt, Turkey and Italy produce 4.2, 3.2, 3.0 and 2.0% of global citrus fruits, respectively. South Africa is another important actor, producing 2% of citrus fruits globally (FAO, 2021). Given the great importance of citrus fruit production in the agri-food sector, reducing its impacts can contribute positively to the environment. Farmers and managers of agri-food businesses need to understand where these impacts come from and how to deal with them in order to optimise production systems (Martin-Gorriz et al., 2020). Thus, reliable methods are required to identify the impact of the agricultural and horticultural product groups that have the greatest environmental damage potential.

Life Cycle Assessment (LCA) constitutes a recognised and accepted tool that aims to analyse objectively, methodically, systematically, and scientifically the environmental impacts caused by the products from their origins, such as the extraction of the raw materials necessary for their manufacture, until the products are consumed and become waste, through their processing. LCA is increasingly used to evaluate and analyse food environmental issues, but much remains to be done to attain sustainable food security; LCA, in combination with other disciplines, arises as a powerful tool with which to address these issues. It is thus important to expand the assessment of food environmental impacts, also including those of citrus fruits, to more regions and countries, considering the current systems and practices. To this end, methodological aspects should be harmonized as variations in assumptions, methodological choices, inventory data and emission factors used by LCA practitioners could lead to different results, even for similar products, increasing the uncertainty of the impact results (Escobar Lanzuela et al., 2015) and also affecting the comparability of studies (Brandão et al., 2012). Agricultural and bio-based systems are naturally variable due to the variability of climate and other agroecological factors, in addition to uncertainties related to data and process modelling (Brandão et al., 2022). Particularly, when considering the complexities of environmental interactions of agri-food systems in general, and perennial fruit crops in particular, a specific viewpoint on methodological choices and assumptions is required to perform LCAs (Sala et al., 2017). Bessou et al. (2013) reviewed LCA studies on perennial crops, paying particular attention to the farm stage, and made some recommendations for applying LCA to those systems. One year later, Cerutti et al. (2014) reviewed the state-of-the-art practice in LCA on fruit production and described a reference framework for LCA applications in fruit production systems. Among other issues, the authors propose an approach to model the whole life cycle in the orchard, recommending a four-year time interval as a minimum data requirement and advising the inclusion of at least three orchards. Since then, many studies from diverse geographical locations have been published regarding fruit production (e.g. Coppola et al., 2022; Vinyes et al., 2017; Zhu et al., 2018). Generally, fruit LCAs aim to be representative of a specific country or region, which poses methodological challenges related to a huge variability of farming systems and to a lack of data to represent the farm typologies (Pradeleix et al., 2022). In addition, regionalized case studies also require the use of regionalized impact assessments (Morais et al., 2016).

In view of the increasing application of LCA, the updating of methodological issues, and taking into account the complexity and regional particularities found in perennial fruit production systems, an updated review in this area is needed. Specifically, citrus fruits are chosen due to their importance worldwide and since, to the best of the authors' knowledge, there is so far no review study focused on this crop. In sum, this study provides an actualized descriptive and critical review on the state of the art of LCA research applied to citrus fruit, where methodological decisions of the practitioners are presented and discussed thoroughly. Throughout the review process, the authors aim at answering the following key questions:

1. How LCA has been applied in evaluating the environmental impacts of citrus fruit production and its derivatives?
2. In particular, how is the crop cycle modelled and the regional representability addressed?
3. Based on the review, is it possible to obtain recommendations to carry out LCAs into citrus fruits and on perennial fruit crops in general?
4. Which are the life cycle stages with the greatest contribution to each impact category in LCAs into citrus fruit?

With the first two questions we aim to identify trends among the key methodological choices, which will allow us to answer the third question, that is, the proposal of recommendations towards a harmonised application of LCA for regionalised citrus fruits production and, in addition, allow for the identification of areas worthy of further research. The fourth question would benefit the promotion of a more responsible and sustainable citrus fruit production, since hotspots will be detected, and farmers and managers of agri-food businesses will understand where the main changes must be implemented.

3.2. STATE-OF-THE-ART LCA APPLIED TO CITRUS FRUIT PRODUCTION

3.2.1. Literature review method

To perform the review, the methodology proposed by Denyer and Tranfield (2009) was used as a guide. The search was carried out considering two main steps (Fig. 3.1). First, the identification step, where a systematic search in Scopus and Web of Science (WOS) databases was performed to identify the articles to be considered and then a screening and eligibility step, analysing the abstract, introduction and reference sections. In the identification phase, articles, articles-in-press, books, book chapters and proceedings were screened from WOS and Scopus databases to identify scientific publications focusing on the environmental LCA of citrus fruits and derived products. The search strategy was limited to records written in the English language and combined a group of terms related to citrus fruits, namely "citrus", "orange" and "lemon", with another group including terms associated with environmental sustainability and LCA; "life cycle assessment", "LCA", "sustainability assessment", "environmental impact assessment" and "environmental sustainability", focusing their identification either in the title, keywords or abstracts, and with no filter as regards the year of publication. Then, in the screening and eligibility phase, the selected records were revised to ensure their adjustment to the scope of the review.

Given the large number of studies found by applying the aforementioned filters, an initial screening was made to select the articles that explicitly mentioned citrus fruits or fruits in the title (n=210). A second screening was performed on this group of articles, perusing the abstract and introduction, and it was found that 30% of the articles (n=63) address the use of by-products from citrus fruit processing and were, consequently, excluded. 19% of the initial sample (n=39) is related to technological aspects linked to fruit sustainability, such as remote sensing or deficit irrigation, but do not constitute environmental impact studies themselves, for which they were also excluded from the review. Finally, 39% of the 210 studies (n=82) were discarded as they deal with other sustainability issues without an LCA perspective, studying social and economic impacts or consumer preferences. A total of 26 articles (12%) were obtained. 6 records were excluded as they reviewed or integrated the others. To enrich the search, a third screening was carried out within the references cited in the selected articles and 3 new articles that meet the search criteria, that is, LCA studies on citrus fruits and derived products, were added. After applying the filters, a final sample of 23 research articles remained, which can be divided into two groups: (i) 16 studies on fresh citrus fruits (Table 3.1.), mainly focused on the agricultural stage, although 4 of them also include the postharvest stage; and (ii) 7 studies into citrus-derived products (Table 3.2.), mainly concerning the processing stage, specifically juice and essential oil manufacturing.

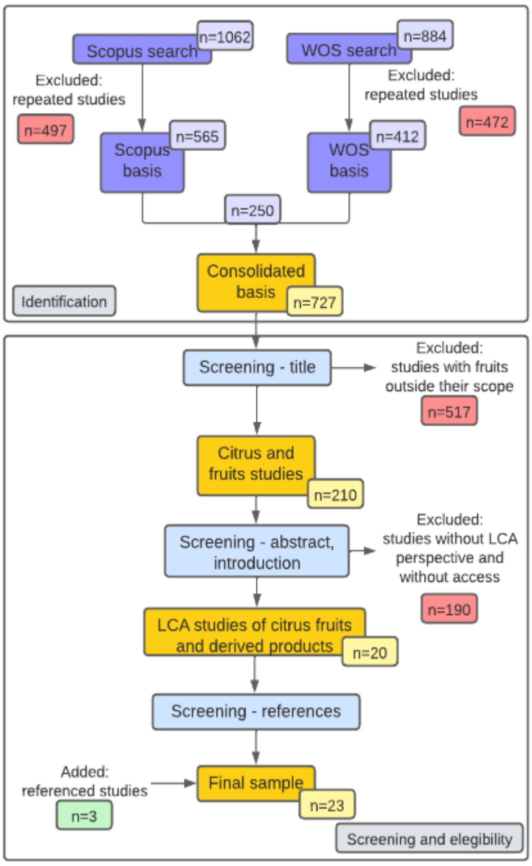


Fig. 3.1. Review strategy followed to select the LCA studies of citrus fruits based on Denyer and Tranfield (2009)

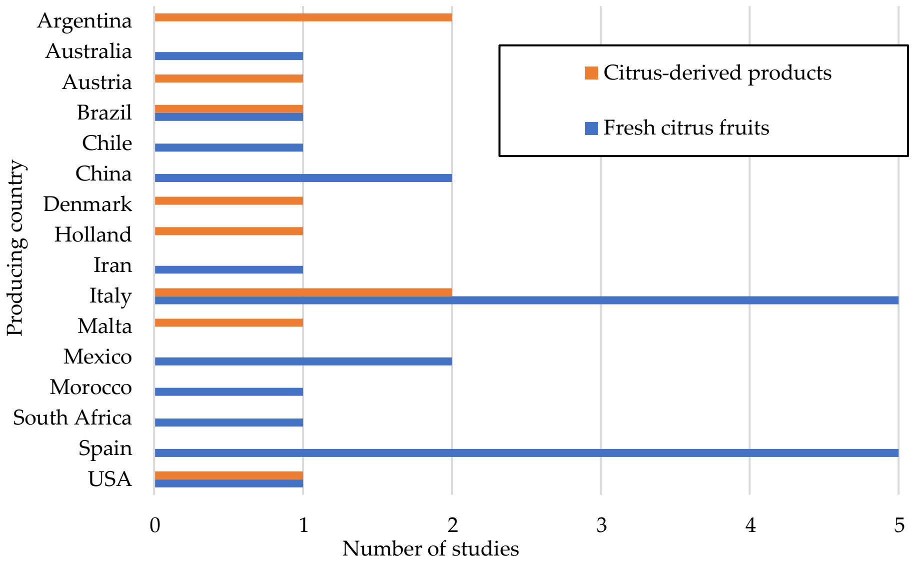
3.3. RESULTS OF SYSTEMATIC LITERATURE REVIEW ON LCA OF CITRUS FRUITS

3.3.1. General aspects of the LCA studies selected

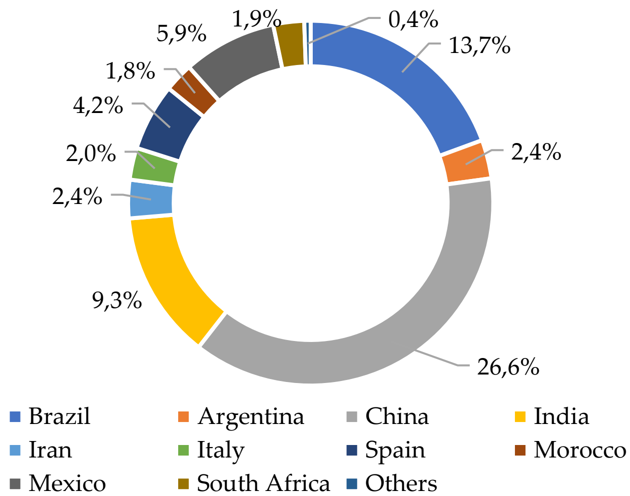
Data from the reviewed studies have been extracted and combined into several tables. The group of LCA studies on fresh citrus fruits, which is the largest, is also the most heterogeneous (Table 3.1.). It includes research articles ranging from 2009 to the most recent in 2022, which reaffirms the validity of the present research field. As shown in Table 3.1., most of them focus on western countries, specifically Italy and Spain, which are among the largest citrus fruit producers in the Mediterranean region, as remarked in Section 1. Studies have also been carried out in Brazil, the largest orange producer in South America, and China. Studies in other countries, such as India, Mexico, Iran and Argentina, are more recent. Fig. 3.2a illustrates the number of studies according to the producing country and the product analysed. To highlight the relevancy of citrus fruit production in those studies, Fig. 3.2b shows the share of worldwide citrus fruit production of each producing country identified in the review.

Among citrus fruit species, oranges are the most studied, followed by lemons and mandarins, leaving grapefruit aside. This is coherent with the world production ranking, where over 53% of the production of citrus fruit corresponds to oranges and grapefruits account for under 7 % (FAO, 2021). Only one study into Navel oranges (Nicolo et al., 2017) follows the Product Category Rules (PCRs) for fruits and nuts. The reviewed studies only cover the environmental dimension of sustainability except for four studies (De Luca et al. 2014; Nicolo et al., 2017; Pergola et al., 2013; Ribal et al., 2009), which consider the economic dimension through Life Cycle Costing (LCC). None of the reviewed studies includes the social dimension.

Fewer studies analyse the environmental impacts of citrus by-products. Beccali et al. (2009; 2010) study the environmental impacts of the production of lemon and orange essential oils and natural and concentrated juice in Italy. Machin Ferrero et al. (2021) and Machin Ferrero et al. (2022) assess the production and processing of lemons in Argentina to obtain juice and other coproducts (e.g. essential oil and dehydrated peel, among others). Knudsen et al. (2011) assess the manufacturing of organic orange juice in Brazil that is then exported to Denmark. Roibás et al. (2018) calculate the carbon footprint of orange juice marketed in Malta, while Dwivedi et al. (2012) assess the global warming impact of concentrated orange juice produced in Florida (USA).



(a)



(b)

Fig. 3.2. (a) Number of LCA studies according to the producing country and the product analysed. (b) Percentage of worldwide citrus fruit production corresponding to each producing country identified in the review. 'Others' are countries with negligible contribution (USA, Australia, and Chile)

Table 3.1. Main methodological choices as refers to the goal and scope of the reviewed LCAs of fresh citrus fruits

Reference	Producing country	Functional unit	Main goals	System boundaries
Alishah et al. (2019)	Iran	1 kg oranges and 1 ha orange orchard	Assess energy indicators and environmental impacts during the initial 7years of orange orchards	Cradle to farm gate
Bell and Horvath (2020)	Florida, Mexico, Texas, California, Australia, Chile, South Africa	1 kg oranges	Estimate the impact of cradle-to-market life-cycle seasonal GHG emissions of fresh produce commodities	Cradle to market
Bessou et al. (2016)	Morocco	1 kg fresh fruits (Sidi Aissa clementines)	Analyse how the partial modelling of the perennial cycle may affect results Make recommendations on modelling strategy and data needs	Cradle to farm gate (including nursery)
Bonales-Revuelta et al. (2022)	Mexico	1 tonne of fresh orange	Assess the environmental performance of orange production in Veracruz, Mexico	Cradle to farm gate
Coltro et al. (2009)	Brazil	1000 kg oranges for frozen concentrated orange juice	Develop a cradle-to-door inventory study of oranges for frozen concentrated juiceContribute to the development and use of the LCA in Brazil	Cradle to fruit centre entry

Table 3.1. (cont.) Main methodological choices as refers to the goal and scope of the reviewed LCAs of fresh citrus fruits

Reference	Producing country	Functional unit	Main goals	System boundaries
De Luca et al. (2014)	Italy	1 ha of planted clementines	Analyse the level of sustainability from an economic and environmental standpoint of different clementine production systems (conventional, integrated, and organic) in the Calabria Region (Italy)	Cradle to farm gate
Lo Giudice et al. (2013)	Italy	"1 p" = production of oranges in an orchard of 10.8 ha in a lifetime of 50 years (13,500 tonnes)	Quantify environmental impacts of integrated production of Tarocco oranges Assess possible improvements in the production	Cradle to distributor
Martin-Gorriz et al. (2020)	Spain	1 kg citrus fruits (oranges, lemons, and mandarins)	Quantify environmental impacts and identify key impact factors of irrigated agriculture Assess farming practices that promote sustainable production	Cradle to farm gate (including nursery)
Nicoló et al. (2015)	Italy and Spain	1 hectare	Assess environmental impacts of clementine farming systems (conventional and organic) in Italy and Spain	Cradle to farm gate

Table 3.1. (cont.) Main methodological choices as refers to the goal and scope of the reviewed LCAs of fresh citrus fruits

Reference	Producing country	Functional unit	Main goals	System boundaries
Nicolo et al. (2017)	Italy	1 kg packaged oranges	Implement an LCA for the production and packaging of Navel oranges, following the PCRs	Cradle to fruit centre
Pergola et al. (2013)	Italy	1 hectare and 1 kg oranges and lemons for fresh consumption	Compare the sustainability of organic and conventional farming methods for lemon and orange through an energy, environmental and production cost analysis	Cradle to farm gate
Ribal et al. (2009)	Spain	1 kg oranges	Assess the eco-efficiency of 24 representative scenarios of citrus production in the Valencian Community	Cradle to farm gate
Ribal et al. (2017)	Spain	1 kg citrus fruits and 1 hectare	Compare the environmental impact of organic and conventional citrus fruits systems in the Valencia region (Spain) Assess the variability within both farming systems	Cradle to farm gate
Ribal et al. (2019)	Spain	1 kg oranges	Analyse the variability in the carbon footprint of organically and conventionally produced Valencian oranges (Spain) Determine confidence intervals from small samples and how to calculate the variability of the carbon footprint when the inventory is derived from different sources	Cradle to distributor

Table 3.1. (cont.) Main methodological choices as refers to the goal and scope of the reviewed LCAs of fresh citrus fruits

Reference	Producing country	Functional unit	Main goals	System boundaries
Yan et al. (2016)	China	1 hectare, 1 kg oranges (among other fruits), 1 g vitamin C, 1 dollar	Quantify the carbon footprint of China's orange production (among other fruits) to assess the contributions of different farm inputs Generate information for policymakers so they can identify key options to reduce GHG emissions	Cradle to farm gate
Yang et al. (2020)	China	1 hectare and 1-tonne fresh citrus fruits production	Quantify and locate the environmental cost of citrus fruits production using the LCA method Test the potential of reducing environmental costs by addressing the problems detected through field demonstrations	Cradle to farm gate

Table 3.2. Main methodological choices as refers to the goal and scope of the reviewed LCAs of citrus-derived products

Reference	Producing country	Functional unit	Main objectives	System boundaries
Beccali et al. (2009)	Italy	1 kg of each citrus fruit product (fruits, juices, essential oils)	Estimate environmental impacts of the citrus fruits chain	Cradle to distributor
Beccali et al. (2010)	Italy	1 kg of each orange and lemon-based final product (natural and concentrated juice and essential oils)	Assess environmental impacts of citrus fruits production and transformation processes to identify the most significant issues and suggest options for improvement	Cradle to distributor
Dwivedi et al. (2012)	USA	A Not From Concentrate (NFC) orange 1.893 L juice carton	Assess the global warming impact of not-from-concentrate orange juice produced in the state of Florida	Cradle to consumer
Knudsen et al. (2011)	Brazil - Denmark	1 L of organic orange juice imported to Denmark (for the analysis of organic orange juice) 1 tonne of oranges leaving the farm gate (for the comparison of orange production processes)	-Identify the environmental hotspots in the production chain of organic orange juice -Compare environmental impacts of organic and conventional orange production	Cradle to distributor

Table 3.2. (cont.) Main methodological choices as refers to the goal and scope of the reviewed LCAs of citrus-derived products

Reference	Producing country	Functional unit	Main objectives	System boundaries
Machin Ferrero et al. (2021)	Argentina	1 tonne of lemons transported to the factory 1 tonne of each final product at the factory gate (fresh fruit, essential oil, clarified concentrated juice, cloudy concentrated juice, and dehydrated peel)	-Estimate the WF profile of lemons and lemon-derived products in Tucumán -Identify the parts of the production system that contribute the most to its environmental impact and infer process options that reduce this impact	Cradle to factory gate
Machin Ferrero et al. (2022)	Argentina	1 tonne of lemons transported to the factory 1 tonne of each product (Scenario A: essential oil, concentrated juice and dehydrated peel Scenario B: essential oil, concentrated juice, limonene and ethanol)	-Present the environmental profile of lemons and derivatives in Argentina -Analyse the environmental implications of shifting from the conventional production scheme to a biorefinery that includes circular economy strategies	Cradle to the entrance of the factory Cradle to factory gate Cradle to market

Table 3.2. (cont.) Main methodological choices as refers to the goal and scope of the reviewed LCAs of citrus-derived products

Reference	Producing country	Functional unit	Main objectives	System boundaries
Roibás et al. (2018)	Pre-processing: Austria, Holland. Final processing: Malta	A 250 ml bottle of packaged orange juice	Calculate the carbon footprint of ten multi-fruit juices marketed in Malta (including orange juice)	Cradle to market

3.3.2. Review of the main methodological choices

In this section, by considering the two first research questions defined, the main methodological choices implemented in the reviewed papers are presented (Fig. 3.3.). As commented in section 1, special emphasis is made on both crop cycle modelling and data representativeness.

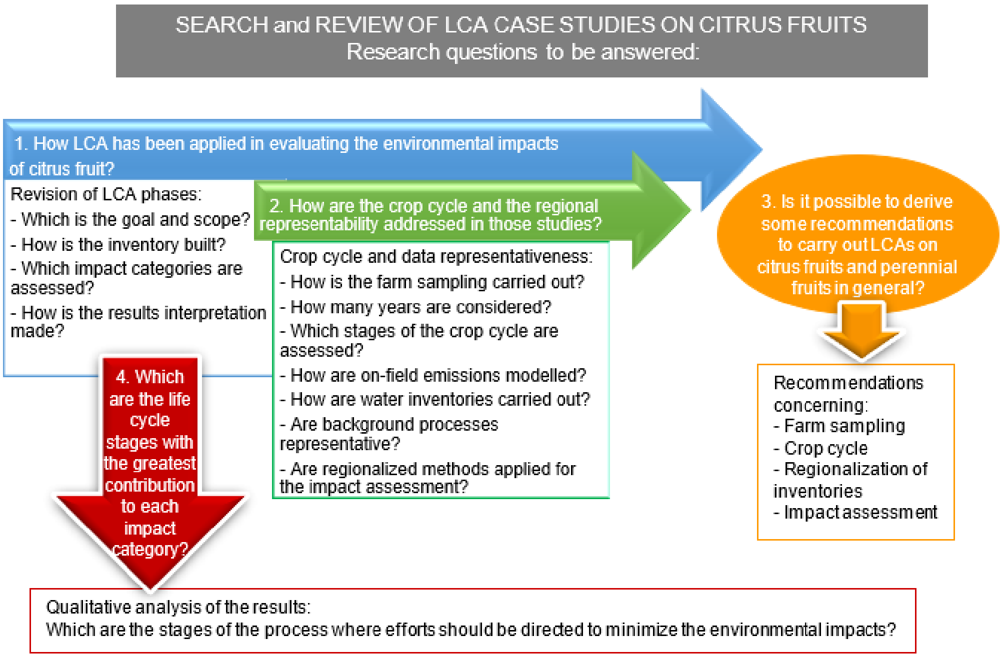


Fig. 3.3. Main methodological aspects of the LCA revised to answer the research questions

3.3.2.1. Goal and scope

Each of the LCAs reviewed aims to quantify the environmental impact of citrus fruits, with some nuances depending on the case study (Table 3.1 and Table 3.2). As for the studies on fresh citrus fruits (Table 3.1), the main goal is to assess the environmental impacts of the crop, although some authors also seek to propose practices to improve sustainability or compare production systems. Some studies, in addition, make a methodological contribution to enrich LCA practice and result analysis. Among them, Bessou et al. (2016) analyse how the partial modelling of the perennial crop cycle through non-holistic data collection may affect LCA results. Ribal et al. (2017) assess the variability of the environmental impacts due to the variability of agricultural management practices by applying a bootstrap technique. Whereas Ribal et al. (2019) go a step further and analyse the variability in the subsequent life cycle stages and how they influence the carbon footprint of oranges.

Taking into account that the main function of agricultural systems is providing food, a mass-based functional unit (e.g., 1 kg or 1 tonne) is mostly used (Table 3.1), which reflects the effects of yield on the environmental impacts. Only De Luca et al. (2014) and Nicoló et al. (2015) consider an area-based functional unit (1 ha), which refers to the ability of agricultural systems to provide ecosystem services. Several studies combine mass with area-based analysis. Yan et al. (2016) explore other functional units and use vitamin C content, as a characteristic of food that influences its commercial value, and the dollars earned from the sale of the product. This kind of functional unit, however, is heavily influenced by the economic context (Cerutti et al., 2014).

Temporal boundaries are a relevant aspect for these types of studies since citrus fruits are perennial crops, and thus they present different growth phases. As Ribal et al. (2017) specify, the total life period of an orchard is around 50 years; the first 6-7 years correspond to the low productivity phase and the following 30-35 years to the full production phase. Later, when the yield decreases (senescence phase) the trees are usually uprooted due to economic reasons. Both the dose of applied inputs and the resulting yield vary according to the growth stage.

Most of the studies set 'cradle to farm gate' system boundaries (Table 3.1), where allocation does not make sense because only one product, harvested oranges, is obtained. As regards the studies which include the postharvest stage where oranges are classified, only Ribal et al. (2019) and Machin Ferrero et al. (2021) allocate the environmental loads. The former between the main product (commercial oranges) and the by-products (oranges with unstable or stable defects, used for fodder or sold for juice manufacturing, respectively) performing an economic allocation following PAS 2050-1 guidelines (PAS 2050, 2012) and considering the price of each product when leaving the post-harvest centre. Machin Ferrero et al. (2021) consider a mass allocation between lemons destined for fresh consumption and those that will be further processed, neglecting lemon losses.

As to capital goods, most of the studies do not refer to their inclusion or exclusion and only five studies give a rationale for their exclusion. Namely, Ribal et al. (2009), Roibás et al. (2018), and Knudsen et al. (2011), because their long life means that they have minor impacts on the results. Whereas in Nicoló et al. (2015) and Ribal et al. (2017), the machinery is mostly rented, therefore its impact is also negligible as the use is more intensive than if it was used only on the studied farm.

The main goal of the LCAs of citrus-derived products is to assess the environmental impacts by identifying the main critical points (Table 3.2), and only Beccali et al. (2010) and Machin Ferrero et al. (2021) suggest improvement options. As far as the functional unit is concerned (Table 3.2), both volume (for juice) and mass of the final products are used. As to temporal boundaries, almost all the studies that provide this information use data from 1 year. Only Machin Ferrero et al. (2021) use data corresponding to the period 2012 to 2018.

Concerning the life cycle stages included in the system boundaries, a 'cradle to market/distributor' approach is considered in most of the studies, and only Dwivedi et al. (2012) assess the consumption stage (Table 3.2). A variety of allocation procedures can be found for these products. Roibás et al. (2018) allocate all the annual inputs and outputs to the final product based on their annual mass production. Knudsen et al. (2011) handle the environmental burdens between the frozen concentrated orange juice and the by-products by subtracting the avoided environmental burden of producing barley, a marginal representative for carbohydrate fodder. Beccali et al. (2009) apply mass or economic allocation depending on the process stage and the product, whereas in Dwivedi et al. (2012), only mass allocation is applied. Machin Ferrero et al. (2022; 2021) both perform mass and economic allocations based on the rationale that this decision significantly influences results for the lemon derivatives. The most affected is essential oil production, which is obtained in a much smaller mass proportion than other co-products, but its market value (per tonne) is significantly higher, while the opposite happens for dehydrated peel.

3.3.2.2. Inventory analysis

In this section, the data sources used, and their representativeness are discussed. In addition, the methods used for estimating on-field emissions from fertilisers and pesticides and water use, central to the inventories of agri-food products and highly dependent on site-specific characteristics, are reviewed.

3.3.2.2.1. Data representativeness

One of the main challenges of LCAs is to collect representative data; it is a time-consuming procedure and difficult due to the lack of sources containing detailed or quality-checked datasets, which, in turn, can affect data uncertainty (Beccali et al., 2010). The reviewed studies mostly follow the common LCA practice as to the data sources used. In particular, primary sources are used for the foreground system, that is, central processes under study (mainly farming, post-harvest operations, or juice manufacturing). These are then connected with the background process, corresponding to upstream and downstream life cycle stages (e.g., electricity, fertiliser and pesticide production, transport), which are taken from secondary data sources. Only Bell and Horvath (2020) and Martin-Gorriz et al. (2020) use secondary data for both the foreground and background systems. This can be explained by the fact that these studies aim to assess the average environmental impact of citrus fruit production in a region, namely California (USA) and Murcia (Spain), instead of studying specific farms or factories. In addition, Martin-Gorriz et al. (2020) state that the quality of all input data was evaluated following the ILCD Handbook (Joint research center, 2011) requirements and was classified as "high-quality".

Primary data are mainly gathered through direct questionnaires and interviews with farmers or other workers, offline surveys, or direct measurements. When assessing the agricultural production in a region, farm representativeness is a key issue and, as Avadí et al. (2016) state, the quality of the data gathered will influence the final accuracy of the impact results. The principal characteristics of the orchards sampled in the reviewed studies are presented in Table 3.3 as concerns both the number of farms and the number of years sampled. To take into account the interannual variability, Bessou et al. (2016) emphasize that choosing one single year of production can lead to highly uncertain results, especially in the case of alternating yield. However, most studies focus on one farming season corresponding to the full production years. Among them, Ribal et al. (2019) justify their decision on the grounds that not all the citrus fruit varieties present alternating yield and that it can be reduced through practices, such as chemical and manual thinning, a widespread technique among farmers.

Most of the reviewed authors consider sample representativeness by retrieving data from a typical farm in the region under study although they do not justify how the representativeness of the assessed farm is guaranteed. In addition, they do not explicitly state which growth stages are evaluated and, among those who do so, it is mostly the full production stage that is assessed. Three studies (Bessou et al., 2016; De Luca et al. 2014; Pergola et al., 2013) evaluate the complete cycle by extrapolating data from specific years. Alishah et al. (2019) focus specifically on the initial 7 years of cultivation due to the variable application of agricultural inputs during this period, and Machin Ferrero et al. (2021) gather data from 6 harvest seasons. In addition, Bessou et al. (2016) analyse three alternative modelling choices for the perennial crop cycle. The first is chronological modelling throughout the complete crop cycle, collecting data over the first 9 years of the crop, which includes the non-productive phase (1-3 years), and the increasing-yield phase (4–9 years), and using averaged data corresponding to years 7, 8 and 9 as a proxy for the full production years (10-25 years). For the second model, they use 3-year average data from the full production phase. The third modelling approach covers a selection of different single years from the last three years recorded (7, 8 and

9). They conclude that the share of non-productive years in the environmental impacts of perennial crops is considerable and should thus be included. De Luca et al. (2014) gather data from 5 years, which are extrapolated to the whole clementine orchard cycle (40 years), whereas Pergola et al. (2013) extrapolate data from 4 years to the whole orchard period of 50 years. In no case the authors specify to which crop maturity stage the years used for the extrapolation correspond.

The productive cycle of citrus fruits includes a nursery stage and, according to Bessou et al. (2013) and Cerutti et al. (2014), this stage must be accounted for, as well as the transport of the seedlings to the orchards. Despite this, only Martin-Gorriz et al. (2020) and Bessou et al. (2016) analyse this stage, the latter as secondary data, using the Ecoinvent process "seedling production for fruit tree". Whereas Martin-Gorriz et al. (2020) adapt the same process to the input consumption in the area of study, although they do not provide information on which data of the process is modified. The results obtained when assessing this stage are key to decide whether its inclusion is relevant when assessing citrus fruit production. In this respect, Bessou et al. (2016) state that the share of this non-productive stage to terrestrial ecotoxicity is non-negligible and Martin-Gorriz et al. (2020) highlight nursery as an important stage, although no explicit comment on its contribution to the impact results is made.

Table 3.3. Main characteristics of the orchards assessed in the reviewed LCAs of fresh citrus fruits

	Data source	Sample representativeness	Number of years sampled	Growth stages assessed
Alishah et al. (2019)	51 questionnaires	Cochran's formula is used to obtain the sample size	7 years	Initial 7 years of cultivation
Bell and Horvath (2020)	Secondary data sources (enterprise budget reports and literature averages)	Not specified	Not specified	Not specified
Bessou et al. (2016)	1 small citrus fruit orchard	The orchard represents recent production technologies	9 years (3 non-productive years and 6 years of increasing yield) (2000-2008)	Whole cycle. 3-year average of the full production phase. The last 3 years recorded.
Bonales-Revuelta et al. (2022)	Questionnaires to six regional orange farmers	Data from three municipalities of Veracruz, Mexico's largest orange producer state	Not specified	Not specified
Coltro et al. (2009)	30 orange farms. Data was gathered through in-depth questionnaires.	A sampling of 19.5% of the total orange production area of the State of São Paulo	1 season (2002-2003)	Full production

Table 3.3. (cont.) Main characteristics of the orchards assessed in the reviewed LCAs of fresh citrus fruits

	Data source	Sample representativeness	Number of years sampled	Growth stages assessed
De Luca et al. (2014)	27 farms. Questionnaires and direct interviews with farmers.	Non-probability sampling with reasoned choice and allocation in stratified sampling, where the three main techniques of cultivation are represented	5 growing seasons (2008-2013)	Full production and the whole cycle
Knudsen et al. (2011)	5 organic small-scale farms, 2 organic large-scale farms, and 6 conventional small-scale farms. Questionnaires and direct interviews.	Organic large-scale farms: 40% of the volume produced (2 out of 5 farms producing organic oranges for juice in the state of São Paulo)	1 growing season (2006-2007)	4- to 20-year-old productive orange plantations
Lo Giudice et al. (2013)	1 citrus fruit orchard	A reference farm, part of an association of citrus fruits producers	Not specified	Full production
Machin Ferrero et al. (2021)	Interviews and surveys with local experts, lemon growers, and governmental institutions to provide a regional representative sample	Not specified	6 harvest campaigns (2012-2018)	Not specified

Table 3.3. (cont.) Main characteristics of the orchards assessed in the reviewed LCAs of fresh citrus fruits

	Data source	Sample representativeness	Number of years sampled	Growth stages assessed
Machin Ferrero et al. 2022)	Interviews and surveys with local experts, lemon growers and manufacturers and technical reports	Not specified	Not specified	Not specified
Martin-Gorriz et al. (2020)	Secondary data sources (reliable public sources, scientific studies and Ecoinvent database)	Not specified	Not specified	Not specified
Nicoló et al. (2015)	Spain: 12 organic farms and 11 conventional farms Italy: 9 organic farms and 11 conventional farms. Questionnaires and interviews with farmers.	Not specified	1 growing season (2009-2010)	Not specified
Nicolo et al. (2017)	1 farm (8 plots of 1ha). Direct interviews, measurements, and secondary data sources	Not specified	1 growing season (2013-2014)	Not specified

Table 3.3. (cont.) Main characteristics of the orchards assessed in the reviewed LCAs of fresh citrus fruits

	Data source	Sample representativeness	Number of years sampled	Growth stages assessed
Pergola et al. (2013)	4 orchard systems 80 face-to-face interviews and secondary data	Representative farm size with the homogeneous characteristics of the cultivation and environment of the region	4 years (2008-2011)	Whole production cycle (*)
Ribal et al. (2009)	24 representative scenarios	A smallholding representative of current farms in the Valencian Community	Not specified	Full production
Ribal et al. (2017)	142 organic and 123 conventional. Surveys to farmers.	The average area reflects the typical smallholding of the region. Outlier detection technique applied to remove non-representative farms	1 growing season (2012–2013)	Full production
Ribal et al. (2019)	21 organic and 21 conventional. Data from surveys.	Trees in full production. Outlier detection technique applied to remove non-representative farms	1 growing season (2012–2013)	Full production

Table 3.3. (cont.) Main characteristics of the orchards assessed in the reviewed LCAs of fresh citrus fruits

	Data source	Sample representativeness	Number of years sampled	Growth stages assessed
Yan et al. (2016)	7 orange orchards. Field survey.	Authors claim they chose '5 representative sites'	1 season (2012–2013)	Not specified
Yang et al. (2020)	155 orchards. Surveys to farmers.	Typical citrus fruits orchards of Danling County, southwest China	1 season (2017-2018)	Not specified

(*) The authors do not specify how the whole production cycle was modelled from the sampled years

The analysed studies on citrus-derived products cover two stages, the farming and the industrial. Except for Knudsen et al. (2011) and Machin Ferrero et al. (2022, 2021), data for the farming stage is gathered from literature, as it is regarded as a background process. For the industrial phase, all the authors use data from one processing plant, except for Dwivedi et al. (2012) and Machin Ferrero et al. (2022, 2021), who work with data from three companies. Beccali et al. (2009) and Beccali et al. (2010) chose a representative company of the region with an annual production close to the regional average for one year. In this regard, Ribal et al., (2019) highlight the "many to few" relationship, with many farmers and few processing companies, representing the current structure of global food supply chains.

3.3.2.2.2. On-field emissions from fertilisers and soil management

The estimation of on-field emissions from fertilisers is crucial in agricultural LCAs since these have a considerable weight in the impact results and a variety of methods is available, where the most applied do not take into account the specificities of the studied site. In the following paragraphs, the methodologies used are reviewed in order to observe trends, although not all the literature reviewed explicitly states the methods used to calculate these emissions. Almost all the studies estimate nitrous oxide (N_2O) emissions by using the coefficients proposed by the Intergovernmental Panel on Climate Change (IPCC). Ribal et al. (2009) and Alishah et al. (2019) follow Brentrup et al. (2000), which in turn is based on the 1996 IPCC (Houghton et al., 1997), whereas the remaining studies use the Tier 1 emission factors of IPCC (2006). Machin Ferrero et al. (2022; 2021) use the emission factor proposed by Renouf

(2006) (6.7% of applied N) who study sugarcane production in Queensland, although their study is located in Argentina.

To estimate the ammonia (NH_3) emissions, various methods of different complexity are applied. Alishah et al. (2019) and Bonales-Revuelta et al. (2022) apply the Tier 1 emission factor from the IPCC (2006), whereas Martin-Gorriz et al. (2020) and Ribal et al. (2017) follow the Tier 2 method from EMEP/EEA guidebook (EEA, 2013). Nicoló et al. (2015) and Ribal et al. (2009) follow Brentrup et al. (2000), who estimate these emissions based on parameters such as temperature, infiltration rate and pH. Knudsen et al. (2011) estimate these emissions as 4% of N-fertiliser input, based on a study into N losses in Brazilian citrus fruits by Cantarella et al. (2003) whereas Yang et al. (2020) assume that 11.1% of N- fertiliser input is lost as NH_3, based on Ti et al. (2015), who made a nitrogen balance using data corresponding to China. Other authors use emission factors for countries different to those assessed, without giving a clear rationale for this selection. Among them, the Argentinian case studies (Machin Ferrero et al. 2022; Machin Ferrero et al., 2021) refer to Renouf (2006), who assesses emissions from sugarcane production in Queensland (Australia) and estimates them as 14.9% of N-urea applied. Beccali et al. (2009) use data from Goebes et al. (2003), an inventory of ammonia emissions from fertiliser application in the USA, although the study is located in Italy.

Nitrate (NO_3^-) leaching is mostly estimated from nitrogen balances and only Alishah et al. (2019) apply the Tier 1 emission factors from the IPCC (2006). Some authors make their own balances, and others use balance results from official publications or literature. In the first group are Bessou et al. (2016) and Beccali et al. (2009), who make their own nitrogen balances based on Brentrup et al. (2000) and Oenema et al. (1998), respectively. Nicoló et al. (2015)

and Ribal et al. (2017) use the results of the Nitrogen Balance in the Valencian Region (MARM, 2010; MAAM, 2014). Ribal et al. (2009) assume that 33% of applied N is leached, based on the study of Ramos et al. (2002) in the Valencian region, whereas Martin-Gorriz et al. (2020) assume 5% following the study of Martínez-Alcántara et al. (2012) on the Mediterranean coast of Spain and Machin Ferrero et al. (2022, 2021) assume 6.5% of the N applied, following Renouf (2006). Knudsen et al. (2011) consider a leaching rate of 15% of applied N based on studies in central Florida, Israel, and Brazil. Yang et al. (2020) use 9.97% of applied N, based on the study of Zhao et al. (2010) in Central China.

Few studies estimated nitrogen oxides (NO_x) emissions to air. Bessou et al. (2016), Alishah et al. (2019) and Bonales-Revuelta et al. (2022) follow Nemecek and Kägi (2007), who estimate NO_X as 21% of N_2O emissions. Martin-Gorriz et al. (2020) refer to Sanz-Cobena et al. (2014), who aim to represent the current Spanish N application rates and practices for croplands. Yang et al. (2020) estimate these emissions as 10% of the N_2O emissions, based on Perrin et al. (2014) and Machin Ferrero et al. (2022, 2021) estimate them as 5.3% of applied N based on the study for Australia from Renouf (2006).

As regards phosphate (PO_4^{3-}) emissions, most of the studies apply the SALCA-P model (Nemecek and Kägi, 2007). Yang et al. (2020) use a specific model for China whereas Knudsen et al. (2011) and Beccali et al. (2009) apply models from countries different to the assessed ones, the USA and the Netherlands, respectively. Ribal et al. (2017), on the other hand, do not consider phosphate leaching following Brady and Weil (2008), who argue that the leaching of this compound is very low as mineral surfaces tightly adsorb inorganic forms of soluble phosphorus.

Any change in land use or land management practices (e.g., from tillage to no-tillage) affecting soil organic carbon content must be quantified, both as a measure of soil fertility and to mitigate possible Greenhouse Gas (GHG) emissions. Only Knudsen et al. (2011) estimate changes in soil organic carbon by using the Tier 1 methodology of the IPCC (2006). In the remaining studies, the rationale behind the non-estimation of these emissions could be explained by the fact that changes in soil organic carbon mostly occur within the first 20 years of cultivation (IPCC, 2006), although any reference to this is made.

Pruning residues can also influence on-field emissions depending on their management. These are usually ground and incorporated into the soil, burnt, or used as mulching material. Very few of the reviewed studies specify the management of the pruning residues. Particularly, Lo Giudice et al. (2013) and Pergola et al. (2013) propose scenarios where the residues are left on the ground as mulch and scenarios where they are burned, but the emissions related to those practices are not modelled. Mulching contributes to increase soil organic carbon pool, and as stated above, the effects of this practice are accounted for only when it is recently introduced, that is, less than 20 years; in addition, this practice also reduces water and nitrogen losses, and it should be thus considered when estimating N emissions. On the other hand, pruning waste burning releases emissions to air (biogenic CO_2, NO_x, SO_x, particulate matter) that should also be modelled, although biogenic CO_2 is generally not considered in LCAs. Bessou et al. (2016) report that pruning residues were included in the nitrogen balance, although they do not specify how. Ribal et al. (2009) model the emissions from burning following Van Holderbeke et al. (2004) and conclude that, both in integrated and organic production, shredding pruning residues is preferable to burning them.

3.3.2.2.3. Primary distribution of pesticides

Pesticides are another relevant issue when assessing the environmental impact of agricultural activities. There are controversies regarding permitted products and maximum limits, as well as the health and environmental consequences of their application. The methods used to apply the pesticides and the climate and soil characteristics influence the primary distribution of pesticides. In particular, concerning their primary distribution immediately after application, assumptions are made, underpinned by different literature sources.

An aspect that comes to light is that most of the studies apply fixed distribution percentages, even after the publication of distribution models such as PestLCI (Birkved and Hauschild, 2006), that accounts for site-specific characteristics. Alishah et al. (2019) follow Van der Berg (1999), who stipulates that 30% of the chemicals are released into the air, and the rest is transferred to the soil. Ribal et al. (2017) refer to Berthoud et al. (2011), who assume that 0.5% of the applied doses go to surface water; they then estimate the fraction going to air from the vapour pressure of the pesticide, and finally consider that the remaining fraction goes to soil (with a maximum of 85%). Machin Ferrero et al. (2022, 2021) assume that the pesticide runoff is 1.5% of the active ingredient applied, following Renouf (2006). By following Nemecek and Kägi (2007), Bessou et al. (2016) and Bonales-Revuelta et al. (2022) assume that the soil is the final reception compartment of all pesticides. Nicolo et al. (2017) chose to model pesticide distribution following the assumptions of Margni et al. (2002), whereas Nicoló et al. (2015) apply the methodology developed by Hauschild (2000), who contemplates various dispersion routes for the applied pesticides with redistribution factors for the different routes.

3.3.2.2.4. Water inventory

Accounting for water flows is a prerequisite for the assessment of the impacts associated with water use and again there is a variety of available tools with which to carry out the inventory of water flows in agricultural LCAs (Payen et al., 2018). In this section, the methods used to estimate water withdrawal for citrus fruit irrigation at the farm level and at the processing plant are reviewed. Most of the studies elicit data from direct sources, such as questionnaires or interviews, with some exceptions which are detailed next. Bessou et al. (2016), Martin-Gorriz et al. (2020) and Beccali et al. (2009; 2010) estimate the amount of irrigation water using models based on crop water requirements considering agro-meteorological information. Ribal et al. (2009) take the recommended water dose, for both furrow and drip irrigation systems, for integrated citrus fruit production in the Valencian region according to the official regulations (DOGV, 2001). For organic production, these authors assume an 8% reduction in the water dose since, in that case, the content of organic matter in soil is greater, which increases its water retention capacity. Nicoló et al. (2015) and Ribal et al. (2017) exclude water from their inventories due to a lack of reliable data and Bonales-Revuelta et al. (2022) assume that irrigation water is negligible as, according to farmers, precipitation provides all their water requirements. As to citrus fruit processing, Knudsen et al. (2011) and Machin Ferrero et al. (2022, 2021) obtain the information from questionnaires and interviews. Nicolo et al. (2017) measure the amount of water used in the postharvest central with a water flow meter. Beccali et al. (2009) and Beccali et al. (2010) estimate the water used at the processing plant considering the operation time and power of the equipment. Roibás et al. (2018) use data from the corporation responsible for the complete drinking and wastewater cycle in the Maltese Islands, where the juices are processed.

3.3.2.2.5. Background data

As commented in 3.2.1., secondary data is used for background processes. Within the secondary sources used in the reviewed studies, estimations and approximations, reliable public sources, LCA databases, scientific studies and other databases can be highlighted. Ecoinvent (Ecoinvent, 2022) and GaBi professional (Sphera, 2021) are generic databases widely used, although other specific databases for food systems have been also identified, such as Agrifootprint (Blonk Consultants, 2019) and LCA Food (Nielsen et al., 2003).

An aspect that cannot be overlooked is the observation made by some authors on the completeness of the databases used to model background processes. Knudsen et al. (2011) highlight the absence of country-specific datasets for the production of mineral fertilisers and truck transport. Nicoló et al. (2015) and Ribal et al. (2017) highlight the lack of information corresponding to the production of some active principles of pesticides and inorganic fertilisers in the inventory databases. As to the emissions from the production of organic fertilisers, those from manure, when used, are disregarded in most of the reviewed LCAs, probably because it is considered as waste from livestock activity. However, manure cannot be always considered as waste if it has economic value (Montemayor et al., 2022). Bonales-Revuelta et al. (2022) stand out the lack of inventory datasets for some organic fertilisers and Lo Giudice et al. (2013) state that the machinery used specifically for citrus fruit processing is not present in the chosen database.

3.3.2.3. Impact assessment methods and impact categories

The impact assessment methods and impact categories evaluated in the reviewed studies are summarised in Table 3.4 and Table 3.5. All the studies use midpoint approaches, except De Luca et al. (2014), who also use Eco-Indicator 99 as an endpoint approach. The most widely used impact assessment methods are CML2001 (Guinée & Lindeijer, 2002) and ReCiPe (Goedkoop et al., 2013; Huijbregts et al., 2016). Climate change is the most commonly studied impact category, followed by eutrophication and acidification, categories which are closely related to agricultural practices according to the literature. Notwithstanding, any of the reviewed studies applies regionalized methods.

Table 3.4. Impact categories employed in the reviewed LCAs of fresh citrus fruits. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories												
		GWP	AP	EuP	MDP	FDP	ODP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Alishah et al. (2019)	CML2001	FE-FP	FP-FE-PP	FE	FP-PP	FP-DC	PP-FP-DC	FP-PP-FE-DC	FE	FE	FE-FP	FP-PE		
Bell and Horvath (2020)	Literature	T-PS	-	-	-	-	-	-	-	-	-	-	-	-
Bessou et al. (2016)	ReCiPe 2008	FE-I	FE-I	FE-I	-	-	-	-	PE	I-PE	-	I	I	I
Bonales-Revuelta et al. (2022)	CML2001	FE Co: DP - DC	FE-FP-FO	FE-FP-FO	PP-FP		FP-DC-PP-FO	FP-DC	O: FE Co: PE-DC	Co: PE O: FP-FE-LPS	FP	FP Co: PP		FP Co: PP
De Luca et al. (2014)	ReCiPe Eco-Indicator 99	FE-FP	-	-	-	-	-	-	-	-	-	-	-	I

Table 3.4. (cont.). Impact categories employed in the reviewed LCAs of fresh citrus fruits. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories												
		GWP	AP	EuP	MDP	FDP	ODP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Lo Giudice et al. (2013)	IMPACT 2002+	**	**	**	**	**	**	**	**	**	**	**	**	-
Martin-Gorriz et al. (2020)	CML2001	EP-FO	I-FP-FO	FO-I-FP	PP-FP	I-FO	-	-	-	-	-	-	-	I
Nicoló et al. (2015)	CML2001 USEtox	Co: FP O: FP-FO-MP	Co: FP O: FO	Co: FP-FO O: FO	FP-PP	Co: FP O: FP-FO-MP	Co: FP O: FP-PP	Co: FP O: FP-FO-MP	-	Co: FO O: FP-FO	-	FP	Co: FP O: FP-MP	-
Nicolo et al. (2017)	EPD 2015	FO-FE	FO-FE	FE-FO	-	FO-FE	FE-FO	FE-FO	-	-	-	-	-	-
Pergola et al. (2013)	CML2001	Co: FP O: FE-I-FO	Co: FE-FP	Negative numbers due to MA	Co: FE-FO O: FE-FO-I	-	-	Co: FE-FO O: FE-FO-I	-	-	-	-	-	-

Table 3.4. (cont.). Impact categories employed in the reviewed LCAs of fresh citrus fruits. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories												
		GWP	AP	EuP	MDP	FDP	ODP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Ribal et al. (2009)	CML2001	PB*-FP-FE	FP-FE	Eco: FE In: FP	FP	-	FP-PP-MU	PB* In: FP Eco: FO	-	-	-	-	-	I
Ribal et al. (2017)	CML2001 USEtox	Co: FP O: MA-MU	Co: FE O: MA	Co: FE O: MA	Co: FP O: MU-PP	Co: FP O: MU-PP	Co: FP O: PP	Co: FP O: MU	-	Co: PE O: MU-PP	-	Co: FP O: MU-PE	Co: FP O: MU-PE	-
Ribal et al. (2019)	CML2001	**	-	-	-	-	-	-	-	-	-	-	-	-
Yan et al. (2016)	Literature and IPCC 2007	FE-PE	-	-	-	-	-	-	-	-	-	-	-	-
Yang et al. (2020)	Literature	FP-FE	FE	FE	-	-	-	-	-	-	-	-	-	-

Impact categories: GWP= Global Warming Potential; AP= Acidification Potential; EuP= Eutrophication Potential; MDP= Mineral Depletion Potential; FDP= Fossil Depletion Potential; ODP= Ozone layer Depletion Potential; POP= Photochemical Oxidation Potential; TEP= Terrestrial Ecotoxicity Potential; FWAEP= Freshwater Aquatic Ecotoxicity Potential; MAEP= Marine Aquatic Ecotoxicity Potential; HTPc= Human Toxicity Potential, cancer; HTPnc= Human Toxicity Potential, no cancer; WU=Water Use. Process stages: T=Transport; FE=Fertiliser Emissions;

FP=Fertiliser Production; MU= Machinery Use; PP=Pesticide Production; PE= Pesticide Emissions; EP=Energy Production; I= Irrigation; FO= Field Operations; MA= Manure Application; PB= Pruning Burning; DP=Diesel Production; DC=Diesel consumption; LPS=Land Preparation Stage; MP=Machinery production; PS=Production Stage; EU=Energy Use. Production system: Co=Conventional: O= Organic; In= Integrated; Eco= Ecological

* The authors do not consider CO_2 fixation by the trees, but they do consider the CO_2 released into the atmosphere from the burning of pruning waste since the latter occurs over a shorter time than the former

** The study does not explicitly state which stages contribute the most to the impact category.

Table 3.5. Impact categories assessed in the reviewed LCAs of citrus-derived products. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories											
		GWP	AP	EuP	MDP	FDP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Beccali et al. (2009) *	CML2001	FU1: PP-FP FU2: PP-FP-T FU3 and FU4: PP-FP-EP FU5: T-PP-FP-PE-FE FU6: EP-T	FU1: PP-FP-PE-FE FU2, FU3, FU5 and FU6: T FU4: PP-FP-PE-FE-EP	All FUs: PP-FP-PE-FE	-	-	FU1 and FU4: EP- PP-FP-PE-FE-T FU2, FU3, FU5 and FU6: T	-	-	-	-	-	-
Beccali et al. (2010)	CML2001	**	**	**	-	-	**	-	-	-	-	-	**

Table 3.5. (cont.) Impact categories assessed in the reviewed LCAs of citrus-derived products. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories											
		GWP	AP	EuP	MDP	FDP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Dwivedi et al. (2012)	GHG emissions from literature Global warming potentials from the TRACI database	EP-FE	-	-	-	-	-	-	-	-	-	-	-
Knudsen et al. (2011)	EDIP97	T-PS	T	PS	-	T-PP-FP	-	-	-	-	-	-	-
Machin Ferrero et al. (2021)	AWARE ReCiPe 2016 IMPACT World + 1.25 (Roy et al., 2014, 2012) USEtox 2.0	-	FU4 and FU7: PP-FE FU6 and FU8: EP	All FUs: PP-FE	-	-	-	-	FU4, FU6: and FU8: PP-PE FU7: PM-PP-PE		All FUs: PE	All FUs: PE	All FUs: I

Table 3.5. (cont.) Impact categories assessed in the reviewed LCAs of citrus-derived products. The life cycle stages contributing the most to each impact category are highlighted

Reference	Impact Assessment method	Midpoint Impact Categories											
		GWP	AP	EuP	MDP	FDP	POP	TEP	FWAEP	MAEP	HTPc	HTPnc	WU
Machin Ferrero et al. (2022)	ILCD	FU7: FE FU4: PS-EU	FU7: FE FU4: PS	FU7: PP-FE FU4: PS	FU7: PP FU4: PS	FU7: PP FU4: PS	FU7: DC-FE FU4: PS	FU7: DC-FE FU4: PS	FU7: PP FU4: PS-EU	FU7: FP FU4: PS	FU7: PP FU4: PS-EU	FU7: I FU4: PS	FU7: I FU4: PS
Roibás et al. (2018)	CF from literature	EU	-	-	-	-	-	-	-	-	-	-	-

Impact categories: GWP= Global Warming Potential; AP= Acidification Potential; EuP= Eutrophication Potential; MDP= Mineral Depletion Potential; FDP= Fossil Depletion Potential; POP= Photochemical Oxidation Potential; TEP= Terrestrial Ecotoxicity Potential; FWAEP= Freshwater Aquatic Ecotoxicity Potential; MAEP= Marine Aquatic Ecotoxicity Potential; HTPc= Human Toxicity Potential, cancer; HTPnc= Human Toxicity Potential, no cancer; WU=Water Use. Process stages: T=Transport; FE=Fertiliser Emissions; FP=Fertiliser Production; PP=Pesticide Production; PE= Pesticide Emissions; EP=Energy Production; I= Irrigation; DC=Diesel consumption; PS=Production Stage; PM=Packaging Manufacturing; EU=Energy Use. Products: FU1=Orange essential oil; FU2=Orange natural juice; FU3=Orange concentrated juice; FU4=Lemon essential oil; FU5=Lemon natural juice; FU6=Lemon concentrated juice; FU7=Fresh lemons; FU8=Lemon dehydrated peel.
* The stages with the highest impact depend strictly on the functional unit considered
**The study does not explicitly state which stages contribute the most to the impact category.

3.3.2.4. Interpretation of results

3.3.2.4.1. Methods for comparative analysis

Some of the studies reviewed compare agricultural practices, mainly organic versus conventional, although, in many cases, impact scores are directly compared without applying any consistent method to support the comparison. In particular, Pergola et al. (2013) and De Luca et al. (2014) make a direct numerical comparison of the impact values obtained for conventional and organic citrus fruits using mass and area as functional units, together with Machin Ferrero et al. (2022) who make numerical comparisons between the assessed scenarios (base scenario vs. biorefinery-based schemes, which implement circular economy strategies). Instead, statistical methods are applied in other studies, such as Bonales-Revuelta et al. (2022), who perform a Principal Component Analysis (PCA) to compare the variation between the environmental impacts of every stage of organic and conventional systems. Analysis of variance (ANOVA) is the statistical method applied by Knudsen et al. (2011) and Yang et al. (2020) to compare farm types, where significant differences between groups are considered at $p<0.05$. Ribal et al. (2017) and Ribal et al. (2019) compare the organic and conventional production of oranges focusing on the farming stage and the whole supply chain, respectively. In both studies, confidence intervals are obtained for the impact results, as they aim to assess the variability in each system, and statistical methods are then applied to compare organic and conventional production. Details on the approaches followed by Ribal et al. (2017) and Ribal et al. (2019) to assess the variability and obtain the confidence intervals are commented on in section 3.4.2.

3.3.2.4.2. Uncertainty and variability assessment

Uncertainty is defined as incomplete or imprecise knowledge, which can be due to troubles in data collection, a lack of detailed information sources, or low data quality, mostly due to the lack of knowledge concerning the actual value of the quantity (Huijbregts, 1998). In the reviewed studies, when quantified, two main methods are used to treat the uncertainty, namely sensitivity analysis and the propagation of uncertainty through Monte Carlo simulation. Sensitivity analysis provides a quantitative means of determining to what extent the results vary when an input changes (Wei et al., 2015). This is done partially, that is, a parameter, assumption or model is changed, whereas the rest is kept constant. Knudsen et al. (2011) perform a sensitivity analysis to elucidate how different assumptions related to the farming stage and processing stages (e.g. manure N content, location of the juice reconstitution plant), and also to modelling choices (e.g., allocation procedures, time perspectives for the modelling of soil organic carbon) affect the results. Bessou et al. (2016) study the sensitivity of the results to modelling choices related to the growth stage of the crop (see Table 3.3 and section 3.2.1). Specifically, those authors perform a sensitivity analysis considering different allocation methods, uncertainty related to secondary data sources, and initial assumptions on cultivation, transport, and waste management.

Monte Carlo simulation quantifies the influence of the uncertainty of different input data on the results of the LCA using probability distributions to generate probabilistic results and shows whether both the quality of the collected data and the uncertainty of the results are appropriate (Kroese et al., 2014). It is one of the most applied methods to analyse the uncertainty caused by parameters, although only two of the reviewed studies quantify the uncertainty of the results obtained. In particular, Bell and Horvath (2020) use Monte Carlo simulation to evaluate the uncertainties arising from the variability due to crop yields and life cycle GHG emissions per hectare of the scenarios contemplated. Martin-Gorriz et al. (2020) also use this method to explore the robustness of LCA results for the baseline scenario, as well as to evaluate the change in the results for the impact mitigation strategies proposed. On the other hand, variability can be defined as intrinsic differences over space and time or within a group. Though it cannot be reduced, it can be represented more precisely by gathering more information about the assessed group (Ribal et al., 2017). In general, agricultural systems show a high variability due not only to local factors, such as climate, water availability and quality, or soil type but also to farmers' decisions as regards the agricultural practices to be performed (Bosco et al., 2013). Among the reviewed studies, Ribal et al. (2017) use a bootstrap technique to assess the farming variability. The bootstrap is a resampling technique, in which several Monte Carlo samples of size "n" with replacement are taken from the primary observations. In this way, the authors estimate the distribution of the different impact categories obtained from a group of conventional and organic farms and build confidence intervals to compare the impact values of each type of farm. Ribal et al. (2019) also use a bootstrap technique together with Monte Carlo analysis to assess the variability of the carbon footprint along the supply chain of Navel oranges for both conventional and organic production. They assess the variability of the farming, postharvest and transport to the distribution centre separately and then they calculate the empirical distribution of the total Carbon Footprint (CF) by adding up piecewise each iteration of the three bootstrap procedures of these subsystems.

3.3.3. Most impacting stages per category

As regards research question number 4, the life cycle stages with the highest score in each impact category are shown in Table 3.4 and Table 3.5.

In the case of the studies into fresh citrus fruits, fertilizers production and their subsequent emissions are the stages that dominate most of the reviewed categories (GWP, AP, EuP, POP, FWAEP, MAEP). It is therefore recommended to pay special attention to the type and dose of fertilizers applied, especially nitrogenous compounds. The production of pesticides and fertilizers are important stages in the MDP category, given that these activities involve the extraction of mineral resources. The importance of the activities linked to field operations stands out in the FDP and HT categories, as they involve the consumption of fossil resources and the exposure to the emissions from the combustion of these resources. As concerns water use (WU), irrigation stands out as the dominant stage. It has to be borne in mind that most of the authors do consider water as an input but do not assess the impact in terms of water scarcity. Only De Luca et al. (2014), Bessou et al. (2016) and Machin Ferrero et al. (2021) assess this impact; the former two by using ReCiPe 2008 (Goedkoop et al. 2013), which are based on the Water Scarcity Index of Pfister et al. (2009), and the latter by applying AWARE (Boulay et al., 2018). As to citrus-derived products, the impact of the farming stage is greater than that of the processing stage, due to the above-mentioned causes. The transportation, either of the agricultural inputs or the final product, and energy production stages are relevant too.

3.4. METHODOLOGICAL RECOMMENDATIONS TO HARMONIZE CITRUS FRUIT LCAS AND INCREASE REPRESENTATIVENESS

In this section, and to answer research question number 3, proposals regarding methodological issues are made to harmonize the application of LCA to citrus fruits, seeking also to enhance the regionalization of inventories and assessment methods. This is a requirement to guarantee that the LCA framework copes with farm characteristics in the assessed country, which have consequences on the final results (Morais et al., 2016). These proposals, which can also be applied to fruit production from perennials in general, have been made taking into account the PCRs for fresh fruits and juices (EPD, 2019a; 2019b) and other literature sources. Recommendations regarding the improvement of regional representativeness of inventories and impact assessment are summarized in Table 3.6. It must be noted that, due to its complexities, proposals mostly focus on the farming stage.

3.4.1. Goal and scope: framing the assessment

Goal definition is pivotal in LCAs because it determines and guides the choices to be made in the subsequent phases of the study (e.g., functional units, system boundaries, data sources, sample representativeness, and impact categories, among others). The choice of the functional unit will obviously depend on the goal of the study. As pointed out in Section 3.3.1, a mass-based unit reflects the main function of agricultural systems and is the functional unit recommended in Environmental Product Declarations (EPDs) according to the PCRs for fresh fruits and juices (EPD, 2019a; 2019b). An area-based unit can hide the influence of agricultural practices on yield (e.g., organic production, intensification, etc.) or the changes in yield in line with the growth stage of the tree. An economic value-based functional unit can be suggested when comparing different commercial fruit categories (e.g., conventional and organic) as it considers the net income gained by fruit growers or product quality (Van Der Werf and Salou, 2015; Yan et al., 2016). The use of a combination of functional units, for example, mass-based and area-based, to compare agronomic systems, avoids the overvaluation of resource use efficiency and the delocalisation of environmental impacts.

System boundaries (also temporal ones) are critical. This review has detected that most of the studies neglect the nursery stage and unproductive years (see section 3.2.1). According to the PCRs, the emissions and resource consumption of the nursery and the unproductive years must be spread out over the productive years considering the yearly yields and the entire lifetime of the plantation. PCRs claim that if this process is under the direct control of the organisation assessed, primary data should be used. In addition, Perrin et al. (2014) state that the nursery stage should be included unless it can be clearly demonstrated that its contribution to the impacts is negligible. In this regard, the two studies that assess this stage cannot be considered conclusive (see section 3.2.1), as the inventories used are not transparent enough. Hence, LCA studies on the nursery stage from primary data that thoroughly describe the inventory are urged. Following Bessou et al. (2013), a modular assessment, where each stage is modelled independently, is recommended because, given the duration of perennial cropping systems, it is not easy and sometimes even impossible to gather data for the whole cropping cycle. As to capital goods, the EPDs for fresh fruits (EPD, 2019a) state that the technical system shall not include the manufacturing of production equipment, buildings and other capital goods, which is in line with the reviewed studies.

Analyses of the life cycle stages after farming (from farm gate to grave) are often omitted. Although the life cycle stages to be included in the system boundaries depend on the goal defined, the emergence of policies such as the "farm to fork strategy" (CEC, 2020), which seeks to reduce the global footprint of the food system, must be kept in mind. Hence, to support the transition to sustainable food systems more research is required to accurately determine the impact contribution of the post-farm stages, mainly as concerns the case of packaging and transport (Pernollet et al., 2017), as well as the end-of-life, which is hardly included in the literature reviewed. In this regard, PCRs define the attributional processes that are classified as 'downstream' and the data requirements related to them.

LCA practitioners have several options when carrying out allocation and must choose the method that best suits the goal of the study, while also considering data availability. The PCRs for fresh fruits (EPD, 2019a) state that fruits and nuts for human consumption, even though they may be of potentially different grades, are considered equivalent in terms of the service they deliver, and allocation between them is thus not needed. In addition, where substandard or waste fruits or nuts are used as animal feed displacement of other feedstock must not be considered. When needed, the optimal choice would be to divide the main process into subprocesses, otherwise, as the PCRs suggest, allocation methods should reflect the physical relationships between products by using mass allocation. When these relationships cannot be determined, economic allocation can be used, as recommended for the farming stage in the LCAs of juices (EPD, 2019b) and when the co-products do not have similar characteristics and/or functionality (PAS 2050, 2012).

3.4.2. Inventory analysis and data representativeness

Representativeness involves both temporal and geographical (regional) variability. The first can be captured by gathering data corresponding to different years. Cerutti et al. (2014) recommend collecting field data in an even number of years (at least 4), whereas the PCRs for fruits and nuts do not specify the number of years to be used. Whenever possible, gathering data for more than one year is advised, because even if yield variations are not detected, agricultural practices can change due to external factors (e.g., climate conditions or input prices). As to the fruit processing phase, one year could be enough because, unlike in the farming stage, no variations in the juice manufacturing process are usually observed from one year to another, since the conditions are more closely controlled, making the process more repeatable.

When geographical representativeness comes into play, the selection of a representative sample is required, taking into account all types of farms in the region under study, which can entail complexity (Avadí et al., 2016). To this end, different approaches can be applied, as summarised in Fig. 3.4., mainly the sampling of real farms (preferably a stratified sample to better represent the types of farms), the selection of a representative real farm, giving a rationale for the selection such as by taking into account the experts' opinion, or the building of a simulated farm incorporating the typical features of a specific typology. In turn, farm typologies can be defined by using statistical methodologies (e.g. clustering or principal component analysis). In practice, the farmers' willingness to share data about their practices can be a limitation (Avadí et al., 2016); thus, selecting or modelling representative farms can be a useful approach when a proper sampling cannot be carried out.

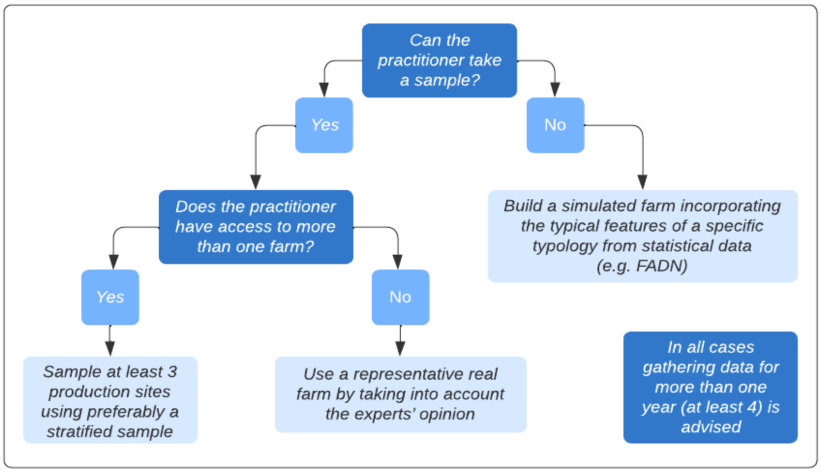


Fig. 3.4. Recommendations to improve the temporal and geographical representativeness of LCAs of fruits.

The modelling of on-field emissions is also crucial to obtaining representative inventory data and entails difficulties as these emissions are closely related to site-specific soil and climate conditions. Along these lines, the PCRs for fresh fruits (EPD, 2019a) recommend the use of site or region-specific data, such as Tier 2 and Tier 3 models; otherwise, specific Tier 1 coefficients are proposed. As concerns Tier 1 emission factors, revised coefficients with respect to soil and climate conditions are starting to be developed; IPCC (2019), a refinement of IPCC (2006), disaggregates some of the emission factors by climate region (wet and dry climates) for direct and indirect N_2O emissions. Andrade et al. (2021) compared different Tier 2 and Tier 3 models and recommend Tier 3 models for estimating N_2O and NO_3^- emissions and Tier 2 models for NH_3 volatilisation. In general, Tier 2 models, such as SALCA (Nemecek et al., 2019), are an excellent alternative for reducing complexity and improving precision, although Tier 3 mechanistic models, such as Daisy (Hansen, 2002), Animo (Rijtema & Kroes, 1991) and LEACHN

(Wagenet & Hutson, 1989) allow greater certainty in the estimations. These models are also useful to improve the modelling of the emissions from organic fertilisers (Montemayor et al., 2022). It must be noted that mechanistic models require a high amount of input data (e.g., soil composition, application practices, precipitation, etc.) and, due to their complexity, understanding and adapting these models to the region of study requires more effort.

Farmers are encouraged to measure nutrient contents on their soils to obtain more adjusted parameters when using the models. Nevertheless, to help practitioners, there are databases that collect relevant information on soil composition, such as LUCAS (Orgiazzi et al., 2018), which presents information for 23 member states of the European Union, or SIGRAS (INIA-GRAS, 2012), which gives information of Uruguayan soils. Concerning phosphate emissions, Tier 3 models, such as DNDC (University of New Hampshire, 2007), LEACHN (Wagenet & Hutson, 1989) and Indigo v3.0 (Avadí et al. 2020) can be used. To account for changes in soil organic carbon stocks, recent publications (Bessou et al., 2020; Joensuu et al., 2021) test the effect of models of differing complexity on other crops and also make interesting recommendations. As to emissions from pruning leftovers, modelling depends on the management practice. EMEP/EEA (EEA, 2019) gives Tier 1 emission factors for those emissions from the burning of agricultural residues not associated with biogenic carbon. When this residue is incorporated into the agricultural soil, the above-mentioned mechanistic models allow the N mineralization to be accounted for.

The PestLCI Consensus model v1.0 (Fantke et al., 2017), is recommended to estimate the primary distribution of pesticides immediately after their application, as it considers different crop types, plant growth stages, drift deposition curves, and pesticide application methods. Another important aspect related to pesticides to be considered, especially in agri-food LCAs although it has been omitted in the reviewed studies, is the intake fraction, that is, the portion of emitted pesticide that effectively enters the human population, commonly through inhalation and ingestion. In the case of citrus fruit processing (including postharvest treatment), a processing factor must also be considered (Juraske and Sanjuán, 2011), which accounts for the reduction in pesticide residues caused by the processing steps. To this end, the DynamiCROP model is recommended; this is a dynamic plant uptake model that quantifies human exposure and the related health impacts caused by the application of pesticides to food crops and the subsequent ingestion intake of residues (DynamiCROP, 2021). As to toxicity impacts, it has to be noted that in USEtox databases there is a lack of information about the impact of some inorganic and organic compounds used frequently in agriculture, hence more research is needed in this aspect.

As Notarnicola et al. (2022) claim, available datasets for agri-food processes may not be fully representative of the site-specificity of the food product under examination. There is thus a compelling need to develop country-specific datasets for fertilisers, pesticides and growth regulators. Those authors found that, specifically for citrus, no datasets concerning the production of Italian agricultural inputs are included within inventory databases. The lack of inventory datasets for the production of plant protection products, biological control agents, and organic fertilisers, key for organic agriculture, is highlighted in Montemayor et al. (2022), who make recommendations and give examples on how to create LCIs for these products. As to manure allocation, these authors recommend following the guidelines from the Livestock Environmental Assessment and Performance (LEAP) Partnership by the Food and Agriculture Organization of the United Nations (FAO 2016a, 2018).

As regards water inventory, the optimum is to gather primary data of the water used for irrigation (e.g., water bills, water flow meters) although water balances, accounting for the soil and climate specificities, are also recommended when primary data is not available. In addition, irrigation infrastructure and the origin of the water used (surface, underground) should be detailed in LCAs. Payen et al. (2018) make a thorough review of models for field water flows for agricultural LCAs and recommend the CropWat model (Smith, 1992) as it allows actual crop irrigation requirements to be accounted for. The AquaCrop model (FAO, 2016b), the updated version of CropWat, is also highlighted by Payen et al. (2018) as an interesting alternative since it accounts for possible water, salinity, and nutrient stresses, which can affect crop growth and, thus, water flows. Its main weakness as regards the purpose of this research is that it still does not incorporate the modelling of perennials.

It must be borne in mind that two types of water can be defined, water extracted, that is the total amount of water withdrawn from water bodies (e.g. irrigation water, or water used for cleaning), and water consumed, which is the amount of water that the watershed of origin loses (Huijbregts et al., 2016). For the farming stage, water consumed corresponds to water evapotranspiration, which depends on parameters such as climatic conditions, type of crop and its phenological stage. This is crucial data in the inventory and can be obtained by performing measurements on the field, using national databases or applying the method proposed by Allen et al. (1998).

3.4.3. Impact Assessment

Most of the literature reviewed corresponds to multi-indicator studies. In fact, these are preferable as a means of reproducing the effect on the environment in a more representative way and identifying and preventing the burden-shifting between life cycle stages and between environmental indicators (Espadas-Aldana et al., 2019). This review shows that impact categories, such as climate change, eutrophication, acidification, or those that are toxicity related, are relevant in the LCAs of agri-food products. Notwithstanding, to regionalise the impact calculation, the recommendations are to apply global spatialized models that are regionally applicable and aligned with the geographic scope of the study and to apply continent- and country-level aggregated characterisation factors whenever possible (Patouillard et al., 2018). IMPACTWorld+ (Bulle et al., 2019) and LC-IMPACT (Verones et al., 2020) are recently developed regionalised methods. IMPACT World+ (Bulle et al., 2019) is a midpoint-damage framework that allows calculating midpoint indicators and endpoint indicators based on damage to three areas of protection (human health, ecosystem quality, and natural resources), together with two areas of concern related to water and carbon. In addition, the LC IMPACT method (Verones et al., 2020) provides characterization factors at the damage level for 11 impact categories related to the three areas of protection.

In addition, there are two impact categories that are relevant in agricultural LCAs and are barely assessed, namely water scarcity and biodiversity loss. Water scarcity, due to the intensive use of irrigation in citrus fruit crops and the fact that they are often located in contexts of water stress, should be systematically assessed. Recently, the working group of the UNEP-

SETAC Life Cycle Initiative proposed the AWARE -Available WAter Remaining- method (Boulay et al., 2018), based on the quantification of the relative available water remaining per area once the demand of humans and aquatic ecosystems has been met. This method considers different spatial and temporal resolutions, proposing monthly characterization factors, with a spatial specificity that reaches the country and even the basin level. In addition, different uses of water are considered as characterization factors for both agricultural and non-agricultural activities are presented.

Although the impact on biodiversity is currently a relevant issue (e.g. the biodiversity strategy of the European Union for 2030) historically it was not considered, since agricultural lands were managed as industrial production sites (Notarnicola et al., 2017). In this regard, UNEP's consensus method uses the characterisation factors developed by Chaudhary & Brooks (2018), which enables to discern the damage caused by three levels of intensity within a particular broad land-use type, including three management regimes, as well as to contemplate taxon affinity to different types of land-use intensity. With regard to the toxicity of pesticides, the chosen characterisation method is important, as toxicity-related impacts vary significantly among them (Parajuli et al., 2019). The USEtox 2.0 model (Fantke, 2017) is the scientific consensus model endorsed by the UNEP/SETAC Life Cycle Initiative and the most up-to-date. Nevertheless, it must be pointed out that the terrestrial and marine ecotoxicity characterisation factors are still missing, and food ingestion is not accounted for in the human toxicity model.

Table 3.6. Updated methods to improve the regional representativeness of inventories and impact assessment in LCAs of fruits

LCI Input	Modelling	Midpoint impact method	Impact indicator
N-emissions	Tier 3 methods: Daisy (Hansen, 2002) Animo (Rijtema & Kroes, 1991) LEACHN (Wagenet & Hutson, 1989)	ImpactWorld+ (Bulle et al., 2019)	Climate change (kg CO_2 eq) Freshwater acidification (kg SO_2 eq) Marine eutrophication (kg N N-lim eq) Terrestrial acidification (kg SO_2 eq) Photochemical oxidant formation (kg NMVOCeq) Ozone layer depletion (kg CFC-11eq)
P- emissions	Tier 3 methods: DNDC (University of New Hampshire, 2007) LEACHN (Wagenet & Hutson, 1989) Indigo v3.0 (Avadí et al. 2020)	ImpactWorld+ (Bulle et al., 2019)	Freshwater Eutrophication (kg PO_4 P-lim eq)

Table 3.6. (cont.) Updated methods to improve the regional representativeness of inventories and impact assessment in LCAs of fruits

LCI Input	Modelling	Midpoint impact method	Impact indicator
Primary distribution of pesticides	PestLCI Consensus model v1.0 (Fantke et al., 2017)	USEtox (Fantke, 2017) + DynamiCrop (DynamiCROP, 2021)	Freshwater ecotoxicity (CTUe) Human health toxicity (CTUh)
Water consumed in irrigation	Allen et al. (1998) CropWat model (Smith, 1992) AquaCrop (FAOb, 2016) (not for citrus fruits) Meteorological databases	AWARE (Boulay et al., 2018)	Water scarcity (m^3 world-eq)
Land occupation Land transformatio n	Chaudhary & Brooks (2018)	Chaudhary & Brooks (2018)	Potential species loss Global: percent disappeared fraction of species Regional: regional species loss

3.4.4. Results interpretation and policy implications

LCAs have been used to support evidence-based policymaking, for instance, to inform consumers by comparing the environmental impacts of food supply, to communicate about the impact of mitigating interventions, as scientific basis for policies on products design, and to monitor sectoral progress toward sustainable development goals (Gava et al., 2020; Sala et al., 2021). In addition, Gava et al (2020) point out how LCA studies could be beneficial for policymaking related to agricultural sustainability and food security. According to those authors, LCA can act as information providers, that is, by bringing new knowledge about the impacts concerning existing or novel products, they can highlight specific parameters in which policy measures (e.g., taxes or subsidies) or environmental performance standards could be sustained, or they can act as passive regulators, that is, helping to decide among various mitigating alternatives.

In this context, several barriers are still hindering the use of LCA in policy-making. Among them, Sala et al (2021) highlight the lack of widespread technical knowledge on LCA, the lack of trust in the LCA process and results, and the need for verification of LCA results by surveillance authorities. Especially, weaknesses in the interpretation phase may contribute to reducing the trust of policymakers in LCA (Agostini et al., 2020). All this reinforces the need to develop harmonised methodologies, as well as an appropriate quantification of the uncertainty of the results to get grounded and representative results.

The goal of most of the reviewed articles is to provide information (see Table 3.1 and Table 3.2). In addition, many of the articles reviewed propose measures to mitigate the identified hotspots, from more basic approaches, i.e., listing them, establishing theoretical scenarios that contemplate various alternatives or even making practical approximations. As well, comparisons between production systems are carried out, mainly between organic and conventional production. Along these lines, when performing a comparative analysis, it is crucial to assess whether the differences identified are significant or not, as noted in section 3.4. This can provide a consistent base to support decisions at the governmental level on which productive system to support. Hence, harmonization is also required in this regard, by boosting the application of statistical inferential analysis (Grant et al., 2016; Sinisterra-Solís et al., 2020).

The Ecolabel Regulation (EC, 1992, 2010) constitutes a relevant application of LCA in policies establishing a voluntary eco-label award scheme to promote products with reduced life cycle environmental impacts (Sala et al., 2021). Through the use of these environmental certifications and labelling schemes, a reduction in the asymmetry of information from business to consumer can be achieved. In fact, governments and non-governmental organizations are nowadays fostering the use of ecolabels. This can be seen in the emergence of methods to measure the environmental performance of products and organisations, e.g., Environmental Product Declarations (EPD, 2022), and Product Environmental Footprint (EC, 2021), among others.

To give a holistic vision of the impacts of agricultural products, integrating the three dimensions of sustainability (environmental, economic, social) in a single index is recommended, as well as combining LCAs with other indicators, such as thermodynamic-based measures like exergy (Aghbashlo et al., 2021). This can be achieved by adopting a system thinking approach when performing interventions, helping to address multiple dimensions of sustainability at the same time. In this aspect, governments are key players in the adoption of macro-scale interventions and supporting research activities concerning progress monitoring.

3.5. CONCLUSIONS AND FUTURE DIRECTIONS

Based on an extensive descriptive and critical literature review, this study analyses the state of the art of LCAs in citrus fruits. It identifies and discusses trends among the key methodological choices and makes recommendations for the development of a framework for a harmonised application of LCA on citrus fruits, which will help LCA practitioners to assess the impacts of fruit production in general. In addition, those system stages contributing the most to the environmental impact categories were identified, aiming to help farmers and managers of agri-food businesses to understand where the main changes should be monitored or implemented.

The production of agricultural inputs and their on-field emissions are the main critical points detected in the reviewed articles, hence, efforts should be directed towards the selection of more environmentally friendly products and to optimise their application rate. From this review, several recommendations and research gaps arise. Firstly, studies into the early stages of citrus fruit production (e.g., nursery stage) from primary data and with an exhaustive description of the inventory used are encouraged to determine whether they should be included or not. Farm representativeness, both temporal and spatial, stands out as a critical issue when assessing the regional production of citrus fruits. This implies improving farm sampling procedures or giving a rationale when only one farm is chosen instead and also increasing the number of years to be assessed to at least four. Regarding the life cycle inventories, the necessity to develop regionalized datasets of agricultural inputs is highlighted, also including specific inputs for organic production. As well, site-specific modelling tools for on-field emissions are crucial to obtain robust results that reflect local conditions; thus, the use and development of Tier 2 and Tier 3 methods should be fostered instead of Tier 1, although more research is needed to fit the models to local conditions. The need to improve water inventories, including not only the water requirements for irrigation but also the water consumption, always accounting for regional representativeness, is highlighted. Farmers are encouraged to monitor the nutrient levels in their soils, which will allow for optimizing emission models while helping to adjust the dose of fertilisers applied.

As to the impact categories, the need to include water scarcity, and impacts on biodiversity in citrus fruits studies is highlighted together with the use of regionalised impact characterisation methods. The representation of uncertainty in the results of citrus fruits LCA studies is recommended, given the characteristics of agri-food processes, which are highly dependent on climate, soil type, farming practices, and other interrelated factors. As well, the use of statistical methods when comparing the impact results of different systems stands out as a key aspect to ensure the consistency of the obtained results.

This study contributes to the harmonisation of citrus fruits LCA studies as a first step that paves the way for the promotion of a more responsible and sustainable citrus fruit production. LCA studies can help product differentiation and its incorporation in new and more exigent international markets. Studies in other citrus-producing regions worldwide should be fostered to acquire a broader picture of the global environmental impacts and its site-specific dependency thus helping policymakers to develop evidence-based environmental policies.

Acknowledgements

Maria Inés Cabot is the recipient of a PhD scholarship (POS_EXT_2018_1_154319) from the National Research and Innovation Agency (ANII, Uruguay)

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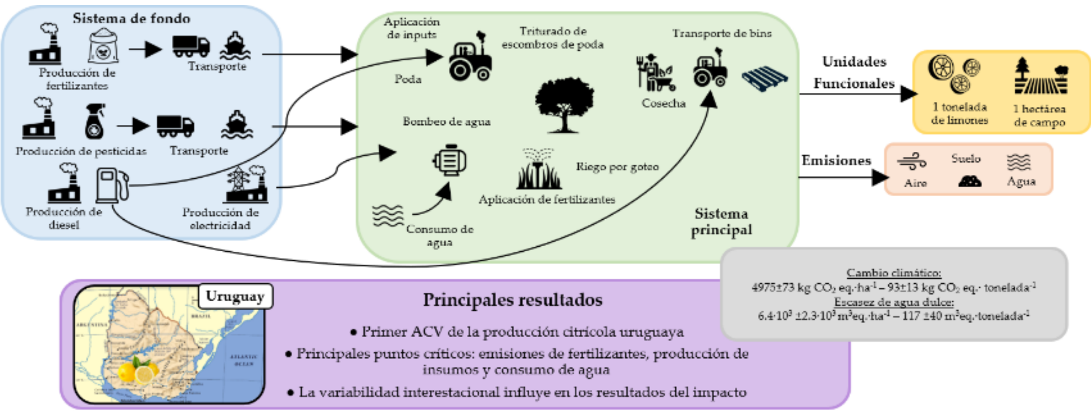
El **capítulo 4** se basa en el siguiente artículo:

Cabot MI, Lado J, Sanjuán N. 2023. Multi-season environmental life cycle assessment of lemons: A case study in south Uruguay. Journal of Environmental Management, 326. https://doi.org/10.1016/j.jenvman.2022.116719

4. ANÁLISIS DE CICLO DE VIDA MULTITEMPORAL DE LIMONES: UN CASO DE ESTUDIO EN EL SUR DE URUGUAY

Resumen gráfico:



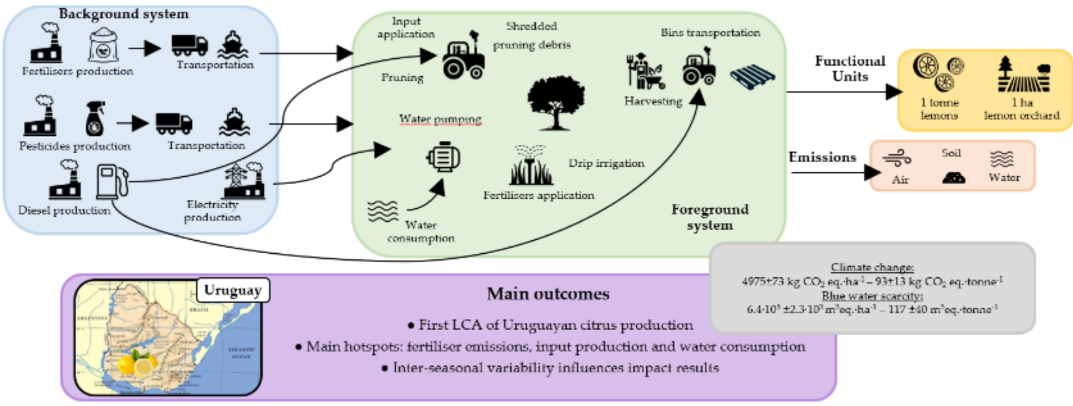
Resumen: Los limones son un producto agroalimentario relevante en Uruguay que se exporta principalmente para su consumo en fresco. Las ecoetiquetas para alimentos están en aumento en el mundo, en línea con que los consumidores y las autoridades las exigen cada vez más. Sin embargo, faltan estudios científicos que estimen los impactos ambientales de la citricultura uruguaya. Este estudio tiene como objetivo evaluar el desempeño ambiental de la producción de limón en Uruguay teniendo en cuenta la variabilidad interanual, aplicando la metodología de análisis de ciclo de vida

(ACV) y siguiendo los lineamientos de las declaraciones ambientales de producto (EPD). Se llevó a cabo una evaluación de la cuna a la puerta del campo basada en unidades funcionales espaciales y de masa. Los datos primarios se recopilaron de un campo representativo de la región durante cuatro temporadas de cosecha (2016-2020). Se evaluaron las categorías de impacto ambiental recomendadas por la norma EN 15804+A2. En concreto, la escasez de agua azul se evaluó mediante el método AWARE. Además, se evaluó la ecotoxicidad humana y de agua dulce utilizando USEtox. Los resultados muestran que las emisiones en campo y la producción de insumos son críticas para la mayoría de las categorías evaluadas (en promedio, 84 % CC, 88 % Ac, 98 % EM y 85 % ET), mientras que el agua azul consumida para riego es el principal punto crítico en escasez de agua azul (86 %, en promedio). Como era de esperar, los impactos presentan una mayor variabilidad al expresar los resultados por tonelada que por hectárea porque, aunque los insumos agrícolas aplicados son los mismos, la variabilidad climática influye en los requerimientos de agua y también afecta el rendimiento del cultivo. La escasez de agua azul muestra mayor variabilidad porque el consumo de agua depende en gran medida de las condiciones agroclimáticas, principalmente de la lluvia y el agua de riego, así como de la dinámica del agua en el suelo. La lixiviación de nitratos es una emisión clave en la eutrofización de agua dulce y, en menor medida, en el cambio climático, y depende de la dosis de agua y el momento de la aplicación, ya sea de lluvia o de riego. La optimización de la aplicación de N es crucial para minimizar las emisiones en el campo, un punto crítico en el presente estudio. Se sugieren prácticas agrícolas para mejorar el perfil ambiental de los limones uruguayos, entre ellas el reemplazo o minimización de la dosis de ciertos insumos (por ejemplo, óxido de cobre) a través de la implementación de prácticas agrícolas complementarias. Finalmente, se proponen técnicas actualizadas para disminuir la escasez de agua azul. Las recomendaciones metodológicas para futuros estudios incluyen la estimación de las emisiones de N mediante modelos mecanísticos, la incorporación de reducciones potenciales en las emisiones de N debido a determinadas prácticas agrícolas y la armonización de la metodología de cuantificación del consumo de agua. Este estudio constituye un ACV de referencia para la producción de cítricos uruguayos. Destaca la variabilidad interanual como un tema a considerar, incluso cuando las prácticas agrícolas no cambian, siendo especialmente relevante en países con alta variabilidad climática como Uruguay. El estudio también proporciona evidencia científica y cuantitativa para respaldar las decisiones ambientales tanto de los productores como de los consumidores de cítricos.

Palabras clave: análisis de ciclo de vida; frutos cítricos; variabilidad interanual; impactos ambientales; sostenibilidad agrícola

4. MULTI-SEASON ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF LEMONS: A CASE STUDY IN SOUTH URUGUAY

Graphical abstract:



Abstract: Lemons are a relevant agricultural commodity in Uruguay, mainly exported for fresh consumption. Food eco-labels are on the rise worldwide as consumers and authorities are increasingly demanding them. However, there is a lack of scientific studies estimating the environmental impacts of Uruguayan citrus production. This study aims to assess the environmental performance of lemon production in Uruguay taking into account inter-seasonal variability by applying the Life Cycle Assessment (LCA) methodology and following the Environmental Product Declarations (EPDs) guidelines. A cradle-to-farm gate assessment was carried out based on both mass and spatial functional units. Primary data was gathered from a representative orchard of the region for four harvest seasons (2016 to 2020). Environmental impact categories recommended by EN 15804+A2 standard were assessed. Specifically, blue water scarcity was assessed using the AWARE method. In addition, human and freshwater ecotoxicity were assessed using

USEtox. Results show that on-field emissions and input production are critical for most of the categories assessed (on average, 84% CC, 88% Ac, 98% MEu, and 85% TEu), whereas blue water consumed for irrigation is the main hotspot in blue water scarcity (86%, on average). As expected, inter-seasonal impacts present higher variability when expressing results per tonne vs. per hectare because, although agricultural inputs applied are the same, climatic variability influences water requirements and also affects yield. Blue water scarcity exhibits the highest variability because water consumption depends strongly on agroclimatic conditions, mainly on rain and irrigated water and on water dynamics in soil. Nitrate leaching is a key emission for freshwater eutrophication and, to a minor degree, for climate change, which also depends on the water dose and timing, either from rain or irrigation. Optimising the N application is crucial to minimise on-field emissions, a hotspot in the present study. Along these lines, improved agricultural practices are suggested to enhance the environmental profile of Uruguayan lemons. Replacement or minimisation of the dose of certain inputs (e.g., copper oxide) through the implementation of complementary agricultural practices is suggested. Finally, up-to-date techniques to decrease blue water scarcity are proposed. Methodological recommendations for future studies include modelling N emissions using mechanistic models, incorporating potential reductions in N emissions due to certain agricultural practices, and harmonizing the methodology to quantify water consumption. This study sets a baseline LCA for Uruguayan citrus fruit production. It highlights inter-seasonal variability as an issue to be considered, even when agricultural practices do not change, and especially relevant in countries with high climatic variability like

Uruguay. The study also provides scientific and quantitative evidence to support the environmental decisions of both citrus producers and consumers.

Keywords: Life cycle assessment; Citrus fruit; Inter-seasonal variability; Environmental impacts; Agricultural sustainability.

4.1. INTRODUCTION

Citrus is the most important fruit crop in Uruguay in terms of production, area, and economic contribution, with 218,671 t, 14,587 ha and 71,489 thousand dollars from exports in 2020, respectively, as well as concerns labour demand (19.000 workers) (Cardeillac Gulla et al., 2020; MGAP, 2021). Uruguayan citrus production is characterised by a few big orchards and many smallholdings. Eight companies concentrate 63% of citrus production and 62% of the productive area. Lemons mean almost a quarter of the national citrus production, with 51,619 tonnes produced in 2020, and 19% of the total citrus area, with 2,763 ha in total (MGAP, 2021). In addition, Uruguayan production is mainly devoted to fresh consumption, where 44% of the citrus production is exported, namely 82,000 tonnes in 2020. At the same time, Uruguay is responsible for 7.21% of total citrus fruit exports from South America (FAO, 2021), with the European Union and the United States of America as the main destinations (MGAP, 2021).

Governments and non-governmental organisations are nowadays fostering the use of food eco-labels. Consequently, there is a proliferation of methods for measuring the environmental performance of products and organisations. In particular, the so-called type III Environmental Product Declarations (EPDs), in compliance with the ISO 14025 standard, aimed to quantify the environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function. EPDs are created and registered in the framework of a programme, such as the International EPD® System, the world's first operational EPD programme, originally founded in 1998 as the Swedish EPD System by the Swedish Environmental Protection Agency and industry. More recently, European Commission (EC) released the Product Environmental Footprint - PEF (EC, 2021) as a standard methodology to assess the environmental impact of products. The former is now in a transition phase, exploring the possibility of integrating the PEF method into the EU Ecolabel criteria, hand in hand with other political actions to accelerate the shift to sustainable food systems, such as the Farm to Fork strategy (European Commission, 2020). Initiatives are also emerging in the USA, a great Uruguayan citrus importing country, such as the Sustainable Citrus Standard (Protected Harvest, 2019) promoted by the non-profit organisation Protected Harvest. This growing complexity of environmental labelling schemes has raised concerns, as these requirements could create difficulties for small and medium-sized enterprises in export markets. In addition, schemes could be misused to protect domestic producers, although according to the Technical Barriers to Trade Agreement of the World Trade Organization (WTO, 2015), they should not create barriers or disguised restrictions on international trade. However, new non-tariff barriers for products from other countries can arise, since importers will not be willing to "finance pollution" when they are making significant investments in this respect (Romero, 2003). In a few words, sustainable consumption is undoubtedly gaining momentum and ecolabels can nudge consumers towards more sustainable food choices (Potter et al., 2021). Meanwhile, the Uruguayan citrus sector is mainly focused on improving productive growth, varietal diversification and fruit quality while shyly becoming aware of the environmental impacts associated with intensive fruit production. Therefore, a detailed analysis of the environmental impacts of citrus fruit farming can constitute a milestone, helping to prioritise actions to improve the environmental profile of the product and promote its commercialisation in increasingly demanding markets.

Life Cycle Assessment (LCA) is a widely accepted methodology to quantitatively evaluate the environmental impact of products across the agri-food chain, in general, and the agricultural production systems, in particular (Martin-Gorriz et al., 2020). Its main challenge lies in the reproducibility and comparability of the results. To handle this issue, in recent years, guidelines have been developed to assist practitioners. Among them, the Product Category Rules (PCRs) provide the rules, requirements, and guidelines for developing the abovementioned EPDs for a specific product category, allowing for comparisons within the same product group (EPD, 2022a). Similarly, the PEF initiative of the EU proposes a multi-criteria measure for the calculation of the environmental footprint of goods or services. These are complemented by the Product Environmental Footprint Category Rules (PEFCRs) that provide further specifications at the level of a specific product category (EC, 2021).

LCA has been used to determine the environmental profile of citrus grown in different countries, mainly in the Mediterranean region, mostly oranges in Italy (Lo Giudice et al., 2013; Nicolo et al., 2017; Pergola et al., 2013) and Spain (Martin-Gorriz et al., 2020; Ribal et al., 2009, 2019). Other studies have been developed more recently, specifically oranges in Mexico (Bonales-

Revuelta et al., 2022) and lemons in Argentina (Machin Ferrero et al., 2021, 2022). Overall, although these studies do not always use the same impact assessment methods or assess the same impact categories, they all highlight the environmental burdens related to fertilisers as concerns. Both their manufacturing and on-field emissions stemming from their application are particularly relevant, as well as irrigation and machinery operations, as highlighted in Cabot et al. (2022). In Uruguay, the LCA tool has been shyly used over the years in the agri-food sector. The published studies focus mainly on the evaluation of a single indicator (e.g. carbon footprint or water footprint), and the productive chains analysed are mostly livestock (Becona et al., 2014; Picasso et al., 2014), dairy (Lizarralde et al., 2014), and annual crops such as maise, soybean, or sorghum (Darré et al., 2019; Bustamante Silveira, 2020). The citrus fruit sector in Uruguay is committed to a mature and conscious analysis of the impact it generates on the environment; therefore, it will require scientific evidence to sustain key decisions. To the best of the authors' knowledge, there is a lack of scientific analysis of the associated environmental impacts. The goal of this study is to carry out an environmental assessment of Uruguayan lemons production, to identify the environmental hotspots in the farming stage and propose improvements. In particular, this study aims at setting up a baseline LCA for Uruguayan citrus fruits, involving the quantification of the environmentally relevant flows of lemon production in Uruguay using several environmental indicators.

Data representativeness is a critical issue when performing LCAs of fruit production, and specially LCAs of perennial crops. Farming is especially sensitive to spatio-temporal differentiation not only due to the practices implemented according to the crop growth stages, but also to the inherent variability in farm management practices (Raschio et al., 2018). Thus, both temporal and geographical representativeness are particularly considered in the present study. The first by gathering data corresponding to four crop seasons, following the recommendations of Bessou et al. (2016) and Cerutti et al. (2014). The second by selecting a representative real orchard as recommended by Cabot et al. (2022) when a great number of orchards cannot be sampled. The studied orchard is located in the south of the country, where lemons production for fresh fruit exportation is concentrated, with 52% of the total production in 2018 (MGAP, 2019). Specifically, the selected cultivars "Lisbon" and "Fino" are two of the most cultivated varieties in Uruguay for fresh consumption (MGAP, 2019). In addition, the orchard belongs to one of the eight aforementioned largest producing and exporting companies, and the agricultural practices follow the Global GAP certification system for exportation (GLOBALG.A.P., 2022). This is the dominant certification for fruits, and citrus in particular, commercialised in both the United States and Europe (Mook and Overdevest, 2021), the leading destination of Uruguayan citrus, and therefore the most widely used by exporting companies in Uruguay (Caputi and Montes, 2010). The GLOBALG.A.P. Integrated Farm Assurance (IFA) standard for fruits covers all stages of production, from preharvest activities such as soil management and plant protection product application.

4.2. MATERIALS AND METHODS

This study follows the LCA methodology based on ISO standards (ISO, 2006a, 2006b; ISO 2017; ISO, 2020a; ISO, 2020b) using GaBi software (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany). In addition, the PCR

2019:01 V1.01 for fruits and nuts (EPD, 2019) and the International EPD framework guided most of the methodological choices adopted, specifically as concerns the functional unit, system boundaries and impact assessment. A mass functional unit was considered, and most of the attributional processes of the upstream and core processes were included. In addition, the impact categories reported in the results also correspond to those suggested in the PCR (EPD, 2019). While this study does not constitute an EPD of Uruguayan lemons, following these guidelines facilitates comparability with studies undertaken under the auspices of the PCRs.

4.2.1. System description

The selected orchard is representative of Uruguayan fresh lemon production for export (mostly located in the south), with middle-aged trees and follows standard integrated production practices. It has a total surface of 243.51 ha with lemon and mandarin; of these, 6.26 ha correspond to lemon trees of the 'Lisbon' and 'Fino' cultivars planted in the same year (2008), with a density of 516 trees·ha^{-1} (3230 trees in total). The orchard is located in Kiyú, in San José Department, south of Uruguay. According to IPCC (2006), this region has a warm temperate moist climate, which corresponds to a subtropical humid zone. For the studied harvest seasons (from 2016 to 2020), and based on data from the nearest weather station, the average annual rainfall was 1010 mm, and the average temperature was 17.0 ºC. A minimum temperature of -2.4º C was recorded in August 2018, and a maximum of 37.9 ºC in January 2016 (INIA-GRAS, 2022). As to soil characteristics, according to CONEAT classification, it is a 10.8b soil, whose geological material corresponds to silt clay sediments of brown colour and normally with calcium carbonate concretions (INIA-GESIR, 2022). The dominant soils are

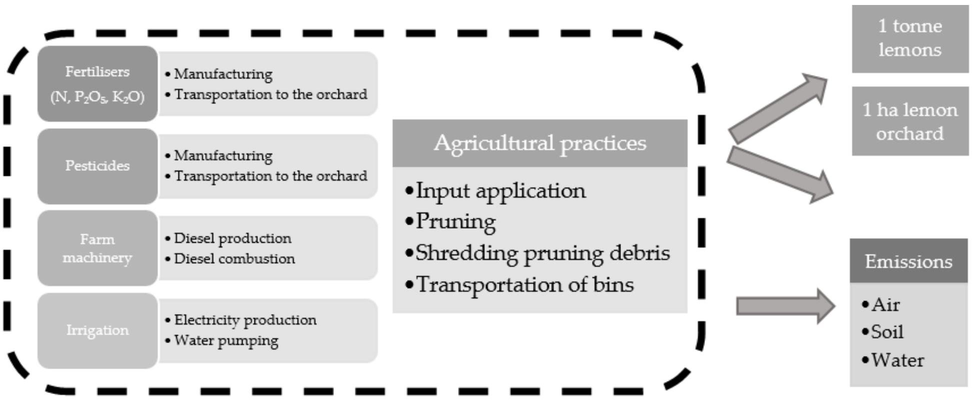
Brunosols/Vertisols corresponding to Hapludert (Vertisols) in the USDA classification and Vertisol Rúptico Lúvico in the DSA-MGAP classification (INIA- SIGRAS, 2022).

Different operations are carried out during each cropping season, beginning immediately after the previous harvest (usually August) and ending with the next harvest (July). Fertilisation is generally carried out from September to December. All pesticides are applied via foliar, as some of the fertilisers, the rest are applied by fertigation. The pesticides are applied from September to November, except for cuprous oxide, which application extends until May. Their main objective is combating pests such as insects or mites and fungi such as Colletotrichum, scabies, botrytis, canker, and melanosis, among others. A tractor, with 44.1 kW of power at rated speed and 1800 rpm rated speed, is employed for input application, pruning, shredding pruning debris, and transporting orange bins. Drip irrigation is performed from September to March, coinciding with the most significant water demand in spring-summer, by using an electric pump fed from an underground well of approximately 30 meters depth. As mentioned, lemons for export are harvested in July; they are picked by hand and then quickly transported to packinghouses, where the fruit is packaged according to the quality requirements at the destination.

4.2.2. Life cycle assessment

4.2.2.1. Functional unit and system boundaries

Two functional units (FUs) are adopted in this study. From a product perspective and related to eco-labelling purposes (e.g. EPD, PEF), a mass-based FU (1-tonne lemon · season^{-1}) is chosen according to the above-mentioned PCR (EPD, 2019). In addition, a land-based FU (1 ha · season^{-1}) is selected to consider land use intensity and to take into account the provision of ecosystem services. By using these FUs, both overvaluation of resource use efficiency and displacement of environmental impacts are avoided (Cerutti et al., 2011). It must also be noted that these two FUs are also used in LCAs of citrus fruits (Alishah et al., 2019; Pergola et al., 2013; Ribal et al., 2017; Yan et al., 2016; Yang et al., 2020). The system boundaries are set from cradle to farm gate (Fig. 4.1). The stages taken into consideration are the production of fertilisers and pesticides, their transport to the orchard and their application, the use of machinery for agricultural practices (including fuel production), and irrigation (including electricity production for the irrigation pump). The manufacturing of capital goods such as tractors is not included because they have a long life and are used on successive seasons within the same farm,



which implies an intensive use, thus the environmental load allocated to the FU is negligible. Furthermore, Frischknecht et al. (2007) showed that the production of capital goods for agriculture has a non-significant contribution to most of the impact categories, except for cumulative energy demand.

Fig. 4.1. System boundaries showing the life cycle stages included in the LCA of Uruguayan lemons.

As regards the temporal system boundaries, a farming season is assessed, beginning in August, immediately after the previous harvest, and ending with the lemon harvest in July. In addition, to analyse the variability of the impact results over time and following the recommendations of Bessou et al. (2016) and Cerutti et al. (2014), four farming seasons corresponding to the years 2016–2020 have been taken into account.

4.2.2.2. Life cycle inventory (LCI)

Information on the agricultural practices, yields, the type and dose of inputs applied, together with their origin, the amount of water for irrigation, and fuel for machinery, was obtained from direct interviews with the agronomist responsible for the orchard. Agroclimatic parameters used to calculate water consumption were retrieved from INIA agroclimatic data bank (INIA-GRAS, 2022), namely maximum, minimum, and average temperatures, wind speed, average relative humidity, effective precipitation and heliophany.

Table 4.1. Main inventory data for the lemon cultivation stage

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	Average	Standard deviation
Yield	tonne · ha^{-1}	47.0	55.0	49.0	66.0	56.0	9.5
Electricity consumption for irrigation	kWh · ha^{-1}	21.0	37.5	26.4	87.8	43.1	30.5
Water withdrawal for irrigation	m^3 · ha^{-1}	520.1	928.6	654.2	2176.2	1069.8	757.0
Rainfall water	mm · season^{-1}	955.6	1062.6	1119.8	901.2	1009.8	99.4
Rainfall + irrigation water	mm · season^{-1}	1007.6	1155.5	1185.2	1118.8	1116.8	77.7
Machinery use	h ·ha^{-1}	27.0	27.0	27.0	27.0	27.0	0.0
Diesel for machinery operations							
Application of inputs	L · ha^{-1}	87.6	87.6	87.6	87.6	87.6	0.0
Pruning	L · ha^{-1}	15.0	15.0	15.0	15.0	15.0	0.0
Crushing of pruning waste	L · ha^{-1}	9.0	9.0	9.0	9.0	9.0	0.0
Harvest and transport of bins	L · tonne^{-1}	1.8	1.8	1.8	1.8	1.8	0.0
Fertilisers							
Total N	kg · ha^{-1}	203.1	203.1	203.1	203.1	203.1	0.0
Total P_2O_5	kg · ha^{-1}	8.5	8.5	8.5	8.5	8.5	0.0
Total K_2O	kg · ha^{-1}	142.8	142.8	142.8	142.8	142.8	0.0
NPK 30-0-0	kg · ha-1	677.0	677.0	677.0	677.0	677.0	0.0
Potassium chloride	kg · ha-1	235.0	235.0	235.0	235.0	235.0	0.0
Phosphoric acid	kg · ha-1	8.0	8.0	8.0	8.0	8.0	0.0

Table 4.1. (cont.) Main inventory data for the lemon cultivation stage

Zinc	kg · ha-1	2.0	2.0	2.0	2.0	2.0	0.0
NPK 0-40-20	kg · ha-1	8.9	8.9	8.9	8.9	8.9	0.0
Fungicides							
Difenoconazole	kg · ha^{-1}	0.4	0.4	0.4	0.4	0.4	0.0
Pyrachlostrobin	kg · ha^{-1}	0.3	0.3	0.3	0.3	0.3	0.0
Cuprous oxide	kg · ha^{-1}	25.2	25.2	25.2	25.2	25.2	0.0
Mancozeb	kg · ha^{-1}	3.2	3.2	3.2	3.2	3.2	0.0
Insecticides							
Pyriproxyfen	kg · ha^{-1}	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	0.0
Acetamiprid	kg · ha^{-1}	0.3	0.3	0.3	0.3	0.3	0.0
Paraffinic oil	L · ha^{-1}	50.7	50.7	50.7	50.7	50.7	0.0
Abamectin	kg · ha^{-1}	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	0.0
Growth regulator							
Gibberellic acid	kg · ha^{-1}	0.2	0.2	0.2	0.2	0.2	0.0
On-field emissions							
Direct N_2O	kg · ha^{-1}	5.1	5.1	5.1	5.1	5.1	0.0
Indirect N_2O (from NO_3^-)	kg · ha^{-1}	3.5	3.9	4.0	3.8	3.8	0.2
Indirect N_2O (from NH_3)	kg · ha^{-1}	0.3	0.3	0.3	0.3	0.3	0.0
NH_3 volatilised	kg . ha^{-1}	13.6	13.6	13.6	13.6	13.6	0.0
NO_2 volatilised	kg . ha^{-1}	8.1	8.1	8.1	8.1	8.1	0.0
NO_3^- leached	kg · ha^{-1}	895.7	1013.2	1036.9	984.1	982.5	61.7

Relevant background processes were mostly taken from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016). However, some specific processes were taken from GaBi v.10 (Sphera Solutions GmbH, 2022) database, namely the electricity mix in Uruguay and the transoceanic transport, which are not available in Ecoinvent 3.8. The irrigation pump and the tractor were retrieved from GaBi v.10 database too because processes are parametrised, which allows specific data of the orchard to be used (e.g., well depth, tractor nominal power, etc.). These processes were then used to develop reference LCI datasets for the LCA models, as explained below. Metadata for these reference LCIs is described in Table 4.3.

4.2.2.2.1. Input production and transportation

Default processes from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016) were chosen for fertiliser production. Those fertilisers not found in the database were modelled as standard NPK fertilisers, considering their respective fertiliser units, as N, P_2O_5 and K_2O. The production of a corrective foliar fertiliser with a high concentration of zinc and the production of gibberellic acid (a growth regulator) could not be modelled due to a lack of data. However, it must be noted that the doses applied are low.

Data on pesticide manufacturing was taken from Ecoinvent 3.8. (Moreno Ruiz et al., 2021; Wernet et al., 2016) considering their active substance, as follows. First, the production process corresponding to the active principle was searched for, if it was not available in the commercial databases mentioned above, the chemical group of the pesticide was considered. In case the compound was not found, then the pesticide production was modelled as the generic "pesticide production" process from Ecoinvent 3.8. As can be seen in Table 4.3, only mancozeb, paraffinic oil and cuprous oxide could be modelled directly, whereas pyraclostrobin and pyriproxyfen were modelled considering their corresponding chemical group and the rest as generic pesticides. The transportation of all the agricultural inputs entailed the transfer by ship and lorry, except for those products that could be transported exclusively by land, for which a lorry with 16-32 metric tonne payload was considered. For all of them, one-way transport was modelled by using the corresponding Ecoinvent 3.8 (Wernet et al., 2016) and GaBi (Sphera Solutions GmbH, 2022) processes (Table 4.3). The distances travelled were obtained from Searates (2022) (Table 4.4).

4.2.2.2.2. Emissions from fertiliser and pesticide application

To model direct and indirect N_2O emissions, the Tier 1 IPCC Guidelines (IPCC, 2006) and the subsequent refinement (IPCC, 2019) were used, inasmuch as they are more recent than those suggested by the PCRs for fruits and nuts (EPD, 2019). IPCC (2019) considers the climate in the region of study and the type of fertiliser, which in this case study correspond to wet climate and synthetic fertiliser, respectively. NH_3 and NO_x were modelled following the EMEP/EEA guidebook (EEA, 2019), an updated version of the EEA (2013) proposed in the PCRs for fruits. In particular, NH_3 emissions were estimated following a Tier 2 approach, considering normal soil pH (7.0 or below) and temperate climate. A Tier 1 emission factor was used for NO_x emissions since the EMEP/EEA guidebook (EEA, 2019) does not propose a Tier 2 emission factor. Nitrate (NO_3^-) leaching was estimated with the Tier 2 model SQCB-NO_3 (Emmenegger et al., 2009), which represents an improvement of the IPCC emission factor proposed in the PCRs (EPD, 2019). Specifically, the model considers climatic parameters, namely precipitation, soil and crop characteristics and data related to agricultural practices, as described below.

Precipitation values were obtained from the nearest meteorological station, INIA Las Brujas, located in the Canelones department, 36 km away from the studied orchard (INIA-GRAS, 2022). The clay content of the soil was obtained by taking into account the soil type according to USDA classification (Vertisols) and using the table proposed by Emmenegger et al. (2009). The nitrogen content in soil organic matter was estimated using the equation and standard values proposed in the SQCB-NO_3 model. The depth of the roots was retrieved from Goñi and Otero (2009). As to the absorption of nitrogen by the crop, values from Gambetta et al. (2021) for Uruguayan citrus fruits were used. Data on the agricultural practices (irrigation, N supply from fertilisers) were obtained from interviews with the agronomist responsible for the orchard. In line with the recommendations of the PCRs (EPD, 2019), phosphate (PO_4^{3-}) leaching was estimated with the SALCA-P model (Nemecek et al., 2019), considering the P_2O_5 content of each fertiliser used.

Primary emissions from pesticide application were calculated following PestLCI Consensus V.1.0 (Fantke et al., 2017), which estimates the fraction of pesticide emitted to the environmental compartments, namely air, field soil surface, crop leaf surface and off-field surface (freshwater and natural soil). It is a consensus model that takes into account several parameters to make a better approximation of the primary distribution of the pesticides. In particular, the model considers the crop type, dose applied, fraction of pesticide intercepted by the leaves -which depends on the stage of the crop- and the application method considering drift reductions. It also accounts for the surface area of the orchard and whether there is a buffer zone (location and width).

4.2.2.2.3. Water use, energy, and blue water consumption for irrigation

The amount of irrigated water per season was primary data provided by the farmer (see Table 4.1). The electricity consumption for irrigation (Table 4.1) was estimated by using the GaBi process "Irrigation pump generic", employing as inputs the amount of water irrigated for each season (1069.77 mm on average) and the depth of the well (30 m). Default values for the nominal operating pressure (3 bar) and the efficiencies of the power unit (0.9), pumping (0.8) and irrigation (1.0) were used, as those are typical values for irrigated agriculture.

The blue water consumption for irrigation was estimated according to Allen et al. (1998). The method is based on a soil balance in the root zone considering the evapotranspiration under water stress conditions:

$$D_{r,i} = D_{r,i-1} - P_{eff,i} - I_i - CR_i + ET_{c,i} + DP_i \qquad \text{(equation 1)}$$

In the following paragraphs, the parameters involved in equation 1 are explained together with the methods or data sources used for their estimation. The subscript "i" refers to daily values.

$D_{r,i}$ and $D_{r,i-1}$ refer to moisture depletion in the root zone (mm). Initial $D_{r,i-1}$ was considered zero since it is assumed that the analysis starts after heavy rain or irrigation which means that, according to Allen et al. (1998), the moisture content in the root zone is close to field capacity and $D_{r,i-1} \approx 0$.

$P_{eff,i}$ is the effective precipitation (mm), retrieved from INIA Las Brujas meteorological station (INIA-GRAS, 2022).

Some previous concepts must be defined to estimate I_i (net layer of irrigation on the day i that infiltrates the soil, mm). The first corresponds to the readily available (extractable) water from the soil root zone (RAW, mm), which is the maximum fraction of the total available water the crop can extract from the root zone without experiencing water stress. The second is moisture depletion in the root zone (D_r), defined as the amount of water missing with respect to the field capacity. Taking as a premise that irrigation is not necessary as long as the crop has readily available water in the soil to consume, the following assumption is made; in the event that the value of the initial moisture depletion in the root zone minus the effective precipitation of that day (which is considered to occur at the beginning of the period) is greater than the RAW value, the dose of irrigation water (I_i) needed to reach the field capacity is ($D_{r,i-1}$ - $P_{eff,i}$) is applied. Otherwise, the crop is not irrigated.

To calculate the RAW, the total water available in the root zone of the soil (TAW, mm) and the average fraction of the total water available in the soil that can be depleted from the root zone before moisture stress (p_i) were calculated, as follows:

$$RAW_i = p_i \cdot TAW \qquad \text{(equation 2)}$$

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r \qquad \text{(equation 3)}$$

Where θ_{FC} is the moisture content at field capacity ($m^3 \cdot m^{-3}$) and θ_{WP} is the moisture content at permanent wilting point ($m^3 \cdot m^{-3}$), both values retrieved from INIA-GESIR (2022) for CONEAT 10.8b soils; Zr is the root depth (m), retrieved from Goñi and Otero (2009). The p_i-value for citrus fruits was calculated according to Allen et al. (1998) as:

$$p_i = 0.4 + 0.04 \cdot (5 - ET_{c,i}) \qquad \text{(equation 4)}$$

$ET_{c,i}$ is the crop evapotranspiration on the day i (mm) and its calculation is detailed below.

CR_i is the capillary rise from the groundwater table on the day i (mm). It is assumed to be zero since the water table in Uruguay is more than 1 m below the root zone (Allen et al., 1998; Fan et al., 2013)

$ET_{c,i}$ was estimated by following FAO guidelines (Allen et al., 1998):

$ET_{c,i} = Kc \cdot ET_{0,i}$ (equation 5)

Where $ET_{c,i}$ corresponds to the crop evapotranspiration ($mm \cdot day^{-1}$), Kc is the crop coefficient (dimensionless), and $ET_{0,i}$ is the reference crop evapotranspiration ($mm \cdot day^{-1}$).
To obtain daily $ET_{0,i}$, climate data for the studied seasons from INIA Las Brujas meteorological station (INIA-GRAS, 2022) was used as an input for the Penman-Monteith equation (Allen et al., 1998). Then, by adding up those daily values, the monthly $ET_{0,m}$ (mm/month) values were calculated, which were subsequently multiplied by the monthly Kc for Uruguayan citrus fruits obtained from García Petillo and Castel (2007) to obtain $ET_{c,m}$ ($mm \cdot month^{-1}$). These authors performed a water balance considering the irrigation, effective precipitation, and parameters related to soil characteristics (drainage and variation in the soil water storage during the studied period) for a citrus orchard located at Kiyú, Uruguay. Finally, the monthly $ET_{c,m}$ ($mm \cdot month^{-1}$) values were added to obtain the $ET_{c,s}$ of the studied seasons ($mm \cdot season^{-1}$), as reported in Table 4.5.

DP_i is the water loss from the root zone by deep percolation on the day i (mm) after heavy rain or irrigation. It was calculated using equation 1, considering that the values of $D_{r,i}$ and CR_i are zero; this means that there is no moisture depletion in the soil root zone or capillary rise from the groundwater table after heavy rain or irrigation, thus equation (1) becomes:

$DP_i = P_{eff,i} + I_i - ET_{c,i} - D_{r,i-1}$ (equation 6)

If the system is below its field capacity, this value is null.

4.2.2.3. Impact categories and impact assessment methods

As recommended by the PCRs for fruits (EPD, 2019), a default list of environmental performance indicators was accounted for, and the latest update of that list, made on 2022-03-29, was considered (EPD, 2022b). In this regard, the impact categories and the corresponding category indicators recommended by the EN 15804+A2 standard were assessed, namely, climate change - CC (CO_2 eq.), acidification - Ac (mol H^+ eq.), freshwater eutrophication - FEu (kg P eq.), marine eutrophication - MEu (kg N eq.), terrestrial eutrophication - TEu (Mole of N eq.), photochemical ozone formation (impacts on human health) - POF hh (kg NMVOC eq.), ozone depletion - OD (kg CFC 11 eq.), resource use of minerals and metals - RU m (kg Sb eq.) and resource use of fossil resources - ADP f (MJ). The AWARE method (Boulay et al., 2018) was applied to assess blue water scarcity - BWS (m^3 eq.) as is the most up-to-date method also recommended for EPDs (EPD, 2022b). Specific monthly characterisation factors (CF) for the corresponding Uruguayan basin (Río de la Plata) were used to calculate the direct water consumption at the field. For indirect water consumption (i.e., inputs manufacturing, irrigation, electricity production and diesel production and combustion), the world average CF for non-agricultural activities (CF = 20.30 m^3 eq.$\cdot$ m^{-3}) was selected, inasmuch as those processes are carried out in locations worldwide.

Besides the listed categories, toxicity impacts were assessed to address consumers' concerns about the widespread use of pesticides. USEtox 2.12 (Rosenbaum et al., 2008) was the method applied to assess freshwater ecotoxicity (CTUe) and human toxicity carcinogenic and non-carcinogenic (CTUh) because it is the most widely used method for agri-food LCAs as well as the recommended method by the ILCD Handbook (Finkbeiner, 2011). Since there are no CFs available in USEtox 2.12 database for paraffinic oil, acetamiprid and pyraclostrobin, a literature search was carried out. Specifically, the CF for paraffinic oil was obtained from Juraske and Sanjuán (2011) and that for acetamiprid from Steingrímsdóttir et al. (2018). Human toxicity CF for Pyrachlostrobin was taken from Fantke and Jolliet (2016), and the one for ecotoxicity from Bennet (2012). As regards cuprous oxide and abamectin, the CFs for substances with similar characteristics, namely copper (II) and avermectin B1A, were used, respectively. According to the PCRs for fruits and nuts (EPD, 2019) and taking into account the EPD (2022) guidelines, indicators for primary energy resources were also assessed following EN 15804+A2.

4.3. RESULTS AND DISCUSSION

4.3.1. <u>Environmental impacts and contribution analysis</u>

Table 4.2 shows the impact results for each impact category and FU for all the periods assessed, together with the average value and the coefficient of variation (CV). The average contribution of the life cycle stages for the assessed seasons is represented in Fig. 4.2, whereas the average values and their standard deviation for both FUs are shown in Tables 4.6 & 4.7.

Table 4.2. Impact results per cropping season, average impacts, and coefficient of variation (CV) of cradle to farm gate lemon cultivation in Uruguay

	FU = 1ha						FU = 1 tonne					
Impact category	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)
Climate change (kg CO_2 eq.·FU^{-1})	4870.1	5009.7	5035.2	4985.4	4975.1	1	103.6	91.1	102.8	75.5	93.2	14
Ozone depletion (kg CFC-11 eq.·FU^{-1})	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	0	$4.3 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$	$3.8 \cdot 10^{-6}$	14
Acidification (Mole of H^+ eq.·FU^{-1})	77.0	77.0	77.0	77.0	77.0	0	1.6	1.4	1.6	1.2	1.4	15
Freshwater eutrophication (kg P eq.·FU^{-1})	1.3	1.3	1.3	1.3	1.3	0	$2.8 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	15
Marine eutrophication (kg N eq.·FU^{-1})	212.8	239.3	244.6	232.6	232.3	6	4.5	4.4	5. 0	3.5	4.3	14
Terrestrial eutrophication (Mole of N eq.·FU^{-1})	290.3	290.3	290.3	290.4	290.3	0	6.2	5.3	5.9	4.4	5.4	15

Table 4.2. (cont.) Impact results per cropping season, average impacts, and coefficient of variation (CV) of cradle to farm gate lemon cultivation in Uruguay

	FU = 1ha						FU = 1 tonne					
Impact category	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)
Photochemical ozone formation, human health (kg NMVOC eq.$\cdot FU^{-1}$)	24.6	24.6	24.6	24.6	24.6	0	0.5	0.4	0.5	0.4	0.5	15
Resource use, mineral and metals (kg Sb eq.$\cdot FU^{-1}$)	0.3	0.3	0.3	0.3	0.3	0	$6.5 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	$5.8 \cdot 10^{-3}$	15
Resource use, fossils (MJ$\cdot FU^{-1}$)	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	0	772.3	660.1	740.8	550.5	680.9	15
Ecotoxicity (CTUe$\cdot FU^{-1}$)	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	0	$1.7 \cdot 10^{6}$	$1.5 \cdot 10^{6}$	$1.7 \cdot 10^{6}$	$1.2 \cdot 10^{6}$	$1.5 \cdot 10^{6}$	15
Human toxicity, cancer (CTUh$\cdot FU^{-1}$)	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	0	$4.7 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	14

Table 4.2. (cont.) Impact results per cropping season, average impacts, and coefficient of variation (CV) of cradle to farm gate lemon cultivation in Uruguay

	FU = 1ha						FU = 1 tonne					
Impact category	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)
Human toxicity, non-canc. ($CTUh \cdot FU^{-1}$)	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	0	$6.6 \cdot 10^{-5}$	$5.7 \cdot 10^{-5}$	$6.4 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$	15
Blue water scarcity ($m^3 eq. \cdot FU^{-1}$)	$6.9 \cdot 10^{3}$	$7.7 \cdot 10^{3}$	$2.9 \cdot 10^{3}$	$7.9 \cdot 10^{3}$	$6.4 \cdot 10^{3}$	37	147.3	140.8	59.4	119.8	116.8	34

Regarding the relative contribution of different cradle to farm gate stages, on-field emissions from fertilisers is the dominant contributor to climate change (55-56% of the total impact, depending on the season), followed by fertilisers production (13-14%). Specifically, the production of NPK 30-0-0 and its subsequent N_2O emissions represent the main hotspots. Marine eutrophication is also led by on-field emissions from fertilisers (97-98%), while freshwater eutrophication is dominated by the production of both pesticides (71%) and fertilisers (20%). On-field emissions from fertilisers, in particular NH_3 and NO_2, together with machinery operations, are the stages with the greatest weight on terrestrial eutrophication (75% and 11%, respectively). Blue water consumption for irrigation is the main contributor to blue water scarcity, with an average of 86% and ranging from 75 to 91%, depending on the season. As to the categories related to resource depletion, the main contributor to fossil use is fertiliser production (57%), followed by machinery operations (23%). Pesticide production (91%) -mostly copper oxide- is the main hotspot detected regarding mineral and metals use. In the acidification category, field emissions -mainly NH_3 and NO_2- and pesticide production are the main contributors, with 61% and 16% of total impacts, respectively. POF is dominated in equal parts by machinery operations and NO_2 field emissions (33% each). In OD, the stage that impacts the most is input production (82% fertilisers and 12% pesticides).

When analysing the results of toxicity-related categories, pesticide production means 90% of total ET, 50% of HTc and 63% of HTnc, being copper pesticides the ones with the highest impact scores. Other two relevant stages in this impact category are fertiliser production (10% of total ET and 45-46% of HTc) and the emissions stemming from pesticide application (26% HTnc). Among the pesticides used, and considering the quantity applied, cuprous oxide, mancozeb, difenoconazole, and abamectin exhibit the highest values in ecotoxicity. Cuprous oxide, acetamiprid, pyraclostrobin and abamectin have the highest scores in human toxicity (Table 4.8). Despite the different origins of the agricultural inputs, their transportation does not represent a hotspot for any of the impact categories analysed, as most of the distances are covered by ship, an efficient transport which generates lower impacts than trucks (Wernet et al., 2016; Sphera Solutions GmbH, 2022).

Average results and standard deviations of resource use indicators (renewable and non-renewable primary energy resources) can be found in Tables 4.9 & 4.10. The stage with the greatest impact on renewable and non-renewable energy is fertiliser production, with 38 to 43% (depending on the season) and 57%, respectively, mainly due to the production of NPK 30-0-0. As to renewable energy, pesticide production -especially copper oxide- and machinery operations, with a similar proportion of 23-26%, are other impacting stages. The second most impacting stage in the category of non-renewable energy is machinery operations (23%).

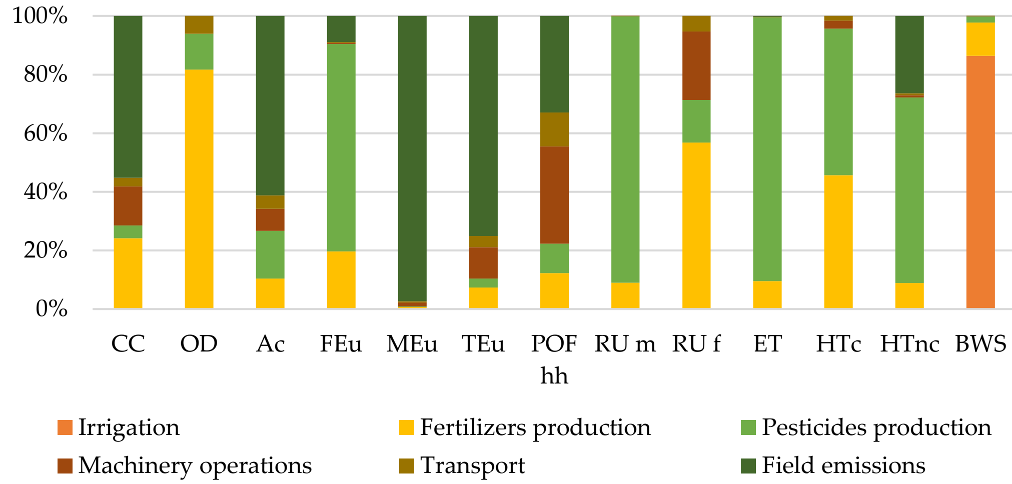


Fig. 4.2. Average percent contribution of the life cycle stages to the environmental footprint of Uruguayan lemons, per tonne of lemon and per ha. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater eutrophication (FEu), Marine eutrophication (MEu), Terrestrial eutrophication (TEu), Photochemical ozone formation impacts on human health (POF hh), Resource use - mineral and metals - (RU m), Resource use - fossils - (RU f), Ecotoxicity (ET), Human toxicity - cancer (HTc), Human toxicity - non-cancer (HTnc), Blue water scarcity (BWS).

4.3.2. Inter-seasonal variability of impacts

To evaluate the inter-seasonal variability of the results, for each cropping season, the coefficient of variability (CV, %) (Table 4.2) and the ratio “impact value in the season/mean impact value” were calculated for each impact category and FU. By plotting this ratio (Fig. 4.3), it is possible to observe how the values for each season and impact category are distributed with respect to the mean.

When the impact categories are expressed per ha, inter-seasonal variability of most impact categories is low, with CVs close to 0%, mainly because of the uniformity of agricultural practices since the applied inputs are the same (see Table 4.1). Only the irrigation water requirements, which depend on agroclimatic conditions, and consequently the energy needed for irrigation, change. In fact, the only categories that have a CV greater than 0% are BWS, MEu and CC, with 37%, 6% and 1%, respectively (Table 4.2). The high CV of BWS can be explained by the dependence of the crop's water demand on climatic parameters (mostly precipitation, relative humidity, wind, and temperature), which vary notably from year to year in Uruguay. In turn, the BWS impact also depends on the monthly scarcity CF of the basin, also influencing the variability of the results. The maximum and minimum BWS are detected for 2019-2020 and 2018-2019, respectively. Specifically, the value for 2018-2019 is the one that contributes the most to the great inter-season CV of this impact per ha, since it is approximately 60% lower than the values obtained for the remaining seasons. When observing in detail the monthly water consumption from November to March (the months with the greatest CFs for the studied basin), the season 2018-2019 exhibits the lowest water consumption (51% of total consumption). On the contrary, in 2019-2020, the water consumed in those months is the greatest (100%), which could explain the CV values obtained.

When analysing the inter-season variability per ha of MEu and CC, it must be borne in mind that on-field emissions is the stage that mostly influences those impact categories, with 97-98% and 55-56%, respectively, as commented in Section 3.1. Specifically, the higher inter-season variability of MEu (Fig. 4.3) mainly depends on NO_3^- leaching, which varies along the cropping seasons since it depends on both precipitation and irrigation, which usually vary from season to season. The extreme values of NO_3^- leached correspond to the seasons 2018-2019 and 2016-2017, where the sum of 'irrigation + rainfall' is maximum (1185.2 mm) and minimum (1007.6 mm), respectively (see Table 4.1). N_2O emissions dominate the CC category; these include direct and indirect N_2O emissions. The former are constant for all crop seasons since they depend on the amount of fertiliser applied, and the latter depends on NH_3 and NO_x emissions to air and on NO_3^- leached to groundwater. NH_3 and NO_x emissions are also constant for all the crop seasons assessed since they also depend on the amount of fertiliser applied. Hence, NO_3^- leaching is again the main source of variation for this impact, which depends on the above-mentioned variable factors. The greatest CC value thus corresponds to 2018-2019, with 5035.16 CO_2 eq.·ha^{-1}, and the lowest to 2016-2017, with 4870.1 CO_2 eq.·ha^{-1} (Table 4.2). It should be noted that these maximum and minimum CC values are not so different since there is not a direct relation between CC and NO_3^- leaching, as in the case of MEu. Finally, it should also be remarked that for the remaining categories in which on-field emissions is a relevant stage (61.15% of total Ac, 75.06% of TEu, 32.98% of POF hh), the CV is low (Table 4.2). The principal explanation lies in the main emissions that influence each of them. In particular, for Ac and TEu, NH_3 and NO_2 are the most influencing emissions, while NO_2 affects POF hh values. These emissions are constant for all the seasons studied since they depend directly on the amount of N applied, which was the same.

An interesting point to be raised is that the Uruguayan data used in this case study reveal an average annual N loss by NO_3^- leaching of 221.6 kg N · ha^{-1}, higher than the amounts of N applied with the fertiliser (203.1 kg N · ha^{-1} on average). This implies that a large part of the applied N fertiliser would be lost through leaching and that there is also a loss of N draining from the soil content. The model used in the present study (SQCB-NO_3 model) does not consider the day the fertiliser is applied, either the rain or irrigation days, which could directly influence the results. In turn, it neither considers the type of crop nor its N absorption dynamics. Using methodologies that contemplate these parameters would conduct to different and more accurate results. Along these lines, Pittelkow et al. (2016), who study the sustainability of the rice intensification process in Uruguay, point out that losses due to NO_3^- leaching depend on climatic factors and crop management, which have a great space-time variability, directly affecting the leaching rates. This highlights the importance of considering several harvest seasons, as in the present case study. The use of mechanistic models is recommended to quantify these emissions, considering the weight that NO_3^- leaching has, mainly in the MEu category but also in the CC category.

As expected, when expressing data per tonne, a greater variability is observed (Table 4.2), with CVs around 15%, except for BWS, which registered a 34% variation (Fig. 4.3). This highlights the strong relationship between impacts and yield, which depends on both climatic variables (e.g. rainfall, temperature-frost damage, irradiance, relative humidity), as well as on the agricultural practices (e.g. pruning, management of yield alternation, harvest time). The greatest variability ratios for all the impact categories per tonne, except MEu, correspond to those obtained in 2016-2017 (season with the lowest yield, 47 tonnes $\cdot ha^{-1}$), while the lowest are the ones for 2019-2020 (season with the greatest yield, 66 tonnes $\cdot ha^{-1}$), with BWS being an exception, showing the lowest ratio in 2018-2019. The greatest variability ratio obtained for MEu corresponds to 2018-2019, in which the sum of 'irrigation + rainfall' was greater, and not to 2016-2017, where the yield is the lowest (see Table 4.1). This reinforces the importance of the amount of water added to the crop for this impact category. As to BWS, 2016-2017 is the only period in which there is an inverse relationship between the impact score and the yield, as the yield was minimum, whereas the impact was the greatest. Along these same lines, 2017-2018 and 2019-2020 have similar water consumption values. Therefore, the main difference in the BWS values obtained (15% lower in 2019-2020) is explained by the yield (17% greater in that period). The BWS value obtained for 2018-2019 is the lowest (Table 4.2), mainly because the blue water consumption is also the lowest (Table 4.5). This can be explained by the fact that the rainfall value was the greatest in that period (1119.8 mm, Table 4.1), where 48% of the total rain is concentrated from November to March, when the crop water demand is the highest. Consequently, the crop consumed the rainwater retained in the soil (green water) instead of consuming the blue water from irrigation, generating a lower BWS impact. These results strongly highlight the relevance of including several years in LCAs of perennials, particularly in countries with highly variable climate conditions (e.g. precipitation).

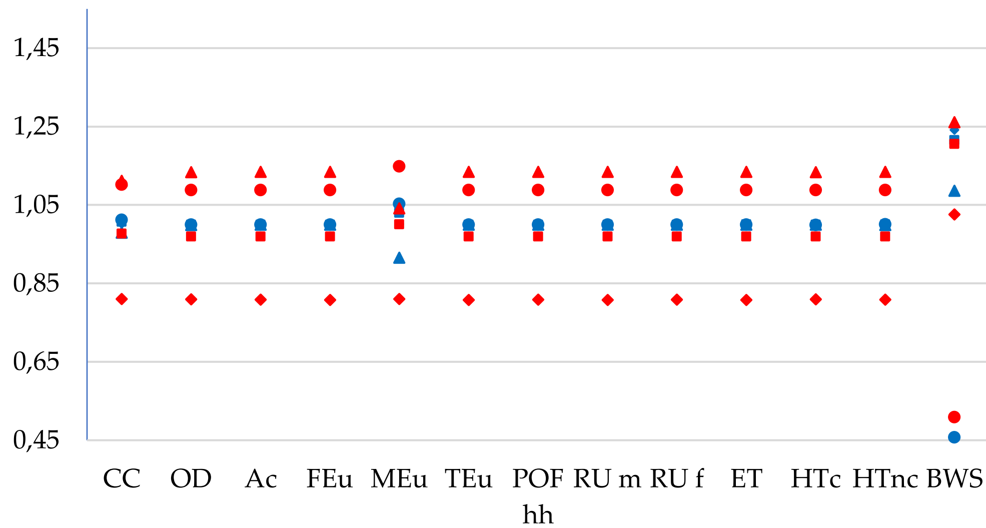


Fig. 4.3. Relative variability of the impact values of Uruguayan lemons with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per hectare of the orchard. ▲ 2016-2017, ■ 2017-2018, ● 2018-2019 ◆ 2019-2020. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater eutrophication (FEu), Marine eutrophication (MEu), Terrestrial eutrophication (TEu), Photochemical ozone formation, human health (POF hh), Resource use - mineral and metals - (RU m), Resource use - fossils - (RU f), Ecotoxicity (ET), Human toxicity - cancer (HTc), Human toxicity - non-cancer (HTnc), Blue water scarcity (BWS).

4.3.3. Sensitivity analysis

A sensitivity analysis is carried out in which a supposedly key inventory parameter is changed to verify the changes in the scores of the impact categories. Three parameters are chosen to perform the analysis: the yield, the amount of irrigated water and the rate of N fertiliser applied. The first two are chosen because they are highly variable from year to year, and the third since, although it does not vary in the case study, both its production and on-field emissions are detected as hotspots.

Yield variation affects all the impact categories when using 1 tonne as FU. Specifically, a 20% reduction in yield increases the results of all impact categories by 25%, whereas a 20% increase in the yield decreases all impacts by 17%. When the results per ha are analysed, the variation in the amount of irrigation water slightly changes the CC and MEu results. Halving the amount of irrigated water reduces CC by 1% and MEu by 5%, and doubling it increases the CC by 2% and the MEu by 8%. The N rate applied affects the stages of fertiliser production, transportation, and field emissions; therefore, varying N rate mainly affects TEu, Ac, OD and CC. TEu and Ac are shown to be more sensitive to on-field emissions, while OD and CC are more sensitive to fertiliser production. Specifically, a 20% increase in the N rate increases TEu by 15%, Ac by 13%, OD by 12% and CC by 11%, whereas a 20% decrease in the N rate decreases TEu by 17%, Ac by 15%, OD by 14%, and CC by 12%.

The results show the influence of the different parameters on the impact scores depending on the selected FU. Maximising the yield of the process results in lower environmental impacts when a mass FU is selected. When a spatial FU is selected, the importance of minimising the amount of N added and, to a lesser extent, the amount of irrigated water stands out.

4.3.4. Comparison with other studies

In this section, this study's cradle to farm gate impacts of lemon cultivation are compared with those from available literature, focusing on CC, FEu, and MEu, together with the water consumption-related impact, which differs depending on the case study analysed (see Table 4.11). It must be noted that, considering that the yields of lemon crops are usually higher than those of 'sweet' citrus fruits (oranges or mandarins), the comparison is carried out with three available studies on lemon (Machin Ferrero et al., 2021, 2022; Martin-Gorriz et al., 2020) and one study on generic citrus fruit (Yang et al., 2020).

When using a mass-based FU, the CC value obtained for Uruguayan lemons was 0.093 CO_2 eq.·kg^{-1}, around two (0.196 CO_2 eq.·kg^{-1}) and four (0.380 CO_2 eq.·kg^{-1}) times lower than in Machin Ferrero et al. (2022) and Martin-Gorriz et al. (2020), respectively. These differences could be related to the lower yield reported in both studies, 29.5 tonnes·ha^{-1} in Martin-Gorriz et al. (2020) and 32.5 tonnes·ha^{-1} in Machin Ferrero et al. (2022) vs 56.0 tonnes·ha^{-1} in this study. In addition, it must be noted that different emission factors are used to estimate N_2O emissions, namely Martin-Gorriz et al. (2020) use 0.01 kg N_2O-N·kg N^{-1} (IPCC, 2006), 0.067 kg N_2O-N·kg N^{-1} (Renouf, 2006) is used in Machin Ferrero et al. (2022), and 0.016 kg N_2O-N·kg N^{-1} (IPCC, 2019) is used in the present study. On-field emissions are the hotspot in this category in the present study and also in Machin Ferrero et al. (2022). As seen, those authors used a greater emission factor which, together with their lower yield, could explain their greater CC impact result. In the study of Martin-Gorriz et al. (2020), the main hotspot is fossil fuel combustion, contrasting with the great relevance of on-field emissions in the present study. The rationale behind these results could lie on the one hand, in the amount of diesel used for field operations in Martin-Gorriz et al. (2020), which is double (535.0 vs 216.0 L·ha^{-1}), increasing the weight of this stage in the total CC. On the other hand, the lower weight of the on-field emissions stage in their study can be explained by the 10% lower total N added (182.0 vs 203.1 kg N · ha^{-1}) and the lower emission factor used to estimate N_2O emissions, as commented above. Yang et al. (2020) show CC values seven times greater than those for Uruguay, also identifying on-field emissions as the most impactful stage. The differences are mainly explained by the greater amount of N applied (234% more) and the crop yield (approximately 50% lower).

Regarding water scarcity, especially relevant in agricultural LCAs (Payen et al., 2018), it must be highlighted that the methodologies and inputs used for its quantification greatly influence the results. In the present study, a value of 0.103 m^3eq.·kg^{-1} is obtained using the AWARE methodology, where the monthly water consumed by the crop, calculated as explained in Section 2.2.2.3, is then multiplied by the corresponding monthly CF. Only Machin Ferrero et al. (2021) assess this impact with the same methodology, although their result is 0.359 m^3eq.·kg^{-1}, that is, almost 3.5 times higher. This could be partially explained by the lower yield obtained for Argentinian lemons (42% lower). Likewise, it must be borne in mind that both the inventory input and CFs are different. In the Argentinian study, the irrigation water (102.94 m^3·$tonne^{-1}$) is multiplied by the average CF corresponding to the months in which the crop is irrigated (3.40 m^3eq.·m^{-3}); both values are about twice greater than those used in the present case study. In case that the average irrigation water (18.64 m^3·$tonne^{-1}$) and the average CF (1.70 m^3eq.·m^{-3}) for the irrigation months were used to calculate BWS, as in the Argentinian study, the final BWS value of the present study would be 54% lower. Therefore the difference with respect to Machin Ferrero et al. (2021) would be even greater. In sum, although both studies use the AWARE consensus method, BWS results are drastically influenced by both the water input and the CFs used. The value obtained by Machin Ferrero et al. (2022) is ten times lower than that obtained in the present case study. However, as previously stated, direct comparisons are not possible since they use the Swiss Ecological Scarcity Method (Frischknecht et al., 2006), which proposes regionalised factors according to water pressure categories.

As to the eutrophication-related categories, the methodologies used in Martin-Gorriz et al. (2020) and Yang et al. (2020) do not discern between freshwater and marine, thus, direct comparisons cannot be made. Regarding FEu, in the present study, the production of pesticides, namely copper production, is a relevant stage, similar to that described in Machin Ferrero et al. (2022, 2021), who also do discriminate between MEu and FEu, obtaining lower values, although of the same order of magnitude. As to MEu, in the present case study, almost all the impact is attributed to on-field emissions (97-98%). In this respect, Machin Ferrero et al. (2022) emphasise that, since Tucumán is in an endorheic basin, and the water has not outflow to the ocean, the impact on MEu due to local on-field emissions is meaningless. Accordingly, the values obtained in the Argentinian study are one order of magnitude lower than those of the present case study, which makes sense considering that on-field emissions (a highly impactful stage in our research) has no weight in their result.

Regarding the categories not included in Table 4.11, for Uruguayan lemons, freshwater ecotoxicity is dominated by pesticide production, mainly copper oxide. The Argentinian studies also highlight pesticide production as a critical point: the production of glyphosate (which is not used in the present study) and the production of copper oxide are highlighted in Machin Ferrero et al. (2021), and the production of copper oxide and abamectin in Machin Ferrero et al. (2022). Regarding human health toxicity, copper oxide production resulted the most relevant stage in this study, agreeing with Machin Ferrero et al. (2022). These observations make clear that the production of pesticides, especially copper oxide, a widespread fungicide, is a hotspot for lemons production in the region. As to mineral depletion, pesticide production is also the stage that contributes the most, as observed by Machin Ferrero et al. (2022) and Martin-Gorriz et al. (2020).

4.3.5. Gap for improvement

In this section, recommendations to improve the environmental performance of Uruguayan lemons are proposed, mainly focusing on farm management practices. The results obtained show that on-field emissions from fertilisers are one of the main hotspots for lemon production in Uruguay, in addition to the production of pesticides and fertilisers. Therefore, the reduction of the environmental impacts should undoubtedly include a revision of this aspect, where the cycle of N is particularly relevant. It is important to highlight that, in the studied orchard, some practices aimed at the reduction of N emissions are already carried out. Firstly, the N fertiliser applied contains a urease inhibitor and DMPP, which decrease the activity of nitrifying bacteria and reduce N emissions. Secondly, cover crops are also used, a widespread practice in Uruguayan citrus orchards, which consists of growing vegetation between the rows of trees to minimise N losses due to leaching (Sanz-Cobena et al., 2014). In addition, drip irrigation is a practice that tends to minimise N_2O and NO_3^-

emissions. Nevertheless, the reduction of N emissions as a consequence of these practices was not quantified since the methods used have no available emission factors linked, and it is thus an interesting point to be addressed in future studies.

The optimisation of N application is strongly linked to crop nutrition management, which is fundamentally based on the synchronisation of fertilisation with plant demand and, therefore, with crop physiology. To this end, a detailed study of the mineral N pool available should be carried out, considering the plant demand according to the physiological stage, the N available in the root zone and that released from applied fertilisers (Skiba et al., 1997). Two useful tools to optimise N application are the Normalized Difference Vegetative Index (Pettorelli, 2013) and the use of Site-Specific Nutrient Management (Buresh and Witt, 2007). The former takes into account the greenness of the leaves combined with previous yield data to design successive split fertiliser applications. The latter considers several factors to calculate the optimum level of N to be applied. In the case of citrus fruits, the selection of rootstocks more efficient in absorbing N during the production cycle could be another interesting option (Morales Alfaro et al., 2021). The selection of the type of fertiliser to be applied appears as a different approach to mitigate on-field emissions. Many authors recommend the incorporation of slow-release forms of N, among them solid organic fertilisers (Cayuela et al., 2017) and fertilisers covered with low permeability materials (Mahmud et al., 2021; Skiba et al., 1997). The incorporation of organic mulches, that is, material spread on the soil surface as a covering (e.g. bark, straw, senescent leaves), comes as a compelling alternative to minimise N losses. Mulch has a high carbon/nitrogen ratio and little available N; therefore, it can trap the residual N present in the soil (Carranca et al., 2018). Lastly, ecological ditches are an innovative strategy to minimise emissions. These are designed to absorb nutrients that otherwise would be lost through surface runoff and make those nutrients available for root uptake or be incorporated into microbial metabolites (Mahmud et al., 2021).

Another alternative to minimise on-field emissions is the optimisation of the irrigation regime (amount, moment, and irrigation technique). Drip irrigation, used in this case study, tends to minimise N_2O production by denitrification and NO_3^- leaching (Cayuela et al., 2017; Sanz-Cobena et al., 2017). Subsurface drip irrigation is an even better technology in terms of minimising emissions. As well, the implementation of fertigation at night hours, when evapotranspiration is reduced, can also reduce losses due to N volatilisation (Denmead et al., 2020).

The selection of the agricultural inputs to be applied is another opportunity for improvement since the manufacture of pesticides and fertilisers is a hotspot for several impact categories. In this respect, the selection of an alternative to copper oxide, as well as practices oriented to reducing pathogen inoculum in the field (pruning, organic mulches, and removing old twigs, among others), would have significant repercussions on the results. Despite the great impact of fertiliser production, their replacement is more complex as they are crucial for crop growth, although optimisation of the N cycle following the previous recommendations would contribute to minimising their use.

It must be taken into account that Uruguay is a country with a baseline water stress lower than 10% (World Resources Institute, 2019). Therefore, there is enough water available for agricultural use and recommendations to decrease

BWS should be thus oriented to the optimisation of the ratio "irrigation dose/crop yield" in the months of greatest scarcity in the basin. Optimising irrigation through the use of up-to-date technologies that minimise unproductive evaporation from the soil and thus reduce water consumption could be a relevant mitigation strategy. Advanced irrigation scheduling or deficit irrigation, which is based on the application of lower amounts of water than those needed by the crop, increases water productivity while maintaining acceptable crop yields (García-Tejero et al., 2012). The aforementioned organic mulch also reduces irrigation requirements, as it increases soil moisture retention. As well, the use of nets to cover the crop decreases irrigation requirements since it reduces the impact of the wind on the crop while increasing the humidity of the surrounding air (Wachsmann et al., 2014). Those authors suggest that the use of nets could also increase the yield, with the subsequent effect on the impacts per mass unit.

4.4. CONCLUSIONS AND FUTURE CHALLENGES

The environmental performance of lemon production in Uruguay was assessed by performing an LCA, revealing key process hotspots. The relevance of including several seasons in the analysis is evidenced, especially under highly variable climatic conditions and even with constant agricultural practices. On-field emissions from fertilisers, input production, and water consumption for irrigation are the main hotspots found, therefore, recommendations oriented to those stages have been proposed.

Results reaffirm the usefulness of considering different FUs for a more complete system analysis. As expected, inter-season variability is greater when results are expressed per unit of mass as, in this study, where the inputs applied are the same across the analysed seasons, yield greatly depends on agroclimatic variables. When expressing the results per ha, the inter-seasonal variability of MEu and CC and their dependence on nitrate leaching are evidenced. BWS shows the greatest inter-seasonal variability, mainly due to the dependence of the crop's water demand on climatic parameters, which are highly variable in Uruguay. This impact depends as well on the basin's monthly scarcity CF, also influencing the variability of the results.

The results obtained are similar and even lower, especially for CC and BWS, than those presented in other LCAs of lemon reviewed. The need to harmonise the method to quantify the water consumed by the crop must be emphasised, since this strongly influences the result of the BWS category when using the AWARE methodology. Given the importance of N emissions, the use of mechanistic models to quantify them is recommended. The quantification of the reduction of environmental impacts due to the measures already established in the orchards (e.g. use of urease inhibitors, cover crops, drip irrigation) is an interesting point to be addressed in future studies.

The present study is the first approach to quantify the environmental impacts of citrus fruit production in Uruguay. It highlights inter-seasonal variability as an issue to be considered, even when agricultural practices do not change from one season to another, which is especially relevant in countries with high climatic variability like Uruguay. The case study provides scientific and quantitative evidence to support both citrus producers and consumers when making decisions to increase the environmental performance of citrus production, in line with the Sustainable Development Goals (SDGs), in particular SDG-12.

Acknowledgements

Maria Inés Cabot is the recipient of a PhD scholarship (POS_EXT_2018_1_154319) from the National Agency for Research and Innovation (ANII, Uruguay).

The authors particularly acknowledge UPEFRUY-Uruguay fruits (http://uruguayfruits.com.uy/en) for their sincere collaboration and for sharing their data for this study.

The authors also especially acknowledge Dr. Matías Manzi from the Soil Fertility group, Soil and Water Department, at the Estación Experimental de Facultad de Agronomía, Salto, Uruguay, for his suggestions and recommendations to improve the manuscript.

Funding for open access charge: Universitat Politècnica de València.

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4.5. MATERIAL COMPLEMENTARIO DEL CAPÍTULO 4

La presente sección se divide en los siguientes apartados:

- Metadatos del modelado del proceso de cultivo de limón
- Distancias de transporte de los insumos utilizados
- Consumo de agua azul para las cuatro temporadas de estudio
- Resultados promedio de los impactos ambientales y desviación estándar por etapa del cultivo de limón, por hectárea y por tonelada
- Toxicidad de los plaguicidas utilizados en el cultivo de limón considerando la cantidad de principio activo aplicado
- Información de estudios de ACV de la producción de limón en otros países

Table 4.3. Life cycle inventory metadata of lemon production

Input	LCI Name	Type of process	Source
Abamectin production	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Acetamiprid production	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Cuprous oxide production	RoW: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.8
Difenoconazole production	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Mancozeb production	RoW: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.8
Paraffinic oil production	RoW: paraffin production	agg LCI result, cut-off method	Ecoinvent 3.8
Pyraclostrobin production	RER: methacrylic acid production	agg LCI result, cut-off method	Ecoinvent 3.8
Pyriproxyfen production	RoW: pyridine-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 30-0-0 production	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 0-40-20 production	US: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 0-40-20 production	US: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
Phosphoric acid production	RoW: phosphoric acid production, dihydrate process	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium chloride production	RER: potassium chloride production	agg LCI result, cut-off method	Ecoinvent 3.8
Diesel production	RSA: Diesel mix at refinery	agg LCI result, cut-off method	GaBi v.10
Electricity production	UY: market for electricity, medium voltage	agg LCI result, cut-off method	Ecoinvent 3.8
Machinery use	GLO: Universal Tractor	u-so, unit process single operation	GaBi v.10
Irrigation	GLO: Irrigation pump generic	u-so unit process single operation	GaBi v.10
Transportation by lorry	RoW: transport, freight, lorry 16-32 metric ton, EURO3	agg LCI result, cut-off method	Ecoinvent 3.8
Transportation by ship	GLO: Transoceanic ship, containers, 27,500 dwt payload capacity, ocean going	agg LCI result, cut-off method	GaBi v.10

Table 4.4. Transport distances for the inputs used in the case study on Uruguayan lemon cultivation (Searates, 2022).

Input	Use	Distance by ship (km)	Distance by lorry (km)
Difenoconazole	Fungicide	23142.2	134.2
Pyrachlostrobin	Fungicide	10864.0	90.8
Cuprous oxide	Fungicide	0.0	4100.0
Mancozeb	Fungicide	15617.8	565.4
Pyriproxyfen	Insecticide	23142.2	134.2
Acetamiprid	Insecticide	23142.2	134.2
Paraffinic oil	Insecticide	0.0	980.0
Abamectin	Insecticide	23142.2	134.2
Gibberellic acid	Growth regulator	10864.0	90.8
NPK 30-0-0	Fertiliser	10864.0	90.8
Potassium chloride	Fertiliser	10864.0	90.8
Phosphoric acid	Fertiliser	23142.2	134.2
Zinc	Fertiliser	n.a.	n.a.
NPK 0-40-20	Fertiliser	12340.7	213.5

n.a.: not available

Table 4.5. Reference evapotranspiration (ETo), calculated with the Penman-Monteith method (Allen et al., 1998), crop evapotranspiration (ETc) and blue water consumption (BWC), estimated following Allen et al. (1998), for the four seasons of study

		2016-2017			2017-2018			2018-2019			2019-2020		
Month	Kc	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)
August	0.8725	43.9	38.3	0.0	48.9	42.7	0.0	48.9	42.6	0.0	48.9	42.7	0.0
September	0.8502	63.3	53.9	0.0	63.8	54.2	0.0	73.9	62.8	0.0	76.7	65.2	0.0
October	0.8095	89.1	72.2	0.0	103.0	83.4	0.0	100.8	81.6	0.0	87.7	71.0	0.0
November	0.7504	123.9	93.0	34.0	138.9	104.2	32.6	126.5	94.9	31.5	136.2	102.2	0.0
December	0.6729	151.3	101.8	64.8	167.1	112.4	66.1	141.4	95.2	35.5	159.2	107.1	63.5
January	0.5134	141.2	72.5	64.3	166.2	85.3	60.9	133.7	68.6	34.2	167.7	86.1	29.8
February	0.6199	111.7	69.2	33.4	138.9	86.1	31.8	122.2	75.8	0.0	149.9	92.9	33.1
March	0.7080	102.1	72.3	33.2	121.8	86.2	63.0	98.7	69.9	0.0	112.7	79.8	63.5
April	0.7777	64.8	50.4	34.2	70.2	54.6	34.13	65.4	50.9	0.0	63.1	49.1	102.7
May	0.8290	34.2	28.3	35.2	43.7	36.3	0.0	40.8	33.8	35.0	37.6	31.2	0.0
June	0.8619	28.9	24.9	0.0	31.2	26.9	0.0	30.4	26.2	0.0	27.3	23.5	0.0
July	0.8764	31.3	27.4	0.0	30.2	26.5	0.0	33.7	29.5	0.0	34.4	30.2	0.0
Total (mm)		514.0	344.94	299.5	602.2	401.9	288.5	524.89	354.7	136.2	592.7	392.8	292.6

Table 4.6. Average impact results per stage and standard deviation of cradle to farm gate cultivation of lemon in Uruguay. FU = 1 ha

	Pesticides production	Fertilisers production	Transport	Machinery operations	Irrigation	Field emissions
Climate change (kg CO_2 eq.·ha^{-1})	$2.2{\cdot}10^{2} \pm 0.0$	$1.2{\cdot}10^{3} \pm 0.0$	$1.4{\cdot}10^{2} \pm 0.0$	$6.6{\cdot}10^{2} \pm 0.0$	8.4 ± 6.0	$2.8{\cdot}10^{3} \pm 7.2{\cdot}10^{1}$
Ozone depletion (kg CFC-11 eq.·ha^{-1})	$2.5{\cdot}10^{-5} \pm 0.0$	$1.7{\cdot}10^{-4} \pm 0.0$	$1.3{\cdot}10^{-5} \pm 0.0$	1.9·10-12 ± 0.0	$3.1{\cdot}10^{-7} \pm 2.2{\cdot}10^{-7}$	0.0 ± 0.0
Acidification (Mole of H^+ eq.·ha^{-1})	$1.3{\cdot}10^{1} \pm 0.0$	8.0 ± 0.0	3.6 ± 0.0	5.7 ± 0.0	$2.1{\cdot}10^{-2} \pm 1.5{\cdot}10^{-2}$	$4.7{\cdot}10^{1} \pm 0.0$
Freshwater eutrophication (kg P eq.·ha^{-1})	$9.2{\cdot}10^{-1} \pm 0.0$	$2.6{\cdot}10^{-1} \pm 0.0$	$4.3{\cdot}10^{-3} \pm 0.0$	$3.9{\cdot}10^{-3} \pm 0.0$	$2.7{\cdot}10^{-4} \pm 1.9{\cdot}10^{-4}$	$1.2{\cdot}10^{-1} \pm 0.0$
Marine eutrophication (kg N eq.·ha^{-1})	$6.6{\cdot}10^{-1} \pm 0.0$	1.6 ± 0.0	1.0 ± 0.0	2.9 ± 0.0	$5.2{\cdot}10^{-3} \pm 3.7{\cdot}10^{-3}$	$2.3{\cdot}10^{2} \pm 1.4{\cdot}10^{1}$
Terrestrial eutrophication (Mole of N eq.·ha^{-1})	8.8 ± 0.0	$2.1{\cdot}10^{1} \pm 0.0$	$1.1{\cdot}10^{1} \pm 0.0$	$3.1{\cdot}10^{1} \pm 0.0$	$5.6{\cdot}10^{-2} \pm 4.0{\cdot}10^{-2}$	$2.2{\cdot}10^{2} \pm 0.0$
Photochemical ozone formation, human health (kg NMVOC eq.·ha^{-1})	2.5 ± 0.0	3.0 ± 0.0	2.8 ± 0.0	8.2 ± 0.0	$1.5{\cdot}10^{-2} \pm 1.1{\cdot}10^{-2}$	8.1 ± 0.0
Resource use, mineral and metals (kg Sb eq.·ha^{-1})	$2.8{\cdot}10^{-1} \pm 0.0$	$2.8{\cdot}10^{-2} \pm 0.0$	$2.0{\cdot}10^{-4} \pm 0.0$	$2.8{\cdot}10^{-5} \pm 0.0$	$3.9{\cdot}10^{-5} \pm 2.7{\cdot}10^{-5}$	0.0 ± 0.0
Resource use, fossils (MJ.·ha^{-1})	$5.3{\cdot}10^{3} \pm 0.0$	$2.1{\cdot}10^{4} \pm 0.0$	$1.9{\cdot}10^{3} \pm 0.0$	$8.5{\cdot}10^{3} \pm 0.0$	$2.2{\cdot}10^{1} \pm 1.6{\cdot}10^{1}$	0.0 ± 0.0
Ecotoxicity (CTUe·ha^{-1})	$7.4{\cdot}10^{7} \pm 0.0$	$7.8{\cdot}10^{6} \pm 0.0$	$7.3{\cdot}10^{4} \pm 0.0$	$1.2{\cdot}10^{3} \pm 0.0$	$1.2{\cdot}10^{4} \pm 8.5{\cdot}10^{3}$	$2.2{\cdot}10^{5} \pm 0.0$
Human toxicity, cancer (CTUh·ha^{-1})	$1.1{\cdot}10^{-4} \pm 0.0$	$1.0{\cdot}10^{-4} \pm 0.0$	$3.6{\cdot}10^{-6} \pm 0.0$	$5.9{\cdot}10^{-6} \pm 0.0$	$4.1{\cdot}10^{-7} \pm 2.9{\cdot}10^{-7}$	0.0 ± 0.0
Human toxicity, non-canc. (CTUh·ha^{-1})	$2.0{\cdot}10^{-3} \pm 0.0$	$2.8{\cdot}10^{-4} \pm 0.0$	$2.1{\cdot}10^{-5} \pm 0.0$	$2.3{\cdot}10^{-5} \pm 0.0$	$9.4{\cdot}10^{-7} \pm 6.6{\cdot}10^{-7}$	$8.2{\cdot}10^{-4} \pm 0.0$
Blue water scarcity (m^3eq.·ha^{-1})	$1.1{\cdot}10^{2} \pm 4.8{\cdot}10^{-2}$	$6.1{\cdot}10^{2} \pm 1.5{\cdot}10^{-1}$	2.1 ± 0.0	$1.0{\cdot}10^{1} \pm 0.0$	$5.6{\cdot}10^{3} \pm 2.3{\cdot}10^{3}$	0.0 ± 0.0

Table 4.7. Average impact results per stage and standard deviation of cradle to farm gate cultivation of lemon in Uruguay. FU = 1 tonne

	Pesticides production	Fertilisers production	Transport	Machinery operations	Irrigation	Field emissions
Climate change (kg CO_2 eq.·tonne^{-1})	$4.1 \pm 6.0\cdot10^{-1}$	$2.2\cdot10^{1} \pm 3.2$	$2.7 \pm 4.0\cdot10^{-1}$	$1.2\cdot10^{1} \pm 1.8$	$1.5\cdot10^{-1} \pm 7.8\cdot10^{-2}$	$5.2\cdot10^{1} \pm 7.2$
Ozone depletion (kg CFC-11 eq.·tonne^{-1})	$4.6\cdot10^{-7} \pm 6.8\cdot10^{-8}$	$3.1\cdot10^{-6} \pm 4.5\cdot10^{-7}$	$2.3\cdot10^{-7} \pm 3.4\cdot10^{-8}$	$3.6\cdot10^{-14} \pm 5.2\cdot10^{-15}$	$5.4\cdot10^{-9} \pm 2.9\cdot10^{-9}$	0.0 ± 0.0
Acidification (Mole of H^+ eq.·tonne^{-1})	$2.4\cdot10^{-1} \pm 3.4\cdot10^{-2}$	$1.5\cdot10^{-1} \pm 2.2\cdot10^{-2}$	$6.8\cdot10^{-2} \pm 9.9\cdot10^{-3}$	$1.1\cdot10^{-1} \pm 1.6\cdot10^{-2}$	$3.6\cdot10^{-4} \pm 1.1\cdot10^{-4}$	$8.8\cdot10^{-1} \pm 1.3\cdot10^{-1}$
Freshwater eutrophication (kg P eq.·tonne^{-1})	$1.7\cdot10^{-2} \pm 2.5\cdot10^{-3}$	$4.8\cdot10^{-3} \pm 7.0\cdot10^{-4}$	$8.0\cdot10^{-5} \pm 1.2\cdot10^{-5}$	$7.4\cdot10^{-5} \pm 1.1\cdot10^{-5}$	$4.6\cdot10^{-6} \pm 2.5\cdot10^{-6}$	$2.2\cdot10^{-3} \pm 3.2\cdot10^{-4}$
Marine eutrophication (kg N eq.·tonne^{-1})	$1.2\cdot10^{-2} \pm 1.8\cdot10^{-3}$	$2.95\cdot10^{-2} \pm 4.3\cdot10^{-3}$	$1.9\cdot10^{-2} \pm 2.74\cdot10^{-3}$	$5.4\cdot10^{-2} \pm 7.9\cdot10^{-3}$	$9.0\cdot10^{-5} \pm 4.8\cdot10^{-5}$	$4.2 \pm 6.0\cdot10^{-1}$
Terrestrial eutrophication (Mole of N eq.·tonne^{-1})	$1.6\cdot10^{-1} \pm 2.4\cdot10^{-2}$	$4.0\cdot10^{-1} \pm 5.8\cdot10^{-2}$	$2.1\cdot10^{-1} \pm 3.0\cdot10^{-2}$	$5.9\cdot10^{-1} \pm 8.5\cdot10^{-2}$	$9.8\cdot10^{-4} \pm 5.2\cdot10^{-4}$	$4.1 \pm 6.0\cdot10^{-1}$
Photochemical ozone formation, human health (kg NMVOC eq.·tonne^{-1})	$4.6\cdot10^{-2} \pm 6.7\cdot10^{-3}$	$5.6\cdot10^{-2} \pm 8.2\cdot10^{-3}$	$5.3\cdot10^{-2} \pm 7.7\cdot10^{-3}$	$1.5\cdot10^{-1} \pm 2.2\cdot10^{-2}$	$2.6\cdot10^{-4} \pm 1.4\cdot10^{-4}$	$1.5\cdot10^{-1} \pm 2.2\cdot10^{-2}$
Resource use, mineral and metals (kg Sb eq.·tonne^{-1})	$5.2\cdot10^{-3} \pm 7.6\cdot10^{-4}$	$5.2\cdot10^{-4} \pm 7.6\cdot10^{-5}$	$3.8\cdot10^{-6} \pm 5.5\cdot10^{-7}$	$5.3\cdot10^{-7} \pm 7.7\cdot10^{-8}$	$6.7\cdot10^{-7} \pm 3.6\cdot10^{-7}$	0.0 ± 0.0
Resource use, fossils (MJ.·tonne^{-1})	$9.8\cdot10^{1} \pm 1.4\cdot10^{1}$	$3.9\cdot10^{2} \pm 5.6\cdot10^{1}$	$3.6\cdot10^{1} \pm 5.3$	$1.6\cdot10^{2} \pm 2.3\cdot10^{1}$	$3.8\cdot10^{-1} \pm 2.0\cdot10^{-1}$	0.0 ± 0.0
Ecotoxicity (CTUe·tonne^{-1})	$1.4\cdot10^{6} \pm 2.0\cdot10^{5}$	$1.5\cdot10^{5} \pm 2.1\cdot10^{4}$	$1.4\cdot10^{3} \pm 2.0\cdot10^{2}$	$2.3\cdot10^{1} \pm 3.4$	$2.1\cdot10^{2} \pm 1.1\cdot10^{2}$	$4.2\cdot10^{3} \pm 6.0\cdot10^{2}$
Human toxicity, cancer (CTUh·tonne^{-1})	$2.1\cdot10^{-6} \pm 3.0\cdot10^{-7}$	$1.9\cdot10^{-6} \pm 2.8\cdot10^{-7}$	$6.8\cdot10^{-8} \pm 9.9\cdot10^{-9}$	$1.1\cdot10^{-7} \pm 1.6\cdot10^{-8}$	$7.2\cdot10^{-9} \pm 3.8\cdot10^{-9}$	0.0 ± 0.0
Human toxicity, non-canc. (CTUh·tonne^{-1})	$3.7\cdot10^{-5} \pm 5.4\cdot10^{-6}$	$5.2\cdot10^{-6} \pm 7.6\cdot10^{-7}$	$3.9\cdot10^{-7} \pm 5.6\cdot10^{-8}$	$4.3\cdot10^{-7} \pm 6.3\cdot10^{-8}$	$1.6\cdot10^{-8} \pm 8.7\cdot10^{-9}$	$1.5\cdot10^{-5} \pm 2.2\cdot10^{-6}$
Blue water scarcity (m^3eq.·tonne^{-1})	$2.1 \pm 3.0\cdot10^{-1}$	$1.1\cdot10^{1} \pm 1.7$	$4.0\cdot10^{-2} \pm 5.8\cdot10^{-3}$	$1.9\cdot10^{-1} \pm 2.8\cdot10^{-2}$	$1.0\cdot10^{2} \pm 4.0\cdot10^{1}$	0.0 ± 0.0

Table 4.8. Toxicity impacts of pesticides used in lemon cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Abamectin (Avermectin B1A)	65195-55-3	ETP	$7.2 \cdot 10^{2}$	$2.1 \cdot 10^{-1}$	0.0	$1.1 \cdot 10^{-3}$	9.3	$7.3 \cdot 10^{2}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$5.0 \cdot 10^{-6}$	$6.2 \cdot 10^{-10}$	0.0	$3.2 \cdot 10^{-12}$	$7.9 \cdot 10^{-8}$	$5.1 \cdot 10^{-6}$
		HTP	$5.0 \cdot 10^{-6}$	$6.2 \cdot 10^{-10}$	0.0	$3.2 \cdot 10^{-12}$	$7.9 \cdot 10^{-8}$	$5.1 \cdot 10^{-6}$
Difenoconazole	119446-68-3	ETP	$8.0 \cdot 10^{2}$	$1.5 \cdot 10^{-1}$	0.0	$1.1 \cdot 10^{-1}$	$9.3 \cdot 10^{2}$	$1.7 \cdot 10^{3}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTP	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mancozeb	8018-01-7	ETP	$3.6 \cdot 10^{3}$	$5.2 \cdot 10^{-1}$	0.0	1.28	$1.1 \cdot 10^{4}$	$1.4 \cdot 10^{4}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$2.6 \cdot 10^{-7}$	$2.1 \cdot 10^{-11}$	0.0	$5.2 \cdot 10^{-11}$	$1.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
		HTP	$2.6 \cdot 10^{-7}$	$2.1 \cdot 10^{-11}$	0.0	$5.2 \cdot 10^{-11}$	$1.1 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$
Cuprous oxide	15158-11-9	ETP	$2.4 \cdot 10^{5}$	3.9	0.0	$1.4 \cdot 10^{2}$	$1.1 \cdot 10^{6}$	$1.4 \cdot 10^{6}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$4.0 \cdot 10^{-4}$	$9.5 \cdot 10^{-12}$	0.0	$3.3 \cdot 10^{-10}$	$4.3 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$
		HTP	$4.0 \cdot 10^{-4}$	$9.5 \cdot 10^{-12}$	0.0	$3.3 \cdot 10^{-10}$	$4.3 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$
Pyriproxyfen	95737-68-1	ETP	6.1	$1.8 \cdot 10^{-2}$	0.0	$2.4 \cdot 10^{-4}$	2.0	8.1
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$3.0 \cdot 10^{-9}$	$2.0 \cdot 10^{-13}$	0.0	$7.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-9}$	$4.0 \cdot 10^{-9}$
		HTP	$3.0 \cdot 10^{-9}$	$2.0 \cdot 10^{-13}$	0.0	$7.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-9}$	$4.0 \cdot 10^{-9}$
Paraffinic oil	-	ETP	$3.5 \cdot 10^{-4}$	$2.2 \cdot 10^{-9}$	0.0	$1.4 \cdot 10^{-7}$	$1.2 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$4.5 \cdot 10^{-8}$	$2.8 \cdot 10^{-13}$	0.0	$1.8 \cdot 10^{-11}$	$1.5 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$
		HTP	$4.5 \cdot 10^{-8}$	$2.8 \cdot 10^{-13}$	0.0	$1.8 \cdot 10^{-11}$	$1.5 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$
Acetamiprid	135410-20-7	ETP	$1.4 \cdot 10^{-2}$	$8.6 \cdot 10^{-8}$	0.0	$5.7 \cdot 10^{-6}$	$4.7 \cdot 10^{-2}$	$6.1 \cdot 10^{-2}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$8.9 \cdot 10^{-5}$	$5.5 \cdot 10^{-10}$	0.0	$3.6 \cdot 10^{-8}$	$3.0 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$
		HTP	$8.9 \cdot 10^{-5}$	$5.5 \cdot 10^{-10}$	0.0	$3.6 \cdot 10^{-8}$	$3.0 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$

Table 4.8. (cont.) Toxicity impacts of pesticides used in lemon cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Pyrachlostrobin	175013-18-0	ETP	$1.2 \cdot 10^{-6}$	$7.5 \cdot 10^{-12}$	0.0	$4.9 \cdot 10^{-10}$	$4.1 \cdot 10^{-6}$	$5.3 \cdot 10^{-6}$
		HTPc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		HTPnc	$4.3 \cdot 10^{-6}$	$2.7 \cdot 10^{-11}$	0.0	$1.7 \cdot 10^{-9}$	$1.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$
		HTP	$4.3 \cdot 10^{-6}$	$2.7 \cdot 10^{-11}$	0.0	$1.7 \cdot 10^{-9}$	$1.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$

*Ecotoxicity potential (ETP) is estimated in PAF.m^3.day. Human toxicity potential (HTP) is estimated in cases and is the sum of the carcinogenic (HTPc) and the noncarcinogenic (HTPnc) human toxicity potentials. n.a.: not available.

Table 4.9. Average and standard deviation of resource use indicators, optional indicators, output flows and waste categories per stage corresponding to cradle to farm gate cultivation of lemon in Uruguay, FU = 1 ha

	Total	Pesticides production	Fertilisers production	Transport	Machinery operations	Irrigation	Field emissions
Use of renewable primary energy (MJ · ha^{-1})	2156.1 ± 123.6	542.9 ± 0.0	888.0 ± 0.0	14.9 ± 0.0	535.5 ± 0.0	174.6 ± 123.6	0.0 ± 0.0
Total use of renewable primary energy resources (MJ · ha^{-1})	2156.1 ± 123.56	543.0 ± 0.0	888.0 ± 0.0	14.9 ± 0.0	535.5 ± 0.0	174.6 ± 123.6	0.0 ± 0.0
Use of non-renewable primary energy (MJ · ha^{-1})	36383.4 ± 17.6	5282.9 ± 1.9	20622.2 ± 14.8	1961.7 ± 1.1	8477.3 ± 1.8	22.0 ± 15.6	0.0 ± 0.0
Total use of non-renewable primary energy resources (MJ · ha^{-1})	36385.6 ± 16.7	5283.1 ± 2.0	20624.2 ± 16.1	1961.7 ± 1.2	8477.3 ± 1.8	22.0 ± 15.6	0.0 ± 0.0

Table 4.10. Average and standard deviation of resource use indicators, optional indicators, output flows and waste categories per stage corresponding to cradle to farm gate cultivation of lemon in Uruguay, FU = 1 tonne

	Total	Pesticides production	Fertilisers production	Transport	Machinery operations	Irrigation	Field emissions
Use of renewable primary energy (MJ · tonne^{-1})	40.2 ± 3.9	10.2 ± 1.5	16.7 ± 2.4	0.3 ± 0.0	10.0 ± 1.5	3.0 ± 1.6	0.0 ± 0.0
Total use of renewable primary energy resources (MJ · tonne^{-1})	40.2 ± 3.9	10.2 ± 1.5	16.7 ± 2.4	0.3 ± 0.0	10.0 ± 1.5	3.0 ± 1.6	0.0 ± 0.0
Use of non-renewable primary energy (MJ · tonne^{-1})	682.2 ± 99.2	99.1 ± 14.4	386.9 ± 56.4	36.8 ± 5.4	158.9 ± 23.4	0.4 ± 0.2	0.0 ± 0.0
Total use of non-renewable primary energy resources (MJ · tonne^{-1})	682.2 ± 99.2	99.1 ± 14.4	387.0 ± 56.4	36.8 ± 5.4	158.9 ± 23.4	0.4 ± 0.2	0.0 ± 0.0

Table 4.11. Information from Life Cycle Assessment studies of lemon production in diverse locations, including yields, N and P_2O_5 fertiliser doses, methods to estimate on-field emissions and selected impact results from cradle to farm gate per FU (kg of lemon)

						Methods for on-field emissions estimation					Impacts at farm gate per 1 kg citrus fruit			
Reference	Geographical location	Yield (tonne $\cdot ha^{-1}$)	N rate (kg ha^{-1})	P_2O_5 rate (kg $\cdot ha^{-1}$)	Impact assessment method	N_2O	NH_3	NO_3^-	NO_x	PO_4^{3-}	CC (kg CO_2 eq.)	WC (m^3eq.)	FEu (kg P eq.)	MEu (kg N eq.)
This study	San José, Uruguay	56.0	203.1	8.5	EN 15804 +A2, AWARE USEtox 2.0	(IPCC 2006) + 2019 update	EEA (2019)	SQCB-NO_3 model (Emmenegger et al., 2009)	EEA (2019)	SALCA-P model (Nemecek et al., 2019)	0.09	0.24 (BWS)	$2.5\cdot10^{-5}$	$4.4\cdot10^{-3}$
Machin Ferrero et al. (2021)	Tucumán, Argentina	32.5	244.6	11.3	ReCiPe 2016 IMPACT World + 1.25 Roy et al. (2012, 2014)	Renouf (2006)	Renouf (2006)	Renouf (2006)	Renouf (2006)	Renouf (2006)	*	0.36 (BWS)	$1.9\cdot10^{-5}$	*
Machin Ferrero et al. (2022)	Tucumán, Argentina	32.5	n.s.	n.s.	USEtox 2.0 Characterisation factors of the ILCD method	Renouf (2006)	Renouf (2006)	Renouf (2006)	Renouf (2006)	Renouf (2006)	0.20	0.02 (WD)	$1.2\cdot10^{-5}$	$4.4\cdot10^{-4}$
Martin-Gorriz et al. (2020)	Murcia, Spain	29.5	182.0	36.0	CML 2001	IPCC (2006)	EEA (2016)	Martínez-Alcantara et al. (2012)	Sanz-Cobena et al. (2014)	SALCA-P model (Nemecek and Kägi, 2007)	0.38	*	$8.3\cdot10^{-5}$ **	

Table 4.11. (cont.) Information from Life Cycle Assessment studies of lemon production in diverse locations, including yields, N and P_2O_5 fertiliser doses, methods to estimate on-field emissions and selected impact results from cradle to farm gate per FU (kg of lemon).

						Methods for on-field emissions estimation					Impacts at farm gate per 1 kg citrus fruit			
Reference	Geographical location	Yield (tonne ·ha^{-1})	N rate (kg ha^{-1})	P_2O_5 rate (kg ·ha^{-1})	Impact assessment method	N_2O	NH_3	NO_3^-	NO_x	PO_4^{3-}	CC (kg CO_2 eq.)	WC (m^3eq.)	FEu (kg P eq.)	MEu (kg N eq.)
Yang et al. (2020)	Danling County, Sichuan, southwest China	24.5	847.0	443.0	Bibliography emission indexes	IPCC (2006)	Ti et. Al. (2005)	Zhao et. al. (2010)	Perrin et al. (2014)	Wang et. al. (2007) Chen et. al. (2011)	0.64	*	$2.0 \cdot 10^{-3}$ **	

*: impact not estimated; **: authors do not discern between freshwater and marine eutrophication. CC: climate change; FE: freshwater eutrophication; ME: Marine eutrophication; WC: Water Consumption related impact; BWS: Blue Water Scarcity; WD: Water Depletion.

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El **capítulo 5** se basa en el siguiente artículo:

Cabot MI, Lado J, Bautista I, Ribal J, Sanjuán N. 2023. On the relevance of site specificity and temporal variability in agricultural LCA: a case study on mandarin in North Uruguay. The International Journal of Life Cycle Assessment – Special Issue: The Role of Developing and Emerging Economies in Sustainable Food Systems. https://doi.org/10.1007/s11367-023-02186-6

5. SOBRE LA RELEVANCIA DE LA ESPECIFICIDAD DE SITIO Y LA VARIABILIDAD TEMPORAL EN LOS ACV AGRÍCOLAS: UN CASO DE ESTUDIO EN MANDARINAS DEL NORTE DE URUGUAY

Resumen:

Objetivo. La mandarina es un cultivo citrícola relevante en Uruguay tanto en términos de rendimiento como de superficie. Este estudio tiene como objetivo evaluar los impactos ambientales del cultivo de mandarina en el país para identificar los puntos críticos ambientales. Se evalúa la variabilidad temporal considerando seis temporadas de cultivo y la especificidad según el sitio mediante el desarrollo de un inventario regionalizado utilizando una metodología de nivel 3 para estimar las emisiones de nitrógeno en el campo. Además, se analiza el efecto de la regionalización de categorías específicas de impacto.

Métodos. Se llevó a cabo una evaluación desde la cuna hasta la puerta del campo basada en unidades funcionales de masa y área. Los datos primarios se recopilaron de un campo representativo de la región para las temporadas de 2016

a 2022. Las emisiones de nitrógeno en el campo se estimaron utilizando LEACHN, un modelo de nivel 3 que considera parámetros climáticos y de suelo específicos del sitio, y las aplicaciones de agua y fertilizantes se modelaron en una escala diaria. Además, se analizaron otros enfoques de modelado siguiendo las declaraciones ambientales de producto (EPD), la huella ambiental del producto (PEF), los lineamientos propuestos en la base de datos mundial para ACV de alimentos (WFLDB) y las pautas actualizadas del IPCC y la Agencia Ambiental Europea (EMEP/EEA). Para la evaluación de los impactos ambientales se siguió la norma EN 15804+A2, excepto para las categorías relativas a la acidificación, donde se utilizó IMPACT 2002+v2.1. Además, para analizar las variaciones en los resultados al regionalizar los impactos de las emisiones en campo, se utilizó IMPACT World+.

Resultados. Los principales puntos críticos detectados son las emisiones en el campo, las operaciones con maquinaria y la producción de pesticidas y fertilizantes. El riego es el principal punto crítico en la escasez de agua azul. En cuanto a los modelos probados para estimar las emisiones de nitrógeno, se detectaron diferencias significativas en la eutrofización marina entre LEACHN y WFLDB, independientemente de la unidad funcional, y en la acidificación terrestre, eutrofización terrestre y acidificación acuática por hectárea entre LEACHN y PEF. Se observaron reducciones significativas en los resultados al regionalizar los impactos ambientales causados por las emisiones en campo.

Conclusiones. Se recomienda el desarrollo de inventarios específicos del sitio y métodos de evaluación de impacto con alta resolución espacial, aunque se necesita más investigación para extraer conclusiones generales sobre la conveniencia de los modelos mecanísticos para estimar las emisiones de nitrógeno en la citricultura uruguaya. Los altos coeficientes de variación obtenidos reafirman la importancia de considerar la variabilidad temporal. Además, se destaca la relevancia de considerar diferentes unidades funcionales, ya que se observan diferentes variables que influyen a lo largo de las temporadas dependiendo de la unidad funcional utilizada.

Palabras clave: análisis de ciclo de vida; frutas cítricas; modelado de emisiones en campo; variabilidad interanual; impactos ambientales; impactos regionalizados

5. ON THE RELEVANCE OF SITE SPECIFICITY AND TEMPORAL VARIABILITY IN AGRICULTURAL LCA: A CASE STUDY ON MANDARIN IN NORTH URUGUAY

Abstract:

Purpose. Mandarin is a relevant citrus crop in Uruguay both in terms of yield and area. This study aims to assess the environmental impacts of mandarin cultivation in the country to identify the environmental hotspots. Temporal variability is assessed by considering six harvest seasons and site specificity by developing a regionalised inventory using a Tier 3 to estimate nitrogen on-field emissions. Also, the effect of regionalising specific impact categories is analysed.

Methods. A cradle-to-farm gate assessment was carried out based on mass and area functional units. Primary data was gathered from a representative orchard of the region for the seasons 2016 to 2022. Nitrogen on-field emissions were modelled using LEACHN, a Tier 3 model that considers site-specific climatic and soil parameters as well as water and fertiliser applications at a daily scale. In addition, other modelling approaches were tested following the Environmental Product Declarations (EPD), Product Environmental Footprint (PEF), World Food LCA Database guidelines (WFLDB), and the updated IPCC and EMEP/EEA guidelines. The EN 15804+A2 standard was followed to assess the environmental impacts, except for the categories concerning acidification, where IMPACT 2002+ v2.1 was used. In addition, to analyse the variations in the results when regionalising impacts of on-field emissions, IMPACT World+ was used.

Results. The main hotspots detected are on-field emissions, machinery operations, pesticides, and fertilisers production. Irrigation is the main hotspot in blue water scarcity. As for the models tested to estimate nitrogen emissions, significant differences were detected in marine eutrophication between LEACHN and WFLDB, regardless of the functional unit, and in terrestrial acidification, terrestrial eutrophication, and aquatic acidification per ha between LEACHN and PEF. Significant reductions in the results were observed by regionalising the environmental impacts caused by the on-field emissions.

Conclusions. The development of site-specific inventories and impact assessment methods with spatial resolution is encouraged, although more research is needed to draw general conclusions about the convenience of mechanistic models to estimate nitrogen emissions in Uruguayan citriculture. The high variation coefficients obtained reaffirm the importance of considering temporal variability. Moreover, the relevance of considering different functional units is highlighted since different influencing variables are observed throughout the seasons depending on the functional unit used.

Keywords: Life cycle assessment; Citrus fruit; On-field emissions modelling; Inter-seasonal variability; Environmental impacts; Regionalised impacts.

5.1. INTRODUCTION

Mandarin is a representative crop in Uruguayan citriculture, both in terms of tonnes produced (99,736 tonnes in 2021) and area occupied (5,712 hectares in 2021), exhibiting a 28% increase in production from 2020 to 2021 (MGAP 2022).

Nearly 95% of the mandarin production is located in the north of the country due to favourable weather conditions, with a high heliophany and alternating high and low temperatures that favour an earlier maturation. Uruguayan citrus fruits are mainly exported, reaching 55% of the total production of mandarins in 2021. The United States is the leading destination, with 57% of exported mandarins (Uruguay XXI 2022). In recent years, Afourer mandarin has gained ground in the citrus sector due to its high yield and outstanding fruit quality (despite its tendency to alternating bearing), being the second variety in the country in terms of tonnes produced (17% of mandarin production) and area (10% of total mandarin surface area) (MGAP 2022).

Life cycle assessment (LCA) is a broadly accepted and used methodology for assessing the impacts of agriculture by quantifying all the emissions and resource consumption along the product life cycle. The use of this methodology is in line with the proposals of the UN through the SDGs (UN 2022), specifically the SGD-12 "Ensure sustainable consumption and production patterns". In particular, the 12.2 target aims to achieve, by 2030, a sustainable management and efficient use of natural resources and proposes as an indicator the "material footprint, material footprint per capita, and material footprint per gross domestic product". LCA has been used to determine the environmental profile of citrus in different countries. Specifically, mandarin production has been studied in Morocco (Bessou et al. 2016), Italy (Nicoló et al. 2015) and Spain (Nicoló et al. 2015; Martin-Gorriz et al. 2020). As for the Southern Cone, the published research on citrus LCAs focuses on oranges in Brazil (Knudsen et al. 2011) and lemons in Argentina (Machin Ferrero et al. 2021, 2022) and Uruguay (Cabot et al. 2023).

The estimation of the environmental impacts of agricultural systems through LCA entails difficulties. Among others, those concerning the system variability are especially relevant in perennial fruit crops (Cabot et al. 2022). On the one hand, this variability is associated with temporal issues related to agroclimatic factors that affect annual crop productivity (Cerutti et al. 2014; Bessou et al. 2016), which is more evident in those perennial crops affected by alternating bearing (Bessou et al. 2016), such as some citrus varieties. As well, as pointed out by Lee et al. (2020), the magnitude of on-field emissions released into the environment also depends on time-varying factors such as farm management practices (i.e., fertilisation rate, irrigation) and climatic ones (temperature, pluviometry). Along these lines, to increase the temporal representativeness of the inventory data, Cerutti et al. (2014) recommend collecting field data in an even number of years (at least four) to assess the impacts of perennial crops in their full production phase (i.e., highest yield). In addition, Cabot et al. (2023) highlight inter-seasonal variability as an issue to be considered when gathering inventory data for the highly productive years, even when agricultural practices remain the same with time. Despite this, a previous literature review on the LCA of citrus fruits (Cabot et al. 2022) shows that only Bessou et al. (2016) consider more than one productive year of the high production stage.

Spatial considerations also play a relevant role when performing agricultural LCAs. Traditionally, LCAs have relied on global or country-level inventory data, even when literature has raised the potential risks it may entail, mainly inaccurately representing a product's environmental impacts at regional or local levels (Potting and Hauschild 2006). Regional LCAs, which involve the collection of specific inventories, allow for more accurate and relevant results. Specifically, the model used to estimate on-field emissions is crucial to obtaining representative inventory data, as they are responsible for many environmental impacts in agricultural LCAs (Bessou et al. 2016; Cabot et al. 2023; Machin Ferrero et al. 2022). However, in the LCA literature of agri-food systems, different approaches with varying complexity are used to estimate these emissions and, depending on the guidelines followed (e.g., EPD, PEF, WFDB, etc.), the recommended approaches to estimate these emissions differ. Mechanistic Tier 3 models have been proposed to quantify N on-field emissions as they are both site and time-dependent, although they require many input data (Andrade et al. 2021; Cabot et al. 2023). Spatial issues should also be considered in the impact assessment since, among the relevant impact categories in the LCAs of agri-food products, regional ones, such as eutrophication and acidification, stand out (Cabot et al. 2022). Along these lines, the regionalisation of the impact calculation accounts for the spatial variability of the impact scores as a function of the characteristics of the receiving environment (Patouillard et al. 2018). To this aim, the use of characterisation factors at the regional level is recommended. Notwithstanding the importance of this aspect, to the best of the author's knowledge, previous LCAs of citrus fruits have not considered spatial aspects when modelling on-field emissions or quantifying some environmental impacts.

Built upon spatially and temporally explicit life cycle data, further analyses capable of capturing the relative influences of weather, soil, and farming practices on life cycle environmental impacts are needed. Bearing all this in mind, this study aims to perform an environmental assessment of Uruguayan mandarin production and identify the environmental hotspots in the farming stage by addressing the temporal and spatial issues of LCAs of perennial crops. In particular, six harvest seasons with different farm management practices and climatology are analysed to account for the temporal variability during the full production phase of the trees. In addition, temporal differentiation is made, as N emissions are modelled per day. This daily differentiation is also applied to estimate water consumption, whereas the remaining processes are assessed per crop season. Site specificity is also addressed, as the inventory is composed mainly of primary data, and the Tier 3 LEACHN model (Hutson and Wagenet 1992) is applied for modelling reactive N on-field emissions using specific soil and agroclimatic data of the region. Finally, the influence of the modelling of N emissions due to fertiliser application is studied by comparing the results using this Tier 3 model and alternative Tier 1 and Tier 2 methods proposed in published guidelines. To assess the relevance of the regional specificity of the impacts, the ImpactWorld+ method (Bulle et al. 2019) is used to analyse the differences between regionalised and non-regionalised impact scores for the on-field emissions stage.

5.2. METHODS

This study follows the LCA methodology based on ISO standards (ISO 2006a, 2006b; ISO 2017; ISO 2020a; ISO, 2020b) using GaBi software v10 (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany).

5.2.1. System description

A representative conventional orchard of Uruguayan mandarin production located in Quebracho, Paysandú department, northwest of Uruguay, was selected for the case study. It has an effective surface of 272 ha with mandarin and orange trees; of these, a plot of 2.71 ha. with 1,509 trees in full production corresponding to the 'Afourer' mandarin cultivar and planted in the same year (2006) was assessed.

The geographical representativeness of the studied orchard is accounted for by following the recommendations proposed by Cabot et al. (2022). The selected orchard can be considered representative in several aspects; it is located in the north of the country, where the production of Uruguayan mandarins is concentrated with 95% of total mandarin production (MGAP 2022). In addition, the Afourer cultivar is the second most important in the country in terms of production (17% of total mandarin production) and area (10% of the area destinated to mandarin production) (MGAP 2022). Likewise, the selected plot has an average yield of 35.8 tonnes $\cdot ha^{-1}$ and a plant density of 557 trees$\cdot ha^{-1}$, similar to the average values in the country (36 tonnes$\cdot ha^{-1}$ for this variety and 543 trees$\cdot ha^{-1}$ for mandarins in general) (MGAP 2022). It must also be highlighted that the orchard belongs to one of the eight companies that concentrate 67% of citrus production in Uruguay (MGAP 2022), and the agricultural practices follow the Global GAP certification system for exportation (GLOBALG.A.P. 2022), widely used by citrus exporting companies in the country.

According to IPCC (2006a) and FAO (2001), Uruguay has a warm temperate moist climate, which corresponds to a subtropical humid zone. Based on data from the nearest weather station (INIA Salto Grande), the average annual rainfall for the studied seasons (from 2016 to 2022) was 1348.9 mm, and the average temperature was 19.6º C. A minimum temperature of -3.6º C was recorded in July 2019, and a maximum of 41.8 ºC in January 2022 (INIA-GRAS 2022a). As to soil characteristics, according to CONEAT classification, the orchard has a 9.3 soil, whose geological material corresponds to sandstones with clayey cement, frequently with pink tones, sometimes reddish or greyish white (INIA-GESIR 2022). In the USDA classification, the soil is Planosol/Argisol corresponding to an Argiabol (Argialboll), and Planosol Dístrico Ocrico in the DSA-MGAP classification (INIA-SIGRAS 2022).

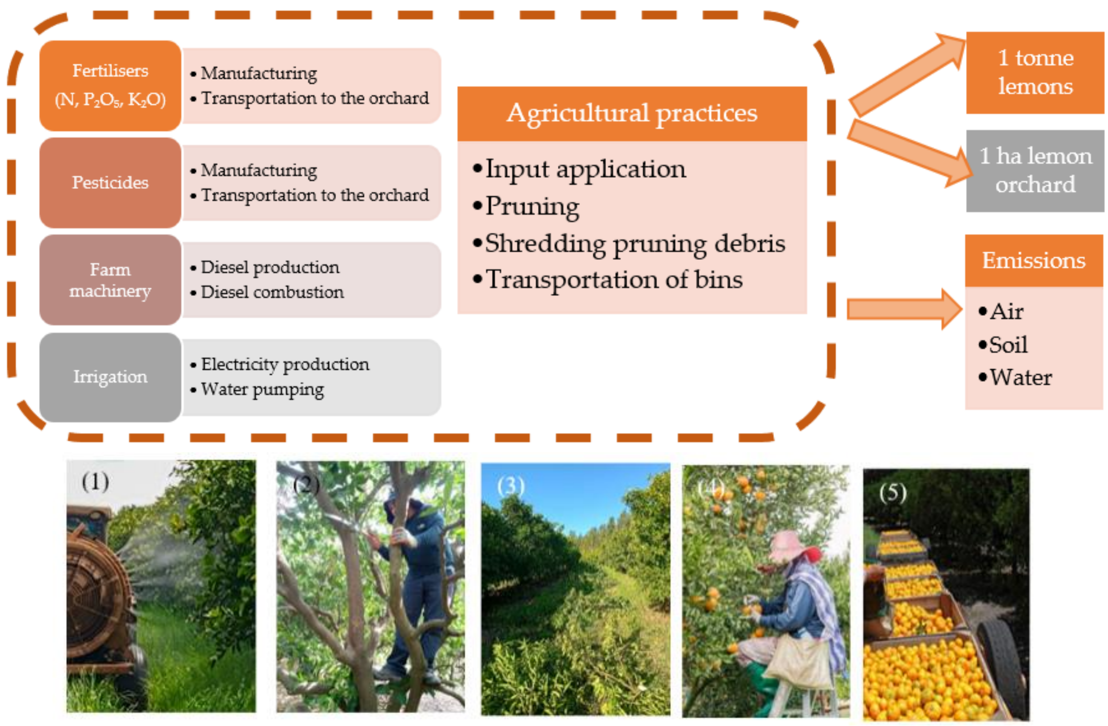
In this study, the term "cropping season" has been used to define the period beginning immediately after the previous harvest (usually August) and ending with the next harvest (July), as it does not correspond to a calendar year. During each cropping season, different operations are performed. Fertilisation is generally carried out from September to March via fertigation, foliar application, and direct application to the soil. The 2018-2019 season constitutes an exception, in which fertigation was not applied for economic reasons. Throughout the year, pesticides are applied via foliar to combat different pests, mainly anthracnose, melanosis, scabies, mites, citrus leaf miner and cochineal. A tractor (48.5 kW and 1700 rpm) is used for shredding pruning debris, transporting harvested mandarin bins and foliar input application, for which a fumigator is attached. Superficial drip irrigation is mainly concentrated from September to February, coinciding with the most significant water demand in spring-summer although, depending on the climatology, it can be extended until April. Irrigation water is withdrawn from a nearby lake, property of the company, by using an electric pump. As mentioned above, Afourer mandarins for export are harvested in July; they are picked by hand and then quickly transported to packinghouses, where the fruit is packaged according to the quality requirements at the destination.

5.2.2. Life cycle assessment

5.2.2.1. Functional unit and system boundaries

Two functional units (FUs) are adopted to observe the sensitivity of the impacts to this variable. A mass FU (1-tonne mandarin) is used to account for the function of food provision. In addition, taking into account that agricultural systems do not only rely on ecosystem services provided by natural ecosystems but they also produce a variety of ecosystem services (Swinton et al. 2007; Power 2010), an area FU (namely 1 ha) has also been considered.

The system boundaries are set from cradle to farm gate, and the stages considered are the production, transportation, and application of inputs (fertilisers and pesticides), the use of machinery, which involves the production and combustion of diesel, as well as the irrigation, which implies the production of electricity for water pumping (Fig. 5.1). Following Frischknecht et al. (2007), the impacts related to the production of capital goods for agriculture were not quantified since, except for resource use (mineral and metals) and land use impact categories, they do not significantly contribute to environmental impacts. Nevertheless, two issues should also be considered in this respect. Firstly, the assessment method used by Frischknecht et al. (2007), CML 2001, does not account for phosphorus and potassium, two relevant mineral resources in the production of fertilisers that, if considered, could reduce the relative contribution of capital goods to this impact category. These two mineral resources are included in the impact assessment method applied in the present study. As well, as reported in Section 2.1., the studied plot is part of a large orchard. Hence farm machinery is not only used where Afourer mandarins are grown, for which the impacts of its manufacture should be divided among all the agricultural activities in which it participates, causing these impacts to be reduced. Regarding the temporal scope, one farming season is considered and, given the relevance of interseason variability, which is a critical issue in LCAs of perennial crops (Cerutti



et al. 2014; Bessou et al. 2016; Cabot et al. 2023), data from 6 seasons corresponding to trees in full production phase are used, namely from 2016 to 2022.

Fig. 5.1. System boundaries showing the life cycle stages included in the LCA of Uruguayan mandarins. Pictures were taken and provided by technicians of the studied orchard

5.2.2.2. Life cycle inventory (LCI)

As described below, several data sources and models were used to carry out the life cycle inventory (LCI). Relevant background processes were taken from commercial databases to develop reference LCI datasets for the LCA model, which are also explained in the following paragraphs. Background processes following the "allocation cut-off by classification" were retrieved from Ecoinvent 3.8. database (Wernet et al. 2016; Moreno Ruiz et al. 2021); nevertheless, to get more reliable results concerning the case study, GaBi database v.10 (Sphera Solutions GmbH 2022) was also used for a selected number of processes. Inventory data for the mandarin farming stage is shown in Table 5.1 and more detailed in Table 5.6, whereas the metadata for the reference LCIs is described in Table 5.7.

Agricultural practices. Information on the farming practices, yields, the type and dose of inputs applied, their origin, the amount of water for irrigation, and fuel for machinery is primary data obtained from direct interviews with the agronomist responsible for the orchard.

Table 5.1. Main inventory data for the mandarin cultivation stage

LCI data	Unit	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	Average	Standard deviation
Yield	tonne · ha^{-1}	49.3	21.4	34.8	31.3	54.0	24.0	35.8	13.3
Electricity for irrigation	kWh · ha^{-1}	70.7	114.3	23.1	38.8	52.4	91.7	65.2	34.0
Water withdrawal for irrigation	mm · $season^{-1}$	211.0	341.0	68.8	115.7	156.5	273.7	194.5	101.5
Rainfall	mm · $season^{-1}$	1716.0	1388.0	1695.0	1364.0	1119.0	1053.0	1389.2	278.2
Rainfall + irrigation	mm · $season^{-1}$	1927.0	1729.0	1763.8	1479.7	1275.5	1326.7	1583.6	262.0
Machinery use (input application)	h ·ha^{-1}	17.7	17.4	12.2	15.1	12.9	13.5	14.8	2.3
Machinery use (harvest and transport of bins)	h ·ha^{-1}	11.8	2.8	29.0	11.1	22.0	12.4	14.8	9.2
Diesel for machinery operations									
Application of foliar fertilisers and pesticides	L · ha^{-1}	141.7	139.1	97.8	121.0	103.3	108.1	118.5	18.6
Harvest and transport of bins	L · ha^{-1}	23.6	5.5	57.9	22.1	43.9	24.7	29.6	18.4
Fertilisers									
N	kg · ha^{-1}	41.3	68.1	3.3	93.7	89.4	114.0	68.3	40.3
P_2O_5	kg · ha^{-1}	0.0	3.3	0.2	2.3	1.7	3.4	1.8	1.5
K_2O	kg · ha^{-1}	28.4	41.4	0.5	51.3	77.2	87.5	47.7	31.9
Pesticides									
Fungicides	kg · ha^{-1}	19.0	25.1	11.3	17.2	14.8	19.9	17.9	4.7
Herbicides	kg · ha^{-1}	3.5	3.7	1.1	3.3	0.7	2.9	2.5	1.3
Insecticides	kg · ha^{-1}	29.1	5.3	0.9	30.6	16.6	16.9	16.6	12.1
Growth regulators	kg · ha^{-1}	$1.9 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	0.0	0.0	$3.0 \cdot 10^{-2}$	$6.2 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$
Dispersants	kg · ha^{-1}	0.5	0.5	0.5	0.7	0.6	0.8	0.6	0.1

Table 5.1. (cont.) Main inventory data for the mandarin cultivation stage

LCI data	Unit	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	Average	Standard deviation
On-field emissions									
Direct N_2O	$kg \cdot ha^{-1}$	$6.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-1}$	0.0	$1.3 \cdot 10^{-1}$	$2.5 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Indirect N_2O (from NO_3^-)	$kg \cdot ha^{-1}$	$2.2 \cdot 10^{-1}$	$3.0 \cdot 10^{-1}$	$8.0 \cdot 10^{-3}$	$1.9 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$	$6.6 \cdot 10^{-1}$	$2.6 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Indirect N_2O (from NH_3)	$kg \cdot ha^{-1}$	$2.6 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$6.8 \cdot 10^{-2}$	$5.1 \cdot 10^{-1}$	$4.9 \cdot 10^{-1}$	$5.8 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
NH_3 volatilised	$kg \cdot ha^{-1}$	$1.4 \cdot 10^{1}$	$2.0 \cdot 10^{1}$	3.7	$2.7 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$3.1 \cdot 10^{1}$	$2.0 \cdot 10^{1}$	$1.0 \cdot 10^{1}$
NO_2 volatilised	$kg \cdot ha^{-1}$	1.7	2.7	$1.3 \cdot 10^{-1}$	3.7	3.6	4.6	2.7	1.6
NO_3^- leached	$kg \cdot ha^{-1}$	$5.6 \cdot 10^{1}$	$7.7 \cdot 10^{1}$	2.0	$4.8 \cdot 10^{1}$	$5.1 \cdot 10^{1}$	$1.7 \cdot 10^{2}$	$6.7 \cdot 10^{1}$	$5.6 \cdot 10^{1}$
PO_4^{3-} leached	$kg \cdot ha^{-1}$	1.1	1.1	1.1	1.1	1.1	1.1	1.1	0.0

Irrigation and blue water consumption. The amounts of irrigated water and the irrigation hours are primary data from the orchard. Values for each season are shown in Table 5.1. The blue water consumption for irrigation was calculated by performing a water balance in the soil using the LEACHM model (Hutson and Wagenet, 1992). The water consumed by the crop, defined as the water withdrawn from a watershed but not returned to it (ISO 2014), was estimated by adding the values for water evaporation and water absorption from the water balance. The climatic parameters used in the water balance were retrieved from INIA agroclimatic data bank (INIA-GRAS 2022a), namely maximum, minimum, and average temperatures. Weekly reference evapotranspiration was calculated using the Penman-Monteith equation (Allen et al. 1998), with climate data for the studied seasons retrieved from the same meteorological station used as inputs (Eq. 5.1). As for precipitation, the amount of water accumulated was recorded every morning in the orchard using a pluviometer. Since the exact moment of the precipitation is not registered, the rain pattern recorded at the closest station, INIA Salto Grande, was thus followed. This station reports hourly values for precipitation (INIA-GRAS 2022b) and is located 90 km north of the orchard.

The electricity consumption for irrigation was estimated from the GaBi process "Irrigation pump generic" (Table 5.7), with the amount of water irrigated for each season as an input and considering that water is withdrawn from a lake. For the parameters 'nominal operating pressure', 'power unit efficiency', 'pumping efficiency' and 'irrigation efficiency', default values were used, which correspond to 3 bar, 0.9, 0.8 and 1.0, respectively.

On-field emissions from fertilisers application. For the estimation of NH_3 and direct N_2O emissions to air, and NO_3^- leached to groundwater, the LEACHN model, the N module of the LEACHM model (Hutson and Wagenet 1992), was used. This is a mechanistic, one-dimensional, and dynamic method in line with the Tier 3 approach proposed by the IPCC (2006b) that simulates water and solute movement, as well as chemical and biological processes in the unsaturated soil. It estimates NH_4^+, urea and NO_3^- lixiviation, NH_3 volatilisation and NO_3^- losses by denitrification. To estimate water and nutrient fluxes, the model uses the numerical integration of Richards' equation and the convection-dispersion equation for solute transport (Eq. 5.2). Specifically, N fluxes among compartments are simulated with first-order kinetics (Hutson and Wagenet 1991). LEACHN offers advantages over IPCC's Tier 1 approach, as it accounts for not only N fertiliser management but also for the influence of soil and climate conditions and water management. The input data corresponds to N added through irrigation (considering that the irrigation water has an N-NO_3^- concentration of 2.8 mg/L) and fertilisation. Three organic N pools (manure, litter, and a relatively stable humus fraction) and three mineral N pools (urea, ammonium, and nitrate) are considered. To estimate N fluxes in drip irrigation, the soil was divided into fertigated/irrigated soil area, which occupies 40% of the surface, and non-fertigated/irrigated soil area, where irrigation or fertigation was not applied. LEACHN was run twice for each harvest season to obtain the emissions in both soil areas, and on-field emissions were estimated as the weighted mean from the two simulations. Potential N uptake by the citrus trees and monthly uptake pattern were obtained from a study for Spanish citrus (Quiñones et al. 2010), adapted to Uruguay's climatic seasons, and incorporated into the model. The use of a specific N uptake pattern to calibrate N balance is encouraged in future studies, as the Uruguayan climate is subtropical, and the growth pattern of the tree, and therefore its N extraction, may differ. Nitrification, volatilisation, and denitrification rates specific to citrus soils were taken from Paramasivam et al. (2002). These authors compare measured values of soil nitrogen in a citrus orchard with the same type of soil as the one in this study with values obtained using the LEACHN model and highlight this modelling approach's usefulness in estimating the N leaching losses and predicting other mass balance components of N and water simultaneously and accurately for the entire crop season. The hydraulic parameters of the model were estimated from the SPAW software (Saxton and Rawls 2006) by using data on soil texture and organic carbon content from the soil (INIA-SIGRAS 2022). The water balance of the LEACHN model was calibrated by adjusting the sum of plant uptake and soil evaporation to crop evapotranspiration using experimental crop coefficients (García Petillo and Castel 2007). The calibrated model was then applied to the remaining scenarios by considering data of the successive seasons as to climatic parameters, water, and fertiliser applications. From the NH_3 and NO_3^- emissions estimated with LEACHN, the indirect N_2O emissions were modelled following the IPCC Guidelines (IPCC 2006b) and the subsequent refinement (IPCC 2019). NO_x emissions were modelled using the Tier 1 EMEP/EEA guidebook (EEA 2019), as no Tier 2 emission factor is proposed. In addition to N emissions, CO_2 emissions from urea application were calculated under the Tier 1 approach of the IPCC (2006b) guidelines. Emissions from phosphorus application, namely phosphate

(PO_4^{3-}) run-off to surface water, was estimated with the SALCA-P model (Nemecek et al. 2019) considering the P_2O_5 content of each fertiliser used and the average quantity of P lost through run-off for arable land.

In addition to the former modelling (i.e., 'LEACHN'), nitrogen emissions have been estimated using four different approaches to compare their influence on the impact scores. Briefly, the guidelines proposed in the Environmental Product Declarations – 'EPD' (EPD 2019), the Product Environmental Footprint – 'PEF' (EC 2018), and the World Food LCA Database – 'WFLDB' (Nemecek et al. 2019), which combine Tier 1 and Tier 2 methods have been used. Furthermore, an additional combination of Tier 1 and Tier 2 methods using the most up-to-date coefficients of the IPCC (2019) and the EEA (2019), named the 'updated method', has also been assessed. The literature sources used for modelling each emission and the inputs needed for each method are detailed in Table 5.8. A statistical analysis was carried out using R software (R Core Team 2022) to assess whether there are significant differences between the results of the N on-field emissions (N_2O, NH_3, NO_3^- and NO_x) estimated with the above-described methods and also between the scores of five impact categories influenced by N on-field emissions (CC, MEu, TEu, AqAc and TAc). A Kruskal-Wallis test (Hollander & Wolfe 1973) was performed to determine the existence of differences at a general level, followed by non-parametric comparisons in pairs, by performing a Dunn's test.

On-field emissions from pesticide application. PestLCI Consensus V.1.0 (Fantke et al. 2017) was used to calculate primary emissions from pesticide application. It estimates the fraction of pesticide that goes to air, field soil surface, crop leaf surface, freshwater, and natural soil by considering parameters of the orchard and input application.

Production of agricultural inputs. A total of 10 fertiliser compounds were modelled for the seasons studied using default processes from Ecoinvent 3.8. database (Wernet et al. 2016; Moreno Ruiz et al. 2021). Those fertilisers unavailable in the database were modelled as standard NPK fertilisers, considering their respective fertiliser units, as N, P_2O_5 and K_2O. The production of gibberellic acid (a growth regulator) was not modelled due to a lack of data, although it must be noted that the dose applied is low, with a maximum application rate of $3.3{\cdot}10^{-2}$ kg · ha^{-1} on 2021-2022.

Ecoinvent 3.8. (Wernet et al. 2016; Moreno Ruiz et al. 2021) was used to model pesticide manufacturing. Firstly, the production process corresponding to the active principle of the pesticide was searched for. If it was not available in the database, the production of the corresponding chemical group was searched for. In the ultimate case that this production was not found either, the pesticide production was modelled as generic ("pesticide production" on Ecoinvent 3.8). Compounds with the same active ingredient but different commercial denominations were modelled separately, as seen in Table 5.6, to differentiate the contribution of each one to the environmental impacts. To model the production of Spinosad and copper oxychloride, which are also used in organic farming, the recommendations of Montemayor et al. (2022) were followed. The former was modelled considering glucose and electricity production in the country of origin, and the second as copper oxide. The productions of the three compounds that stimulate the plant defences against moulds, and whose active principle is potassium phosphite, were modelled as NPK compound productions using their NPK composition since potassium phosphite production is not available in the databases used. As for the remaining compounds, only copper sulphate, cuprous oxide, glyphosate, mancozeb, paraffinic oil and polyether silicone copolymer could be modelled directly (Table 5.7). 2,4-D dimethyl amine salt, 2,4-D isopropyl ester, diuron, flumioxazin, paraquat, phosmet and pyriproxyfen were modelled considering their corresponding chemical group and the rest as generic pesticides. A total of 43 pesticides were modelled.

Input transportation. All agricultural inputs were transported by lorry or ship and lorry, as seen in Table 5.9, where the distances shown were retrieved from Searates (2022). Transportation was modelled as one-way transport using the corresponding processes from Ecoinvent 3.8 (Wernet et al. 2016; Moreno Ruiz et al. 2021) and the GaBi v10 database (Sphera Solutions GmbH 2022), as shown in Table 5.7.

5.2.2.3. Impact categories and impact assessment methods

To carry out the impact assessment, the default list of environmental performance indicators recommended by the PCRs for fruits (EPD 2019) was accounted for, considering the latest update (EPD 2022). Specifically, the EN 15804+A2 standard was followed (Tables 5.2a and 5.2b), except for the categories of aquatic acidification and terrestrial acidification that were assessed according to IMPACT 2002+ v2.1 (Humbert 2012) to discern among those two compartments. As well, USEtox 2.12 (Rosenbaum et al. 2008) was applied to assess freshwater and human toxicity (Tables 5.2a and 5.2b), as they constitute relevant impact categories in agricultural LCAs (Cabot et al. 2022).

To calculate BWS at the farming stage, monthly characterisation factors (CFs) from AWARE (Boulay et al. 2018) for the corresponding Uruguayan basin were retrieved from the Google Earth layer (Google Earth 2022a), whereas for BWS due to indirect water consumption (i.e., inputs manufacturing, irrigation, electricity production and diesel production and combustion), AWARE CFs for non-agricultural activities for the corresponding country were retrieved from WULCA (2022). Regarding toxicity impacts, and since no CFs are available in USEtox 2.12 for paraffinic oil, pyraclostrobin, polyether silicone copolymer, saflufenacil and Spinosad, a search in scientific articles was performed. CFs for paraffinic oil and Spinosad were retrieved from Juraske and Sanjuán (2011), those for acetamiprid from Steingrímsdóttir et al. (2018), and those for pyraclostrobin from Fantke and Jolliet (2016) and Bennet (2012). As regards 2,4-D isopropyl ester, abamectin and copper oxychloride, the CFs for substances with similar characteristics were used, namely 2-(2,4-dichlorophenoxy) acetic acid, avermectin B1A and copper (II), respectively. No CF was found in the literature for polyether silicone copolymer and saflufenacil.

Regionalisation of impacts. In order to assess the influence of the regionalisation of environmental impacts, IMPACT World+ (Bulle et al. 2019), a regionalised impact calculation method that proposes characterisation factors at different resolution scales, was applied to estimate the impact of on-field emissions. The impact categories assessed were those for which the environmental impacts of agricultural activities are relevant and midpoint CFs are available, namely marine eutrophication (MEu), freshwater eutrophication (FEu), terrestrial acidification (TAc) and freshwater acidification (FWAc). The impacts of the emitted flows were regionalised at the native resolution scale, retrieving the CFs from the corresponding Google Earth layer (Google Earth 2022b) and compared to those quantified using the global resolution CFs from IMPACT World+ (2022).

5.3. RESULTS AND DISCUSSION

5.3.1. Environmental impacts and contribution analysis

The scores for all the impact categories assessed per both FU for the six seasons evaluated, as well as their average value and coefficient of variation (CV, %), are shown in Tables 5.2a and 5.2b. Fig. 5.2 shows the average contribution of the life cycle stages to the total life cycle impact of the mandarins for each environmental impact category. The average contribution values of each stage and their standard deviation for both FUs are shown in Tables 5.10 and 5.11.

Table 5.2. (a) Impact scores per cropping season, average values, and coefficient of variation (CV) of cradle-to-farm gate mandarin cultivation in Uruguay. FU = 1 ha

Impact category	Impact Assessment method	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	Average	CV (%)
CC (kg CO_2 eq. · ha^{-1})	EN 15804+A2	1237.8	1445.5	611.1	1561.8	1562.3	2014.3	1405.5	28
FEu (kg P eq. · ha^{-1})	EN 15804+A2	$8.8·10^{-1}$	$9.6·10^{-1}$	$5.4·10^{-1}$	1.0	$7.9·10^{-1}$	$9.5·10^{-1}$	$8.6·10^{-1}$	20
MEu (kg N eq.·ha^{-1})	EN 15804+A2	17.7	23.5	3.3	18.2	18.7	46.4	21.3	66
TEu (mole of N eq.· ha^{-1})	EN 15804+A2	225.5	321.4	76.6	418.8	403.4	472.3	319.7	46
AqAc (kg SO_2 eq.· ha^{-1})	Impact 2002+ v2.1	32.3	47.2	9.3	60.4	56.9	67.6	45.6	47
TAc (kg SO_2 eq.· ha^{-1})	Impact 2002+ v2.1	262.5	370.9	91.7	479.4	460.7	558.6	370.6	46
BWS (m^3eq.· ha^{-1})	AWARE	3849.6	3107.4	3227.9	4071.1	3579.4	4102.5	3656.3	12
ET (CTUe· ha^{-1})	USEtox 2.12	$3.4·10^{7}$	$3.9·10^{7}$	$1.2·10^{7}$	$4.2·10^{7}$	$2.6·10^{7}$	$3.4·10^{7}$	$3.1·10^{7}$	35
HTc (CTUh· ha^{-1})	USEtox 2.12	$8.2·10^{-5}$	$1.0·10^{-4}$	$2.7·10^{-5}$	$1.2·10^{-4}$	$9.4·10^{-5}$	$1.2·10^{-4}$	$9.0·10^{-5}$	37
HTnc (CTUh· ha^{-1})	USEtox 2.12	$1.5·10^{-3}$	$1.5·10^{-3}$	$7.3·10^{-4}$	$1.5·10^{-3}$	$1.2·10^{-3}$	$1.1·10^{-3}$	$1.2·10^{-3}$	26
RUm (kg Sb eq. · ha^{-1})	EN 15804+A2	$1.3·10^{-1}$	$1.5·10^{-1}$	$4.7·10^{-2}$	$1.6·10^{-1}$	$9.8·10^{-2}$	$1.3·10^{-1}$	$1.2·10^{-1}$	34
RUf (MJ· ha^{-1})	EN 15804+A2	$1.6·10^{4}$	$1.6·10^{4}$	$7.8·10^{3}$	$1.8·10^{4}$	$1.7·10^{4}$	$2.0·10^{4}$	$1.6·10^{4}$	27
POFhh (kg NMVOC eq. · ha^{-1})	EN 15804+A2	10.8	11.9	7.0	13.1	12.7	14.2	11.6	22
Ozone depletion (kg CFC-11 eq.· ha^{-1})	EN 15804+A2	$5.2·10^{-5}$	$9.0·10^{-5}$	$2.4·10^{-5}$	$7.1·10^{-5}$	$8.8·10^{-5}$	$1.2·10^{-4}$	$7.4·10^{-5}$	44

Climate Change (CC), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Aquatic Acidification (AqAc), Terrestrial Acidification (TAc), Blue Water Scarcity (BWS), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Photochemical Ozone Formation impacts on human health (POFhh), Ozone Depletion (OD), Coefficient of Variation (CV)

Table 5.2. (b) Impact scores per cropping season, average values, and coefficient of variation (CV) of cradle-to-farm gate mandarin cultivation in Uruguay. FU = 1 tonne

Impact category	Impact Assessment method	2016/17	2017/18	2018/19	2019/20	2020/21	2021/22	Average	CV (%)
CC (kg CO_2 eq.·tonne^{-1})	EN 15804+A2	25.1	67.6	17.5	49.8	28.9	83.8	45.5	45
FEu (kg P eq. · tonne^{-1})	EN 15804+A2	$1.8\cdot10^{-2}$	$4.5\cdot10^{-2}$	$1.5\cdot10^{-2}$	$3.2\cdot10^{-2}$	$1.5\cdot10^{-2}$	$3.9\cdot10^{-2}$	$2.7\cdot10^{-2}$	48
MEu (kg N eq.· tonne^{-1})	EN 15804+A2	0.4	1.1	0.1	0.6	0.3	1.9	0.7	92
TEu (mole of N eq.· tonne^{-1})	EN 15804+A2	4.6	15.0	2.2	13.4	7.5	19.6	10.4	65
AqAc (kg SO_2 eq.· tonne^{-1})	Impact 2002+ v2.1	0.7	2.2	0.3	1.9	1.1	2.8	1.5	66
TAc (kg SO_2 eq.· tonne^{-1})	Impact 2002+ v2.1	5.3	17.3	2.6	15.3	8.5	22.4	11.9	64
BWS (m^3eq.· tonne^{-1})	AWARE	78.1	145.3	92.8	130.0	66.2	170.7	113.9	36
ET (CTUe· tonne^{-1})	USEtox 2.12	$6.8\cdot10^{5}$	$1.8\cdot10^{6}$	$3.5\cdot10^{5}$	$1.3\cdot10^{6}$	$4.8\cdot10^{5}$	$1.4\cdot10^{6}$	$1.0\cdot10^{6}$	59
HTc (CTUh· tonne^{-1})	USEtox 2.12	$1.7\cdot10^{-6}$	$4.9\cdot10^{-6}$	$7.8\cdot10^{-7}$	$3.7\cdot10^{-6}$	$1.7\cdot10^{-6}$	$5.0\cdot10^{-6}$	$2.9\cdot10^{-6}$	61
HTnc (CTUh· tonne^{-1})	USEtox 2.12	$3.1\cdot10^{-5}$	$6.8\cdot10^{-5}$	$2.1\cdot10^{-5}$	$4.8\cdot10^{-5}$	$2.1\cdot10^{-5}$	$4.4\cdot10^{-5}$	$3.9\cdot10^{-5}$	47
RUm (kg Sb eq. · tonne^{-1})	EN 15804+A2	$2.6\cdot10^{-3}$	$7.0\cdot10^{-3}$	$1.3\cdot10^{-3}$	$5.0\cdot10^{-3}$	$1.8\cdot10^{-3}$	$5.2\cdot10^{-3}$	$3.8\cdot10^{-3}$	59
RUf (MJ· tonne^{-1})	EN 15804+A2	$3.2\cdot10^{2}$	$7.5\cdot10^{2}$	$2.2\cdot10^{2}$	$5.9\cdot10^{2}$	$3.2\cdot10^{2}$	$8.4\cdot10^{2}$	$5.1\cdot10^{2}$	51
POFhh (kg NMVOC eq.· tonne^{-1})	EN 15804+A2	0.2	0.6	0.2	0.4	0.2	0.6	0.4	48
Ozone depletion (kg CFC-11 eq.· tonne^{-1})	EN 15804+A2	$1.1\cdot10^{-6}$	$4.2\cdot10^{-6}$	$7.0\cdot10^{-7}$	$2.3\cdot10^{-6}$	$1.6\cdot10^{-6}$	$4.9\cdot10^{-6}$	$2.5\cdot10^{-6}$	70

Climate Change (CC), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Aquatic Acidification (AqAc), Terrestrial Acidification (TAc), Blue Water Scarcity (BWS), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Photochemical Ozone Formation impacts on human health (POFhh), Ozone Depletion (OD), Coefficient of Variation (CV)

When analysing the relative contribution of the cradle-to-farm gate stages, fertiliser production and machinery operations represent a significant share of CC (both 32% on average), with the production of urea ammonium nitrate and diesel combustion for the tractor as main hotspots. Regarding eutrophication, the main contributors to FEu are pesticide production (45% on average), mainly due to copper compounds production, and on-field emissions (41% on average) due to PO_4^{3-} run-off. On-field emissions lead MEu (85% average contribution) due, to a large extent, to NO_3^- leaching, followed by tractor use (10% on average). On-field emissions also dominate TEu, AqAc and TAc (89%, 87% and 86% on average, respectively), mainly due to NH_3 volatilisation. Blue water consumption for irrigation is the main cause of BWS, with an average of 90%, ranging from 84 to 97%, depending on the season. When analysing the results of toxicity-related categories, pesticide production stands out as the main hotspot (91% of total ET, 52% of HTc and 62% of HTnc, on average). Regarding HT, fertiliser production is a relevant stage in cancer-related impacts (38% on average) and on-field pesticide emissions in non-cancer-related impacts (23% on average). Among the pesticides used, and also considering the dose applied, copper compounds - cuprous oxide, copper oxychloride and copper sulphate - lead the three toxicity impact categories (Table 5.12). As to the categories related to resource depletion, the main contributors to RUf are fertiliser production (38%, on average) and machinery operations (36%, on average). Pesticide production -mostly copper compounds- is the main hotspot detected in RUm (93% on average). POFhh is dominated by machinery operations (50% on average), mainly because of diesel combustion, and by NO_2 on-field emissions (24% on average), whereas input production means a significant share of OD (43% from pesticides and 35% from fertilisers, on average). To sum up, the main hotspots in the impact categories assessed are related to on-field emissions, diesel combustion and the production of copper and urea compounds, especially urea ammonium nitrate. In any case, it must be borne in mind that, as mentioned in section 2.2.2, the production of some crop protection inputs could not be properly modelled, as they were not available in the databases used. Therefore, they were modelled considering their chemical group or, ultimately, as generic pesticides (Table 5.7). The development of more complete databases is a key issue for obtaining more representative LCAs.

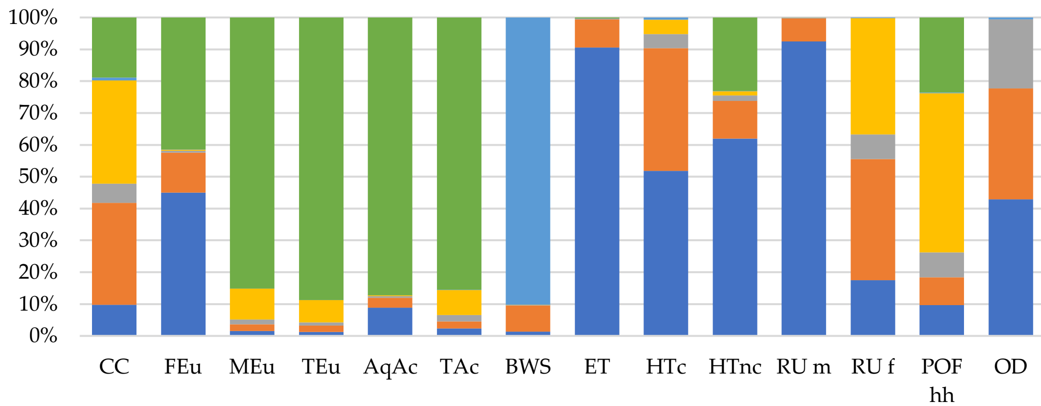


Fig. 5.2. Average percentual contribution of the life cycle stages to the environmental footprint of Uruguayan mandarins per tonne and ha. ■ Pesticides production, ■ Fertilisers production, ■ Transport, ■ Machinery operations, ■ Irrigation, ■ On-field emissions. Climate Change (CC), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Aquatic Acidification (AqAc), Terrestrial Acidification (TAc), Blue Water Scarcity (BWS), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Photochemical Ozone Formation impacts on human health (POFhh), Ozone Depletion (OD)

5.3.2. Inter-seasonal variability of the impact scores

The inter-seasonal variability of the results for each cropping season was analysed through the coefficient of variability (CV, %), as shown in Tables 5.2a and 5.2b, and also by estimating the ratio "impact score in the season/mean impact score", which shows how the impact scores for each season and FU are distributed with respect to the mean (Fig. 5.3). When the impact scores are expressed per ha, the inter-seasonal variability is lower than when expressed per tonne for all the impact categories assessed (Tables 5.2a and 5.2b). The impact categories that exhibit a greater variability are acidification (AqAc and TAc) and eutrophication, specifically MEu and TEu. These depend primarily on on-field emissions, specifically NO_3^- leaching and NH_3 volatilisation. OD also stands out because of its high variability, which depends on the type and dose of inputs applied.

When 1 ha is used as FU, the results obtained for AqAc, TAc, MEu, and TEu follow the pattern of the respective on-field emissions affecting these impact categories, as they mean a great share of these impact categories (more than 85%). In particular, NH_3 is the emission determining AqAc, TAc and TEu, and presents a maximum in 2021- 2022 and a minimum in 2018-2019 (see Table 5.1), corresponding to the seasons with the greatest and lowest N fertilisation rates, respectively, the same as the respective scores of the impact categories (Table 5.2a). It must be noted that the main N sources are ureic compounds and that the hydrolysis of urea releases NH_3, that subsequently volatilises. MEu is mainly influenced by NO_3^- leaching and, according to the N fertilisation rates, also exhibits a maximum in 2021- 2022 and a minimum in 2018-2019, which is consistent with the impact results obtained. As concerns OD, again, the maximum and minimum scores coincide with the years in which more and fewer inputs were applied (2021-2022 and 2018-2019, respectively), as the production of fertilisers and pesticides are the stages with the highest share in this impact category. CC also exhibits the maximum and the minimum scores in the seasons with the greatest and lowest fertilisation rates, as their production is a hotspot that, together with on-field emissions, sums up 50% of this category. BWS is also interesting to be discussed, given its importance in agricultural processes. It presents a minimum in 2017-2018, season with the lowest blue water consumption due to a low evaporation together with a low water absorption by the crop (Table 5.13), which are related to the low value of rainfall in the months of higher water demand (only 27% of the total rain fell from December to April). This low availability of water could have caused water stress, reflected in the low yield of this season (21.4 tonnes · ha^{-1}, Table 5.1). BWS is maximum in 2021-2022, although it is not the season with the highest water consumption. Still, the greatest water consumption in that season is mainly concentrated in the months of highest scarcity in the basin (from December to April). It must be therefore highlighted that it is not only how much blue water the crop consumes what matters in this impact category but also the moment of this consumption.

When using 1 tonne as FU, a new variable is introduced in the analysis, the crop yield, which seems to have more influence on the intermediate values of the impact scores than on the extreme ones, as explained below. Although one could expect the yield to be linked to the fertilisation rates, Afourer mandarins are a variety with an alternating bearing, as commented in the introduction, and therefore, AqAc, TAc, MEu and TEu present a maximum in 2021-2022 and a minimum in 2018-2019, which correspond to the maximum and minimum of influencing emissions (NH_3 and NO_3^-), but not to the minimum and maximum yield (Table 5.1). Therefore, for the extreme scores, N emissions have a greater weight in the results than the yield, whereas for intermediate impact values, the trend reverses, and the crop yield has a greater weight in the results than the emissions released. Regarding CC, the extreme scores per tonne coincide with the extreme values per ha, corresponding to seasons with the highest and lowest fertilisation rates, whereas the intermediate scores respond to the yield pattern. For BWS, the results are mainly dominated by the yield; the greater the yield, the lower the impact and vice versa, except for 2021-2022, the season with the highest score because the blue water consumption is concentrated in the months of higher scarcity (54% of the consumption in the season), as mentioned above.

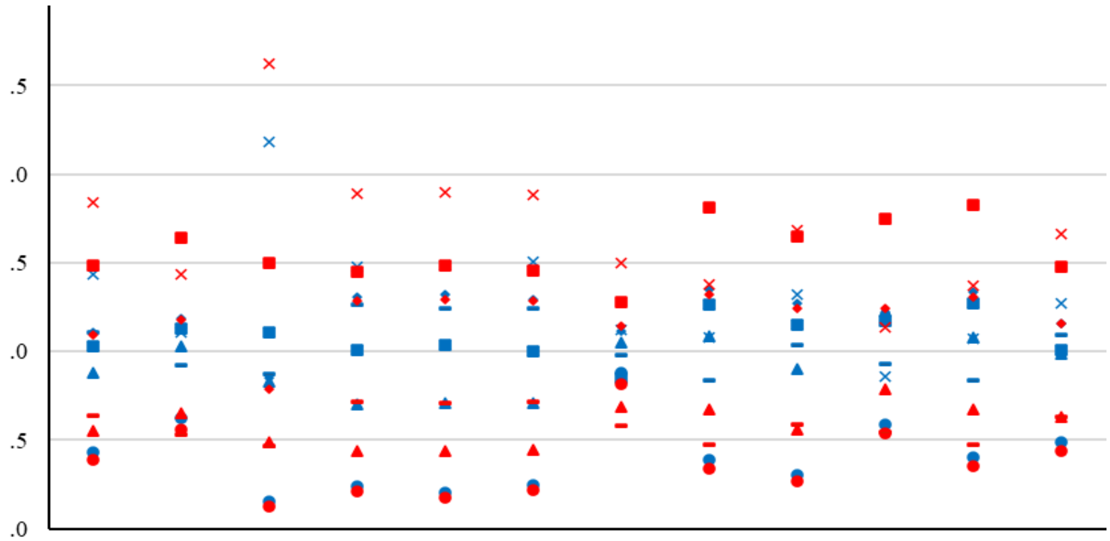


Fig. 5.3. Relative variability of the impact values of Uruguayan mandarins with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per hectare of the orchard. ▲ 2016-2017, ■ 2017-2018, ● 2018-2019, ◆ 2019-2020, – 2020-2021, × 2021-2022. Climate Change (CC), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Aquatic Acidification (AqAc), Terrestrial Acidification (TAc), Blue Water Scarcity (BWS), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Photochemical Ozone Formation, human health (POFhh), Ozone Depletion (OD)

5.3.3. Regionalised environmental impacts

The average scores of the regionalised impact categories for on-field emissions, considering global CFs (not regionalised) and native CFs (regionalised), are shown in Table 5.3.

Table 5.3. Average impact scores of on-field emissions for the regionalised impact categories with and without applying the regionalisation method

	FU = 1 ha		FU = 1 tonne	
	Not-regionalised	Regionalised	Not-regionalised	Regionalised
Freshwater eutrophication (kg PO_4 P-lim eq.)	$3.42\cdot10^{-1}$	$2.13\cdot10^{-2}$	$1.07\cdot10^{-2}$	$6.68\cdot10^{-4}$
Marine eutrophication (kg N N-lim eq.)	1.20	0.84	$3.91\cdot10^{-2}$	$2.74\cdot10^{-2}$
Freshwater acidification (kg SO_2 eq.)	$4.25\cdot10^{-5}$	$1.11\cdot10^{-5}$	$1.38\cdot10^{-6}$	$3.63\cdot10^{-7}$
Terrestrial acidification (kg SO_2 eq.)	$7.73\cdot10^{-2}$	$1.52\cdot10^{-2}$	$2.52\cdot10^{-3}$	$4.94\cdot10^{-4}$

To analyse these results, it must be considered that the ImpactWorld+ method (Bulle et al. 2019) presents CFs for a selected group of output flows, namely the ones with greater environmental effects. In Table 5.14, the native and global CFs used are shown. The environmental impacts of the on-field emissions stage were reduced when applying native CFs. In particular, FEu showed a 94% reduction, followed by an 80% reduction in TAc, a 74% reduction in FWAc and a 30% reduction in MEu. The significant reduction percentages obtained for this stage highlight the importance of applying impact regionalisation methods.

5.3.4. Influence of N emission modelling on the environmental impact scores

Due to the input data complexity of mechanistic models used to estimate N on-field emissions, such as LEACHN, the resulting emissions and the related impact scores have been compared with other approaches (see section 2.2.2) to see if the values are comparable. Table 5.4a shows the average results of the N on-field emissions for both FUs, for the five methods analysed, whereas Table 5.4b shows the average results for the impact categories more influenced by on-field emissions, namely CC, MEu, TEu, AqAc and TAc. In Figs. 5.4 and 5.5, the probability distribution of N on-field emissions and environmental scores results are represented in boxplots for all the seasons studied.

N_2O estimated with LEACHN shows the lowest average value (Table 5.4a) and also the highest variability, with a CV value of 67% when considering 1 hectare as FU. Therefore, LEACHN seems to better capture the inter-season variability of farming practices and climate. As to NH_3, LEACHN applies a higher emission factor, which explains the higher average value. The values obtained present similar variability to the rest of the approaches (around 50% regardless of the method). The estimates for NO_3^- using WFLDB are two orders of magnitude greater than when using the other approaches (Table 5.4a) and much greater than the N rate applied (68.3 kg · ha^{-1} on average). The values of this emission obtained with LEACHN are slightly lower than those obtained with the other approaches, and the estimations present high variability, with a CV of 83%, which also leads us to think that LEACHN better captures the inter-season variability. These high values of NH_3 and low values of NO_3^- obtained with LEACHN are due to the fact that this method predicts higher N volatilisation and lower NO_3^- leaching losses. Therefore, urea hydrolysis and ammonium volatilisation rates should be verified experimentally because, as commented in section 2.2.2, the model was calibrated with data from the literature. PEF does not estimate NO_x, whereas LEACHN, WFLDB and the 'updated approach' use the same emission coefficient, which explains the similar values obtained. Regarding each specific impact score obtained with the approaches analysed (Table 5.4b), LEACHN determines consistently higher scores than the rest in TEu, AqAc and TAc (Table 5.4b), as these categories mainly depend on NH_3 emissions, which are higher, while the highest scores of CC and MEu are those obtained when using WFLDB (Table 5.4b), because of the higher NO_3^- values that also determines higher indirect N_2O emissions influencing the CC score.

Table 5.4. (a) Average results and standard deviation of the N on-field emissions for 2016-2022 estimated with different modelling approaches

	Modelling approach				
Emission	LEACHN	EPD	PEF	WFLDB	Updated method*
N_2O volatilised (kg · ha^{-1})	0.8 ± 0.5	1.5 ± 0.8	1.5 ± 0.9	2.7 ± 1.6	2.2 ± 1.3
N_2O volatilised (kg · tonne^{-1})	$2.8 \cdot 10^{-2} \pm 2.5 \cdot 10^{-2}$	$4.9 \cdot 10^{-2} \pm 3.6 \cdot 10^{-2}$	$5.0 \cdot 10^{-2} \pm 3.8 \cdot 10^{-2}$	$9.0 \cdot 10^{-2} \pm 6.8 \cdot 10^{-2}$	$7.1 \cdot 10^{-2} \pm 5.4 \cdot 10^{-2}$
NH_3 volatilised (kg · ha^{-1})	20.1 ± 10.0	11.9 ± 5.9	3.4 ± 1.9	6.8 ± 3.4	7.5 ± 3.9
NH_3 volatilised (kg · tonne^{-1})	$6.6 \cdot 10^{-1} \pm 4.4 \cdot 10^{-1}$	$3.9 \cdot 10^{-1} \pm 2.6 \cdot 10^{-1}$	$1.0 \cdot 10^{-1} \pm 5.9 \cdot 10^{-2}$	$2.2 \cdot 10^{-1} \pm 1.5 \cdot 10^{-1}$	$2.4 \cdot 10^{-1} \pm 1.7 \cdot 10^{-1}$
NO_3^- leached (kg· ha^{-1})	67.2 ± 55.8	90.7 ± 53.6	30.1 ± 17.7	4184.7 ± 592.1	72.6 ± 42.9
NO_3^- leached (kg · tonne^{-1})	$2.4 \cdot 10 \pm 2.6 \cdot 10$	$3.0 \cdot 10 \pm 2.3 \cdot 10$	$9.9 \cdot 10^{-1} \pm 7.5 \cdot 10^{-1}$	$1.3 \cdot 10^{2} \pm 5.0 \cdot 10^{1}$	$2.4 \cdot 10 \pm 1.8 \cdot 10$
NO_x volatilised (kg· ha^{-1})	2.7 ± 1.6	1.0 ± 0.6	n.e	2.7 ± 1.6	2.7 ± 1.6
NO_x volatilised (kg · tonne^{-1})	$9.0 \cdot 10^{-2} \pm 6.8 \cdot 10^{-2}$	$3.4 \cdot 10^{-2} \pm 2.6 \cdot 10^{-2}$	n.e	$9.0 \cdot 10^{-2} \pm 6.8 \cdot 10^{-2}$	$9.0 \cdot 10^{-2} \pm 6.8 \cdot 10^{-2}$

* emission factors from the updated IPCC (2019) and EEA (2019), n.e.: not estimated

Table 5.4. (b) Average impact scores and standard deviation for 2016-2022 of the impact categories analysed affected by the modelling approaches to estimate on-field emissions

	Modelling approach				
Impact category	LEACHN	EPD	PEF	WFLDB	Updated method*
CC (kg CO_2 eq. ·ha^{-1})	1405.5 ± 464.8	1602.9 ± 560.9	1607.7 ± 571.9	1974.1 ± 786.9	1802.0 ± 683.1
CC (kg CO_2 eq. ·$tonne^{-1}$)	45.5 ± 26.2	51.7 ± 29.7	51.9 ± 30.1	64.0 ± 39.1	58.3 ± 34.8
MEu (kg N eq.·ha^{-1})	21.3 ± 14.1	25.2 ± 13.2	10.3 ± 4.4	950.6 ± 133.1	21.3 ± 11.0
MEu (kg N eq.·$tonne^{-1}$)	$7.3 \cdot 10^{-1} \pm 6.8 \cdot 10^{-1}$	$8.2 \cdot 10^{-1} \pm 5.8 \cdot 10^{-1}$	$3.3 \cdot 10^{-1} \pm 2.1 \cdot 10^{-1}$	$3.0 \cdot 10^{1} \pm 1.1 \cdot 10^{1}$	$7.0 \cdot 10^{-1} \pm 4.9 \cdot 10^{-1}$
TEu (mole of N eq.·ha^{-1})	319.7 ± 147.0	201.7 ± 87.4	81.4 ± 28.8	139.0 ± 57.8	148.7 ± 64.6
TEu (mole of N eq.·$tonne^{-1}$)	10.4 ± 6.7	6.5 ± 4.1	2.5 ± 1.2	4.5 ± 2.8	4.8 ± 3.1
AqAc (kg SO_2 eq.·ha^{-1})	45.6 ± 21.6	29.0 ± 13.3	12.2 ± 4.9	20.5 ± 9.2	21.8 ± 10.2
AqAc (kg SO_2 eq.·$tonne^{-1}$)	$1.5 \pm 9.9 \cdot 10^{-1}$	$9.4 \cdot 10^{-1} \pm 6.2 \cdot 10^{-1}$	$3.9 \cdot 10^{-1} \pm 2.2 \cdot 10^{-1}$	$6.7 \cdot 10^{-1} \pm 4.4 \cdot 10^{-1}$	$7.1 \cdot 10^{-1} \pm 4.8 \cdot 10^{-1}$
TAc (kg SO_2 eq.·ha^{-1})	370.6 ± 170.2	238.3 ± 103.5	103.9 ± 35.8	169.9 ± 71.4	180.6 ± 79.1
TAc (kg SO_2 eq.·$tonne^{-1}$)	11.9 ± 7.7	7.6 ± 4.7	3.1 ± 1.5	5.4 ± 3.3	5.7 ± 3.6

*emission factors from the updated IPCC (2019) and EEA (2019)

Table 5.5. Results of the post-hoc non-parametric paired comparisons performed using Dunn's test for N emissions and impact categories that present differences detected using the Kruskal-Wallis test

	LEACHN vs. EPD	LEACHN vs. PEF	LEACHN vs. WFLDB	LEACHN vs. 'updated method'	EPD vs. PEF	EPD vs. WFLDB	EPD vs. 'updated method'	PEF vs. WFLDB	PEF vs. 'updated method'	WFLDB vs. 'updated method'
N_2O (kg · ha^{-1})	-	-	-	-	-	-	-	-	-	-
N_2O (kg · tonne^{-1})	-	-	-	-	-	-	-	-	-	-
NH_3 (kg · ha^{-1})	-	0.01[a]	-	-	0.05[a]	-	-	-	-	-
NH_3 (kg · tonne^{-1})	-	0.04[a]	-	-	-	-	-	-	-	-
NO_3^- (kg · ha^{-1})	-	-	0.02[a]	-	-	-	-	0[a]	-	0.03[a]
NO_3^- (kg · tonne^{-1})	-	-	0.02[a]	-	-	0.05[a]	-	0[a]	-	0.02[a]
NO_x (kg · ha^{-1})	-	0[a]	-	-	-	-	-	0.01[a]	0[a]	-
NO_x (kg · tonne^{-1})	-	0[a]	-	-	-	-	-	0.01[a]	0.01[a]	-
CC (kg · ha^{-1})	-	-	-	-	-	-	-	-	-	-
CC (kg · tonne^{-1})	-	-	-	-	-	-	-	-	-	-
AqAc (kg · ha^{-1})	-	0.01[a]	-	-	-	-	-	-	-	-
AqAc (kg · tonne^{-1})	-	-	-	-	-	-	-	-	-	-
MEu (kg · ha^{-1})	-	-	0.03[a]	-	-	-	-	0[a]	-	0.03[a]
MEu (kg · tonne^{-1})	-	-	0.02[a]	-	-	0.03[a]	-	0[a]	-	0.02[a]
TAc (kg · ha^{-1})	-	0.01[a]	-	-	-	-	-	-	-	-
TAc (kg · tonne^{-1})	-	-	-	-	-	-	-	-	-	-
TEu (kg · ha^{-1})	-	0.01[a]	-	-	-	-	-	-	-	-
TEu (kg · tonne^{-1})	-	-	-	-	-	-	-	-	-	-

-: not significant. [a]: significant at 0.05 level

A summary of the results from the statistical analysis is shown in Table 5.5. In general, both for N emissions and environmental impacts, more differences are observed per hectare than per tonne because, as commented in section 3.2., the alternating yield makes the variability per tonne to be greater, which masks potential differences. When analysing MEu, significant differences are detected between WFLDB and the other four approaches. These are closely related to the differences observed in NO_3^- leaching, which is the emission that dominates this impact category, and as commented above, exhibits values two orders of magnitude greater when using WFLDB, which are much higher than the N applied (Tables 5.1 and 5.4a). The main difference between LEACHN and WFLDB with EPD, PEF and the so-called 'updated method' is that these last three do not consider the irrigation and rainfall nor soil or crop parameters. On the other hand, the emission flows are modelled on a daily basis with LEACHN, while WFLDB considers the inputs application (N and water) in a single instance, causing the values of leached NO_3^- to increase, especially in countries with high values of precipitation like Uruguay. As for TAc, TEu and AqAc, when considering 1 hectare as a FU, significant differences are detected between LEACHN and PEF related to the significant differences in the influencing emission, NH_3, which is higher with LEACHN, and NO_x, which is not estimated in PEF. To quantify NH_3 emissions, LEACHN considers the daily hydrolysis of urea using a rate of 0.36 kg N-NH_3 · kg N-urea^{-1} day^{-1}, while in the PEF method, a lower emission factor is applied depending on the type of fertiliser applied, ranging from 0.024 to 0.18 kg NH_3 · kgN^{-1}. When expressing the results per tonne, these significant differences are not detected, probably due to the effect of the yield. Regarding CC, no differences were detected between the analysed methods, neither per tonne nor per hectare, which is explained by the absence of significant differences in the influencing emission, N_2O.

Summarising, in this case study, no significant differences are detected in the results obtained between LEACHN and the rest of the methods tested, except with WFLDB when quantifying MEu and with PEF when quantifying TAc, TEu, and AqAc per ha. However, considering the number of parameters that mechanistic methods such as LEACHN take into account and that both the soil and the agricultural system itself are dynamic, more research is encouraged to draw general conclusions about the convenience of using this method.

5.3.5. Comparison with other studies

The environmental impact scores of mandarin cultivation in this study are compared with those of the literature (Table 5.15); in particular, with two studies on mandarin (Bessou et al. 2016; Martin-Gorriz et al. 2020), two studies on citrus fruits in general (Ribal et al. 2017; Yang et al. 2020), and a previous study carried out by the authors on lemon cultivation in Uruguay (Cabot et al. 2023). The focus is on CC, FEu, MEu, TAc, and water consumption-related impact for a mass FU.

The average CC score obtained for Uruguayan mandarins is 0.045 CO_2 eq.$\cdot kg^{-1}$, lower than all the studies it is compared with. It must be remarked that, unlike in most reviewed studies, on-field emissions from fertiliser application are not a hotspot in the present study. This could be due to the lower N rate applied compared to the reviewed studies (59 to 92% lower). Likewise, a Tier 3 approach is used for modelling N_2O emissions (the main emissions influencing CC), while the reviewed studies use the IPCC Tier 1 approach (IPCC 2006b). As can be seen in Table 5.4b, using a Tier 1 approach in the present study (e.g., 'PEF') would give a 14% higher score for this impact category. The yield is another decisive factor, especially in Martin-Gorriz et al. (2020) and Yang et al. (2020), where it is 37% and 32% lower, respectively, making their scores per mass unit higher. On the other hand, the production of fertilisers (highlighted as a hotspot in the present study) is also remarked as a critical point in Cabot et al. (2023), Ribal et al. (2017) and Yang et al. (2020). Martin-Gorriz et al. (2020) highlight machinery operations as a hotspot; in particular, the impact score for that stage is 0.11 CO_2 eq.· kg^{-1}, eight times greater than the results shown in the present study (0.01 CO_2 eq.· kg^{-1}), which can be explained by the diesel consumption (four times higher than in the present study), and the yield (37% lower).

The average score obtained for FEu in the present study is $2.8 \cdot 10^{-5}$ kg P eq.· kg^{-1} and for MEu $5.3 \cdot 10^{-4}$ kg N eq.· kg^{-1}. The FEu score of the present study is similar to that of Cabot et al. (2023) and half the value reported by Bessou et al. (2016), even though these studies consider a higher yield. This difference could be due to the lower amount of P_2O_5 applied in our study (5 and 36 times less, respectively), as phosphate emission to freshwater is the leading cause of this environmental impact in the on-field emissions stage. Martin-Gorriz et al. (2020), Ribal et al. (2017), and Yang et al. (2020) do not discern between MEu and FEu, thus, direct comparations cannot be made. Concerning the hotspots for FEu, Cabot et al. (2023) remark pesticide production also due to copper pesticides, as in the present study, whereas Bessou et al. (2016) highlight the role of on-field emissions in this impact. As for MEu, both Cabot et al. (2023) and Bessou et al. (2016) highlight fertiliser emissions as a hotspot, despite using different methods to estimate NO_3^- emissions. The present study uses the Tier 3 LEACHN (Hutson and Wagenet 1992), while Cabot et al. (2023) use the SQCB-NO_3 method (Emmenegger et al. 2009) and Bessou et al. (2016) follow Brentrup et al. (2000). The three methods take into account different parameters in the model. However, it is interesting to make a preliminary comparison with Cabot et al. (2023) study, also located in Uruguay, and even though the amount of N added is three times higher than in the present study and the reported yield is nearly two times greater, the MEu score is almost six times higher. In case NO_3^- had been modelled in the present study using the SQCB-NO_3 method as proposed in the 'WFLDB' approach (Table 5.4a), the MEu score would have been almost thirty times higher (see Table 5.4b). This reaffirms what was highlighted in Cabot et al. (2023), that the SQCB-NO_3 method is not the most appropriate for modelling NO_3^- leaching, at least in the case of Uruguayan citrus production, as this emission depends on climatic factors and crop management that have a great space-time variability.

Regarding TAc, comparisons are only made with Bessou et al. (2016) since the other studies do not distinguish between terrestrial and aquatic acidification. The score obtained in the present study is $1.2 \cdot 10^{-2}$ kg SO_2 eq.·kg^{-1}, ten times higher than that of Bessou et al. (2016), which could be influenced by the higher yield of that study (18% higher on average). On-field emissions, mainly NH_3 volatilisation, is the leading cause of this impact in both studies. However, these authors use a fixed emission factor to quantify NH_3 emission from mineral fertilisers, while in the present article, dynamic modelling is carried out using LEACHN. This could explain the greater scores obtained in the current study despite adding 68% less N. In case this emission was modelled with a Tier 1 approach, as proposed in 'PEF', the impact score for this category would be 74% lower ('PEF', Table 5.4b), whereas using the Tier 2 approach of EEA (2019) like in the 'updated method', a 52% reduction would be observed (Table 5.4b).

The BWS score obtained in this study is 0.11 m^3 eq.·kg^{-1}, similar to that of Cabot et al. (2023) for Uruguayan lemons, even with half the yield and an almost four times higher blue water consumption. This is mainly due to the basin CFs, which are 58-85% lower than those of Cabot et al. (2023), depending on the month. This result reaffirms the importance of considering the monthly scarcity of the basin in the BWS calculations. Bessou et al. (2016) also assess this impact category but use the amount of water irrigated as an input. However, they emphasise that the impacts due to water use should be modelled based on a proper inventory of input and output water fluxes accounting for soil, climate, and agricultural practices. In addition, the authors use the method proposed in Recipe 2008 (Goedkoop et al. 2013), which does not distinguish the origin of the water, suggesting a characterisation factor of 1 for all types of water (lake, river, well), regardless of the basin.

It must be noted that for the impact categories not included in Table 5.15, the scores of Cabot et al. (2023) for ET, HT, RUm, and RUf are similar to those obtained in the present study, where the production of inputs (pesticides and fertilisers) stand out as hotspot. Ribal et al. (2017) highlight pesticide emissions as a hotspot in toxicity impact-related categories. As for RUf, Martin-Gorriz et al. (2020) also emphasise machinery operations as a hotspot, obtaining ten times higher impact scores, mainly because of the higher fuel consumption (four times higher) and the 37% lower yield. Martin-Gorriz et al. (2020) also highlight pesticide production as a hotspot in RUm, obtaining similar results to the present study.

5.4. CONCLUSIONS

The present study is a first approach to quantify the environmental impacts of mandarin production in Uruguay, seeking to achieve a more sustainable agricultural production in line with the SDGs. The main hotspots found are on-field emissions from fertilisers, input production, and water consumption for irrigation. Therefore, actions towards their minimisation are encouraged, mainly by better adjusting the applied doses. The importance of considering more than one FU is reaffirmed.

Two key issues of agricultural LCAs are addressed: temporal variability during the full production phase and site specificity. As to temporal variability, the importance of evaluating different harvest seasons, even when assessing the full production stage and especially under variable climatic conditions and agricultural practices, is emphasised. In fact, a high inter-season variability is detected for all the impact categories, particularly when using a mass-based FU, due to the yield effect. When analysing the impact categories with more variability, the results expressed per hectare mainly respond to the most influential on-field emissions. However, when expressing the results per tonne, the environmental impacts are not always inversely proportional to the yield since the studied variety is characterised by its alternating bearing, therefore, the application of higher input rates does not always imply a greater yield. Regarding site specificity, significant reductions in the impact scores are observed when applying a global spatialised model to on-field emissions, and their use should be thus boosted. As well, when data is available, the development of site-specific inventories is encouraged. As regards the modelling of N on field emissions, LEACHN seems to better capture the interseason variability of farming practices and climate, given the higher CV of most of the emissions per ha. The statistical test showed significant differences in the MEu impact category when modelling NO_3^- following WFLDB compared to LEACHN. This method is thus not recommended for quantifying MEu impact, at least for Uruguayan citrus. Significant differences were also observed for TAc, TEu and AqAc per ha when modelling emissions following PEF in comparison to LEACHN, therefore, the use of the former to quantify these emissions is not recommended, at least for this case study. No significant differences were obtained for CC between the five approaches assessed. Nevertheless, more research is needed to improve the application of LEACHN to the agroclimatic characteristics of Uruguay and to draw general conclusions about the advantages of using this mechanistic model to estimate N emissions for better environmental assessment of Uruguayan citriculture.

Regarding the limitations of the present study, some crop protection inputs could not be properly modelled as they were not available in the databases used. Thus, the development of more complete databases is encouraged. As to system modelling, due to the peculiarities of perennial crops, there is a need to standardise the way in which perennial systems should be modelled when performing an LCA (e.g., in forthcoming updates of published guidelines). Along these lines, further studies are needed to assess the influence of the non-productive phases (nursery and the first years in the orchard) in citrus production in order to discuss the relevance of the allocation of their environmental impact among the fruits leaving the system in the full production years.

Acknowledgements

Maria Inés Cabot is the recipient of a PhD scholarship (POS_EXT_2018_1_154319) from the National Agency for Research and Innovation (ANII, Uruguay).

The authors particularly acknowledge UPEFRUY-Uruguay fruits (http://uruguayfruits.com.uy/en) for their sincere collaboration and for sharing their data for this study. Special thanks to Gustavo, Cristina and Gladiana for their kindness and willingness to help.

The authors also especially acknowledge Dr. Antonio Luis Lidon Cerezuela from the Forest Science and Technology research group of the University Institute of Water and Environmental Engineering of the Universitat Politècnica de València for incorporating the pattern of N uptake by citrus to the LEACHN model.

Funding for open access charge: Universitat Politècnica de València.

Declarations

The authors have no relevant financial or non-financial interests to disclose.

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5.5. MATERIAL COMPLEMENTARIO DEL CAPÍTULO 5

La presente sección se divide en los siguientes apartados:

- Inventario ambiental detallado del cultivo de mandarina
- Metadatos del modelado del proceso de cultivo de mandarina
- Fuentes de datos utilizadas y parámetros necesarios para el modelado de cada emisión nitrogenada en las metodologías analizadas
- Distancias de transporte de los insumos utilizados
- Resultados promedio de los impactos ambientales y desviación estándar por etapa del cultivo de mandarina, por hectárea y por tonelada
- Toxicidad de los plaguicidas utilizados en el cultivo de mandarina considerando la cantidad de principio activo aplicado
- Consumo de agua azul para las seis temporadas de estudio
- Factores de caracterización utilizados para la regionalización de los flujos emitidos
- Información de estudios de ACV de la producción de mandarina en otros países
- Diagramas representando la distribución de probabilidad de las emisiones nitrogenadas modeladas y de los resultados de los impactos ambientales para las seis temporadas de estudio
- Descripción de las ecuaciones utilizadas

Table 5.6. Detailed inventory of the mandarin cultivation stage

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Yield	tonne · ha^{-1}	49.3	21.4	34.8	31.3	54.0	24.0	35.8	13.3
Electricity for irrigation	kWh · ha^{-1}	70.7	114.3	23.1	38.8	52.4	91.7	65.2	34.0
Water withdrawal for irrigation	mm · $season^{-1}$	211.0	341.0	68.8	115.7	156.5	273.7	194.5	101.5
Rainfall water	mm · $season^{-1}$	1716.0	1388.0	1695.0	1364.0	1119.0	1053.0	1389.2	278.2
Rainfall + irrigation water	mm · $season^{-1}$	1927.0	1729.0	1763.8	1479.7	1275.5	1326.7	1583.6	262.0
Machinery use (input application)	h · ha^{-1}	17.7	17.4	12.2	15.1	12.9	13.5	14.8	2.3
Machinery use (harvest and transport of bins)	h · ha^{-1}	11.8	2.8	29.0	11.1	22.0	12.4	14.8	9.2
Diesel for machinery operations									
Application of inputs	L · ha^{-1}	141.7	139.1	97.8	121.0	103.3	108.1	118.5	18.6
Harvest and transport of bins	L · ha^{-1}	23.6	5.5	57.9	22.1	43.9	24.7	29.6	18.4
Fertilisers									
N	kg · ha^{-1}	41.3	68.1	3.3	93.7	89.4	114.0	68.3	40.3
P_2O_5	kg · ha^{-1}	$4.69 \cdot 10^{-2}$	3.35	$1.53 \cdot 10^{-1}$	2.25	1.74	3.37	1.82	1.50
K_2O	kg · ha^{-1}	28.4	41.4	0.5	51.3	77.2	87.5	47.7	31.9

Table 5.6. (cont.) Detailed inventory of the mandarin cultivation stage

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Fungicides									
Difenoconazole 1	$kg \cdot ha^{-1}$	0.0	$2.7 \cdot 10^{-1}$	$4.2 \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$	0.0	0.0	$7.0 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Pyrachlostrobin 1	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$1.1 \cdot 10^{-1}$	$7.5 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	0.0
Cuprous oxide	$kg \cdot ha^{-1}$	3.4	1.7	3.5	$1.3 \cdot 10^{1}$	7.0	7.8	6.0	4.0
Pyrachlostrobin 2	$kg \cdot ha^{-1}$	0.0	$7.2 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	$1.2 \cdot 10^{-2}$	0.0
Difenoconazole 2	$kg \cdot ha^{-1}$	$1.5 \cdot 10^{-1}$	0.0	0.0	0.0	$1.3 \cdot 10^{-1}$	$4.7 \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Potassium phosphite 3	$kg \cdot ha^{-1}$	0.0	0.0	3.5	0.0	2.2	2.3	1.3	1.5
Difenoconazole 3	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$1.1 \cdot 10^{-1}$	0.0	$1.8 \cdot 10^{-2}$	0.0
Potassium phosphite 1	$kg \cdot ha^{-1}$	5.3	5.4	0.0	0.0	0.0	0.0	1.8	2.8
Potassium phosphite 2	$kg \cdot ha^{-1}$	0.0	0.0	0.0	2.6	0.0	0.0	$4.3 \cdot 10^{-1}$	1.1
Mancozeb 1	$kg \cdot ha^{-1}$	2.3	6.8	0.0	0.0	0.0	5.9	2.5	3.1
Azoxystrobin 1	$kg \cdot ha^{-1}$	0.0	0.0	$1.8 \cdot 10^{-1}$	0.0	0.0	0.0	$3.1 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Mancozeb 2	$kg \cdot ha^{-1}$	0.0	0.0	0.0	1.4	4.4	0.0	$9.6 \cdot 10^{-1}$	1.8
Mancozeb 3	$kg \cdot ha^{-1}$	0.0	0.0	3.2	0.0	0.0	0.0	$5.4 \cdot 10^{-1}$	1.3
Copper sulphate	$kg \cdot ha^{-1}$	0.0	$5.5 \cdot 10^{-1}$	$8.8 \cdot 10^{-1}$	$4.4 \cdot 10^{-1}$	$9.3 \cdot 10^{-1}$	3.4	1.0	1.2
Azoxystrobin 2	$kg \cdot ha^{-1}$	$4.3 \cdot 10^{-1}$	0.0	0.0	0.0	0.0	0.0	$7.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-1}$
Copper oxychloride	$kg \cdot ha^{-1}$	7.4	$1.0 \cdot 10^{1}$	0.0	0.0	0.0	0.0	2.9	4.6

Table 5.6. (cont.) Detailed inventory of the mandarin cultivation stage

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Herbicides									
Paraquat 1	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$5.3 \cdot 10^{-1}$	0.0	$8.8 \cdot 10^{-2}$	$2.0 \cdot 10^{-1}$
Diuron 1	$kg \cdot ha^{-1}$	0.0	1.8	0.0	0.0	0.0	0.0	$3.0 \cdot 10^{-1}$	$7.0 \cdot 10^{-1}$
2,4-D dimethyl amine salt	$kg \cdot ha^{-1}$	0.0	0.0	0.0	$8.5 \cdot 10^{-1}$	0.0	0.0	$1.4 \cdot 10^{-1}$	$3.0 \cdot 10^{-1}$
Flumioxazin 1	$kg \cdot ha^{-1}$	0.0	0.0	0.0	$2.1 \cdot 10^{-1}$	0.0	0.0	$3.5 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Glyphosate 1	$kg \cdot ha^{-1}$	2.3	0.0	0.0	0.0	0.0	0.0	$3.8 \cdot 10^{-1}$	$9.0 \cdot 10^{-1}$
Glyphosate 2	$kg \cdot ha^{-1}$	0.0	1.1	0.0	0.0	0.0	2.2	$5.5 \cdot 10^{-1}$	$9.0 \cdot 10^{-1}$
Glyphosate 3	$kg \cdot ha^{-1}$	0.0	0.0	0.0	2.1	0.0	0.0	$3.5 \cdot 10^{-1}$	$9.0 \cdot 10^{-1}$
Glyphosate 4	$kg \cdot ha^{-1}$	0.0	0.0	1.1	0.0	0.0	0.0	$1.8 \cdot 10^{-1}$	$4.0 \cdot 10^{-1}$
Glyphosate 5	$kg \cdot ha^{-1}$	0.0	0.0	0.0	$8.0 \cdot 10^{-2}$	0.0	0.0	$1.3 \cdot 10^{-2}$	0.0
Saflufenacil	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	0.0	$1.9 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$	0.0
Diuron 2	$kg \cdot ha^{-1}$	1.2	$5.0 \cdot 10^{-1}$	0.0	0.0	0.0	0.0	$2.9 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$
Paraquat 3	$kg \cdot ha^{-1}$	0.0	$9.2 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	$1.5 \cdot 10^{-2}$	0.0
Paraquat 2	$kg \cdot ha^{-1}$	0.0	$2.4 \cdot 10^{-1}$	0.0	0.0	0.0	$6.6 \cdot 10^{-1}$	$1.5 \cdot 10^{-1}$	$3.0 \cdot 10^{-1}$
Flumioxazin 2	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$1.4 \cdot 10^{-1}$	$3.7 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Insecticides									
Paraffinic oil	$kg \cdot ha^{-1}$	$2.9 \cdot 10^{1}$	4.2	$3.1 \cdot 10^{-1}$	$3.1 \cdot 10^{1}$	$1.7 \cdot 10^{1}$	$1.7 \cdot 10^{1}$	$1.6 \cdot 10^{1}$	$1.2 \cdot 10^{1}$
Buprofezin	$kg \cdot ha^{-1}$	0.0	1.0	$5.1 \cdot 10^{-1}$	0.0	0.0	0.0	$2.5 \cdot 10^{-1}$	$4.0 \cdot 10^{-1}$
Abamectin 4	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$4.6 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.0
Pyriproxyfen 1	$kg \cdot ha^{-1}$	0.0	0.0	$2.2 \cdot 10^{-2}$	0.0	0.0	0.0	$3.7 \cdot 10^{-3}$	0.0
Phosmet	$kg \cdot ha^{-1}$	$3.8 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	0.0	$6.3 \cdot 10^{-3}$	0.0
Pyriproxyfen 2	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$5.5 \cdot 10^{-2}$	$5.1 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	0.0
Abamectin 1	$kg \cdot ha^{-1}$	$1.7 \cdot 10^{-2}$	0.0	0.0	$3.7 \cdot 10^{-2}$	0.0	0.0	$9.1 \cdot 10^{-3}$	0.0
Spinosad	$kg \cdot ha^{-1}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-4}$	0.0	0.0	0.0	0.0	$2.0 \cdot 10^{-3}$	0.0
Abamectin 2	$kg \cdot ha^{-1}$	0.0	0.0	$8.8 \cdot 10^{-3}$	0.0	0.0	0.0	$1.5 \cdot 10^{-3}$	0.0
Abamectin 3	$kg \cdot ha^{-1}$	0.0	$1.6 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	0.0	0.0	0.0	$4.6 \cdot 10^{-3}$	0.0

Table 5.6. (cont.) Detailed inventory of the mandarin cultivation stage

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Growth regulators									
2,4-D isopropyl ester	$kg \cdot ha^{-1}$	0.0	$3.0 \cdot 10^{-2}$	0.0	0.0	$3.0 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.0
Gibberellic acid	$kg \cdot ha^{-1}$	$1.9 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	$3.3 \cdot 10^{-2}$	$8.7 \cdot 10^{-3}$	0.0
Dispersants									
Polyether silicone copolymer	$kg \cdot ha^{-1}$	$5.0 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	$4.7 \cdot 10^{-1}$	$7.3 \cdot 10^{-1}$	$6.4 \cdot 10^{-1}$	$7.8 \cdot 10^{-1}$	$6.0 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$
On-field emissions									
Direct N_2O	$kg \cdot ha^{-1}$	$6.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-1}$	0.0	$1.3 \cdot 10^{-1}$	$2.5 \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Indirect N_2O (from NO_3^-)	$kg \cdot ha^{-1}$	$2.2 \cdot 10^{-1}$	$3.0 \cdot 10^{-1}$	$8.0 \cdot 10^{-3}$	$1.9 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$	$6.6 \cdot 10^{-1}$	$2.6 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Indirect N_2O (from NH_3)	$kg \cdot ha^{-1}$	$2.6 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$6.8 \cdot 10^{-2}$	$5.1 \cdot 10^{-1}$	$4.9 \cdot 10^{-1}$	$5.8 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
NH_3 volatilised	$kg \cdot ha^{-1}$	$1.4 \cdot 10^{1}$	$2.0 \cdot 10^{1}$	3.7	$2.7 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$3.1 \cdot 10^{1}$	$2.0 \cdot 10^{1}$	$1.0 \cdot 10^{1}$
NO_2 volatilised	$kg \cdot ha^{-1}$	1.7	2.7	$1.3 \cdot 10^{-1}$	3.7	3.6	4.6	2.7	1.6
NO_3^- leached	$kg \cdot ha^{-1}$	$5.6 \cdot 10^{1}$	$7.7 \cdot 10^{1}$	2.0	$4.8 \cdot 10^{1}$	$5.1 \cdot 10^{1}$	$1.7 \cdot 10^{2}$	$6.7 \cdot 10^{1}$	$5.6 \cdot 10^{1}$
PO_4^{3-} leached	$kg \cdot ha^{-1}$	1.1	1.1	1.1	1.1	1.1	1.1	1.1	0.0

Table 5.7. Life cycle inventory metadata for Uruguayan mandarin production

Input	LCI Name	Type of process	Source
2,4-D dimethyl amine salt	GLO: phenoxy-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
2,4-D isopropyl ester	RER: phenoxy-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Abamectin 1	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Abamectin 2	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Abamectin 3	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Abamectin 4	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Azoxystrobin 1	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Azoxystrobin 2	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Buprofezin	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Copper oxychloride	GLO: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.8
Copper sulphate	GLO: copper sulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
Cuprous oxide	RER: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.8
Difenoconazole 1	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Difenoconazole 2	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Difenoconazole 3	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Diuron 1	GLO: urea production	agg LCI result, cut-off method	Ecoinvent 3.8
Diuron 2	CN: urea production	agg LCI result, cut-off method	Ecoinvent 3.8
Flumioxazin 1	GLO: phthalimide-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Flumioxazin 2	GLO: phthalimide-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Glyphosate 1	GLO: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.8
Glyphosate 2	GLO: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.8

Table 5.7. (cont.) Life cycle inventory metadata for Uruguayan mandarin production

Input	LCI Name	Type of process	Source
Glyphosate 3	GLO: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.8
Glyphosate 4	GLO: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.8
Glyphosate 5	GLO: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.8
Granulated urea	RER: urea production	agg LCI result, cut-off method	Ecoinvent 3.8
Liquid urea	GLO: urea production	agg LCI result, cut-off method	Ecoinvent 3.8
Magnesium sulphate	GLO: magnesium sulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
Mancozeb 1	GLO: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.8
Mancozeb 2	GLO: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.8
Mancozeb 3	GLO: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.8
Manganese sulphate	GLO: manganese sulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
Molasses	GLO: market for molasses, from sugar beet	agg LCI result, cut-off method	Ecoinvent 3.8
Monoammonium phosphate	GLO: monoammonium phosphate production	agg LCI result, cut-off method	Ecoinvent 3.8
Paraffinic oil	GLO: paraffin production	agg LCI result, cut-off method	Ecoinvent 3.8
Paraquat 1	GLO: bipyridylium-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Paraquat 2	GLO: bipyridylium-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Paraquat 3	GLO: bipyridylium-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Phosmet	GLO: organophosphorus-compound production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Phosphoric acid	GLO: phosphoric acid production, dihydrate process	agg LCI result, cut-off method	Ecoinvent 3.8
Polyether silicone copolymer	GLO: silicone product production	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium chloride	GLO: potassium chloride production	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium phosphite 1	ES: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8

Table 5.7. (cont.) Life cycle inventory metadata for Uruguayan mandarin production

Input	LCI Name	Type of process	Source
Potassium phosphite 1	ES: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium phosphite 2	GLO: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium phosphite 2	GLO: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium phosphite 3	GLO: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium phosphite 3	GLO: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
Potassium sulfate	GLO: potassium sulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
Pyraclostrobin 1	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Pyraclostrobin 2	RER: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Pyriproxyfen 1	GLO: pyridine-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Pyriproxyfen 2	GLO: pyridine-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Saflufenacil	GLO: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Spinosad	GLO: Glucose production	agg LCI result, cut-off method	Ecoinvent 3.8
Spinosad	US: Electricity, bituminous coal, at power plant	agg LCI result, cut-off method	GaBi v.10
Spinosad	US: Electricity, natural gas, at power plant	agg LCI result, cut-off method	GaBi v.10
Spinosad	US: Electricity, nuclear, at power plant	agg LCI result, cut-off method	GaBi v.10
Urea ammonium nitrate	GLO: urea ammonium nitrate production	agg LCI result, cut-off method	Ecoinvent 3.8
Zinc sulfate	GLO: zinc monosulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
Diesel production	RSA: Diesel mix at refinery	agg LCI result, cut-off method	GaBi v.10
Electricity production	UY: market for electricity, medium voltage	agg LCI result, cut-off method	Ecoinvent 3.8
Machinery use	GLO: Universal Tractor	u-so, unit process single operation	GaBi v.10
Irrigation	GLO: Irrigation pump generic	u-so unit process single operation	GaBi v.10

Table 5.7. (cont.) Life cycle inventory metadata for Uruguayan mandarin production

Input	LCI Name	Type of process	Source
Transportation by lorry	RoW: transport, freight, lorry 16-32 metric ton, EURO3	agg LCI result, cut-off method	Ecoinvent 3.8
Transportation by ship	GLO: Transoceanic ship, containers, 27,500 dwt payload capacity, ocean going	agg LCI result, cut-off method	GaBi v.10

Table 5.8. Sources used and inputs needed for the modelling of each emission for all methodologies analysed.

		LEACHN	EPD	PEF	WFLDB	Updated method
NH_3	Source	LEACHN (Hutson and Wagenet 1992)	EEA (2013)	Alternative approach EU (2018)	EEA (2016) Tier 2	EEA (2019) Tier 2
	Inputs	- Fertilisers (Amount of N, type of fertilizer, day and time of fertigation) - Irrigation (Amount, day and time of irrigation, % of soil wet by dripping, amount of NO_3^- in irrigation water) -Precipitation (day, hour and amount) - Soil (Clay, silt, organic carbon, bulk density, parameters of the moisture retention curve and saturated hydraulic conductivity, slope, depth of the water table, initial contents of water, urea, nitric and ammoniacal N, N in residues or added in the form of manure - Rates (decomposition of humus, vegetable residues and manure, urea hydrolysis, nitrification, denitrification and volatilization - Climate (Average temperature, thermal amplitude, ET_0) - Crop (depth of roots, maximum absorption rate of N and P)	- N supply through fertiliser - Type of fertiliser - Soil pH (low soil pH)	- N supply through fertiliser - Type of fertiliser	- Climate (temperate) - Soil pH (normal, of 7.0 or below)	- Climate (temperate) - Soil pH (normal, of 7.0 or below)
NO_x	Source	EEA (2019) Tier 1	Bowman (2002)	Not quantified	EEA (2016) Tier 1	EEA (2019) Tier 1
	Inputs	- N supply through fertiliser	- N supply through fertiliser - Type of fertiliser	-	- N supply through fertiliser	- N supply through fertiliser

Table 5.8. (cont.) Sources used, and inputs needed for the modelling of each emission for all methodologies analysed.

		LEACHN	EPD	PEF	WFLDB	Updated method
N_2O d	Source	LEACHN (Hutson and Wagenet 1992)	Bowman (2002)	Alternative approach EU (2018) - N supply through fertiliser	IPCC (2006)	IPCC (2019)
	Inputs	Same as in NH_3	- N supply through fertiliser - Type of fertiliser		- N supply through fertiliser	- Type of fertiliser (synthetic) - Climate (wet)
N_2O iv	Source	IPCC (2019)	IPCC (2006)		IPCC (2006)	IPCC (2019)
	Inputs	- N supply through fertiliser - Climate (wet)	- N supply through fertiliser		- N supply through fertiliser	- N supply through fertiliser - Type of fertiliser
N_2O il	Source	IPCC (2019)	IPCC (2006)		IPCC (2006)	IPCC (2019)
	Inputs	- N supply through fertiliser - Climate (wet)	- N supply through fertiliser		- N supply through fertiliser	- N supply through fertiliser - Climate (wet)
NO_3^-	Source	LEACHN (Hutson and Wagenet 1992)	IPCC (2006)	Alternative approach EU (2018)	SQCB-NO_3 (Emmenegger et al. 2009)	IPCC (2019)
	Inputs	Same as in NH3	- N supply through fertiliser	- N supply through fertiliser	- Amount of precipitation - Amount of water irrigated - Clay content on the soil - Rooting depth - Nitrogen supply through fertiliser - Nitrogen in organic matter - Nitrogen uptake by crop	- N supply through fertiliser

Table 5.9. Transport distances for the inputs used in Uruguayan mandarin cultivation (Searates 2022)

Input	Use	Distance by ship (km)	Distance by truck (km)
2,4-D dimethyl amine salt	Herbicide	23142.2	483.2
2,4-D isopropyl ester	Growth regulator	10864.0	439.8
Abamectin 1	Insecticide	23142.2	483.2
Abamectin 2	Insecticide	23142.2	483.2
Abamectin 3	Insecticide	0.0	300.0
Abamectin 4	Insecticide	0.0	300.0
Azoxystrobin 1	Fungicide	23142.2	483.2
Azoxystrobin 2	Fungicide	0.0	300.0
Buprofezin	Insecticide	23142.2	483.2
Copper oxychloride	Dispersant	0.0	300.0
Copper sulphate	Fungicide	0.0	300.0
Cuprous oxide	Fungicide	12547.5	524.8
Difenoconazole 1	Fungicide	23142.2	483.2
Difenoconazole 2	Fungicide	0.0	300.0
Difenoconazole 3	Fungicide	23142.2	483.2
Diuron 1	Herbicide	0.0	300.0
Diuron 2	Herbicide	23142.2	483.2
Flumioxazin 1	Herbicide	23142.2	483.2
Flumioxazin 2	Herbicide	23142.2	483.2
Gibberellic acid	Growth regulator	10864.0	439.8
Glyphosate 1	Herbicide	23142.2	483.2
Glyphosate 2	Herbicide	23142.2	483.2
Glyphosate 3	Herbicide	23142.2	483.2
Glyphosate 4	Herbicide	23142.2	483.2
Glyphosate 5	Herbicide	23142.2	483.2
Granulated urea	Fertiliser	16318.3	1547.0
Liquid urea	Fertiliser	0.0	300.0
Magnesium sulphate	Fertiliser	23142.2	483.2
Mancozeb 1	Fungicide	15617.8	913.9
Mancozeb 2	Fungicide	15617.8	913.9
Mancozeb 3	Fungicide	15617.8	913.9
Manganese sulphate	Fertiliser	23142.2	483.2
Molasses	Nutrient	0.0	300.0
Monoammonium phosphate	Fertiliser	13279.9	540.7
Paraffinic oil	Insecticide	0.0	1100.0

Table 5.9. (cont.) Transport distances for the inputs used in Uruguayan mandarin cultivation (Searates 2022)

Input	Use	Distance by ship (km)	Distance by truck (km)
Paraquat 1	Herbicide	23142.2	483.2
Paraquat 2	Herbicide	23142.2	483.2
Paraquat 3	Herbicide	23142.2	483.2
Phosmet	Insecticide	12340.7	560.9
Phosphoric acid	Fertiliser	23142.2	483.2
Polyether silicone copolymer	Dispersant	12340.7	560.9
Potassium chloride	Fertiliser	0.0	1700.0
Potassium phosphite 1	Fungicide	10864.0	439.8
Potassium phosphite 2	Fungicide	0.0	300.0
Potassium phosphite 3	Fungicide	0.0	300.0
Potassium sulfate	Fertiliser	23142.2	483.2
Pyraclostrobin 1	Fungicide	17041.7	444.4
Pyraclostrobin 2	Fungicide	10864.0	439.8
Pyriproxyfen 1	Insecticide	23142.2	483.2
Pyriproxyfen 2	Insecticide	23142.2	483.2
Saflufenacil	Herbicide	0.0	2600.0
Spinosad	Insecticide	12340.7	560.9
Urea ammonium nitrate	Fertiliser	0.0	1100.0
Zinc sulfate	Fertiliser	23142.2	483.2

Considering the size of the country, the average distance for Uruguayan products is established at 300km

Table 5.10. Average impact results per stage and standard deviation of cradle to farm gate cultivation of mandarin in Uruguay. FU = 1 ha

	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions
Climate change (kg CO2 eq.·ha^{-1})	$1.4·10^{2} ± 3.8·10^{1}$	$4.5·10^{2} ± 2.6·10^{2}$	$8.5·10^{1} ± 4.9·10^{1}$	$4.6·10^{2} ± 3.4·10^{1}$	$1.3·10^{1} ± 6.7$	$2.7·10^{2} ± 1.6·10^{2}$
Freshwater eutrophication (kg P eq.·ha^{-1})	$3.9·10^{-1} ± 1.3·10^{-1}$	$1.1·10^{-1} ± 5.9·10^{-2}$	$5.4·10^{-3} ± 3.4·10^{-3}$	$2.7·10^{-3} ± 2.1·10^{-4}$	$4.0·10^{-4} ± 2.1·10^{-4}$	$3.5·10^{-1} ± 6.5·10^{-4}$
Marine eutrophication (kg N eq.·ha^{-1})	$3.4·10^{-1} ± 9.5·10^{-2}$	$4.5·10^{-1} ± 2.5·10^{-1}$	$3.1·10^{-1} ± 1.6·10^{-1}$	$2.1 ± 1.6·10^{-1}$	$7.8·10^{-3} ± 4.1·10^{-3}$	$1.8·10^{1} ± 1.4·10^{1}$
Terrestrial eutrophication (Mole of N eq.·ha^{-1})	$4.0 ± 1.2$	$6.3 ± 3.8$	$3.4 ± 1.7$	$2.2·10^{1} ± 1.7$	$8.5·10^{-2} ± 4.4·10^{-2}$	$2.8·10^{2} ± 1.4·10^{2}$
Aquatic acidification (kg SO_2 eq.·ha^{-1})	$4.0 ± 1.2$	$1.4 ± 8.1·10^{-1}$	$2.2·10^{-1} ± 9.9·10^{-2}$	$1.7·10^{-1} ± 1.2·10^{-2}$	$1.3·10^{-2} ± 6.8·10^{-3}$	$4.0·10^{1} ± 2.0·10^{1}$
Terrestrial acidification (kg SO_2 eq.·ha^{-1})	$8.6 ± 2.6$	$8.5 ± 5.1$	$7.4 ± 9.3$	$2.9·10^{1} ± 2.2$	$1.2·10^{-1} ± 6.3·10^{-2}$	$3.2·10^{2} ± 1.6·10^{2}$
Blue water scarcity (m^3eq.·ha^{-1})	$5.0·10^{1} ± 1.2·10^{1}$	$3.0·10^{2} ± 2.2·10^{2}$	$5.1 ± 3.2$	$1.3 ± 1.0·10^{-1}$	$3.3·10^{3} ± 3.5·10^{2}$	$0.0 ± 0.0$
Ecotoxicity (CTUe·ha^{-1})	$2.8·10^{7} ± 9.8·10^{6}$	$2.8·10^{6} ± 1.7·10^{6}$	$9.3·10^{4} ± 5.8·10^{4}$	$8.4·10^{2} ± 6.3·10^{1}$	$1.8·10^{4} ± 9.5·10^{3}$	$8.2·10^{4} ± 3.0·10^{4}$
Human toxicity, cancer (CTUh·ha^{-1})	$4.7·10^{-5} ± 1.5·10^{-5}$	$3.5·10^{-5} ± 2.1·10^{-5}$	$4.0·10^{-6} ± 2.5·10^{-6}$	$4.1·10^{-6} ± 3.1·10^{-7}$	$6.3·10^{-7} ± 3.3·10^{-7}$	$0.0 ± 0.0$
Human toxicity, non-canc. (CTUh·ha^{-1})	$7.7·10^{-4} ± 2.6·10^{-4}$	$1.5·10^{-4} ± 7.8·10^{-5}$	$2.2·10^{-5} ± 1.4·10^{-5}$	$1.6·10^{-5} ± 1.2·10^{-6}$	$1.4·10^{-6} ± 7.4·10^{-7}$	$2.9·10^{-4} ± 1.2·10^{-4}$
Resource use, mineral and metals (kg Sb eq.·ha^{-1})	$1.1·10^{-1} ± 3.7·10^{-2}$	$8.4·10^{-3} ± 5.3·10^{-3}$	$2.5·10^{-4} ± 1.5·10^{-4}$	$1.9·10^{-5} ± 1.5·10^{-6}$	$5.9·10^{-5} ± 3.1·10^{-5}$	$0.0 ± 0.0$
Resource use, fossils (MJ·ha^{-1})	$2.8·10^{3} ± 8.8·10^{2}$	$6.1·10^{3} ± 3.2·10^{3}$	$1.2·10^{3} ± 7.3·10^{2}$	$5.8·10^{3} ± 4.4·10^{2}$	$3.3·10^{1} ± 1.7·10^{1}$	$0.0 ± 0.0$
Photochemical ozone formation, human health (kg NMVOC eq.·ha^{-1})	$1.1 ± 3.5·10^{-1}$	$1.0 ± 5.7·10^{-1}$	$9.0·10^{-1} ± 4.7·10^{-1}$	$5.8 ± 4.4·10^{-1}$	$2.3·10^{-2} ± 1.2·10^{-2}$	$2.7 ± 1.6$
Ozone depletion (kg CFC-11 eq.·ha^{-1})	$3.2·10^{-5} ± 1.3·10^{-5}$	$2.6·10^{-5} ± 1.4·10^{-5}$	$1.6·10^{-5} ± 1.0·10^{-5}$	$1.3·10^{-12} ± 9.8·10^{-14}$	$4.7·10^{-7} ± 2.5·10^{-7}$	$0.0 ± 0.0$

Table 5.11. Average impact results per stage and standard deviation of cradle to farm gate cultivation of mandarin in Uruguay. FU = 1 tonne

	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions
Climate change (kg CO_2 eq.·tonne^{-1})	4.5 ± 2.5	$1.5\cdot10^{1} \pm 1.1\cdot10^{1}$	2.8 ± 2.1	$1.4\cdot10^{1} \pm 4.5$	$4.4\cdot10^{-1} \pm 3.7\cdot10^{-1}$	8.9 ± 7.5
Freshwater eutrophication (kg P eq.·tonne^{-1})	$1.3\cdot10^{-2} \pm 7.2\cdot10^{-3}$	$3.5\cdot10^{-3} \pm 2.6\cdot10^{-3}$	$1.8\cdot10^{-4} \pm 1.4\cdot10^{-4}$	$8.3\cdot10^{-5} \pm 2.7\cdot10^{-5}$	$1.4\cdot10^{-5} \pm 1.2\cdot10^{-5}$	$1.1\cdot10^{-2} \pm 4.0\cdot10^{-3}$
Marine eutrophication (kg N eq.·tonne^{-1})	$1.1\cdot10^{-2} \pm 6.2\cdot10^{-3}$	$1.5\cdot10^{-2} \pm 1.1\cdot10^{-2}$	$1.0\cdot10^{-2} \pm 7.5\cdot10^{-3}$	$6.4\cdot10^{-2} \pm 2.0\cdot10^{-2}$	$2.7\cdot10^{-4} \pm 2.3\cdot10^{-4}$	$6.3\cdot10^{-1} \pm 6.4\cdot10^{-1}$
Terrestrial eutrophication (Mole of N eq.·tonne^{-1})	$1.3\cdot10^{-1} \pm 7.3\cdot10^{-2}$	$2.1\cdot10^{-1} \pm 1.6\cdot10^{-1}$	$1.1\cdot10^{-1} \pm 8.2\cdot10^{-2}$	$6.9\cdot10^{-1} \pm 2.2\cdot10^{-1}$	$2.9\cdot10^{-3} \pm 2.5\cdot10^{-3}$	9.2 ± 6.3
Aquatic acidification (kg SO_2 eq.·tonne^{-1})	$1.3\cdot10^{-1} \pm 7.8\cdot10^{-2}$	$4.6\cdot10^{-2} \pm 3.5\cdot10^{-2}$	$9.0\cdot10^{-3} \pm 6.3\cdot10^{-3}$	$5.1\cdot10^{-3} \pm 1.6\cdot10^{-3}$	$4.5\cdot10^{-4} \pm 3.8\cdot10^{-4}$	$1.3 \pm 8.8\cdot10^{-1}$
Terrestrial acidification (kg SO_2 eq.·tonne^{-1})	$2.8\cdot10^{-1} \pm 1.6\cdot10^{-1}$	$2.8\cdot10^{-1} \pm 2.1\cdot10^{-1}$	$1.4\cdot10^{-1} \pm 1.0\cdot10^{-1}$	$8.9\cdot10^{-1} \pm 2.8\cdot10^{-1}$	$4.2\cdot10^{-3} \pm 3.5\cdot10^{-3}$	$1.0\cdot10^{1} \pm 7.0$
Blue water scarcity (m^3eq.·tonne^{-1})	$1.6 \pm 8.3\cdot10^{-1}$	$1.0\cdot10^{1} \pm 8.6$	$1.7\cdot10^{-1} \pm 1.3\cdot10^{-1}$	$3.4\cdot10^{-2} \pm 2.1\cdot10^{-2}$	$1.0\cdot10^{+2} \pm 3.3\cdot10^{1}$	0.0 ± 0.0
Ecotoxicity (CTUe·tonne^{-1})	$9.2\cdot10^{5} \pm 5.4\cdot10^{5}$	$9.0\cdot10^{4} \pm 6.9\cdot10^{4}$	$3.1\cdot10^{3} \pm 2.4\cdot10^{3}$	$2.6\cdot10^{1} \pm 8.3$	$6.2\cdot10^{+2} \pm 5.3\cdot10^{+2}$	$2.4\cdot10^{3} \pm 1.1\cdot10^{3}$
Human toxicity, cancer (CTUh·tonne^{-1})	$1.5\cdot10^{-6} \pm 8.8\cdot10^{-7}$	$1.1\cdot10^{-6} \pm 8.7\cdot10^{-7}$	$1.3\cdot10^{-7} \pm 1.0\cdot10^{-7}$	$1.3\cdot10^{-7} \pm 4.0\cdot10^{-8}$	$2.2\cdot10^{-8} \pm 1.8\cdot10^{-8}$	0.0 ± 0.0
Human toxicity, non-canc. (CTUh·tonne^{-1})	$2.5\cdot10^{-5} \pm 1.5\cdot10^{-5}$	$4.3\cdot10^{-6} \pm 2.2\cdot10^{-6}$	$7.3\cdot10^{-7} \pm 5.7\cdot10^{-7}$	$4.9\cdot10^{-7} \pm 1.6\cdot10^{-7}$	$4.9\cdot10^{-8} \pm 4.1\cdot10^{-8}$	$8.4\cdot10^{-6} \pm 4.7\cdot10^{-6}$
Resource use, mineral and metals (kg Sb eq.·tonne^{-1})	$3.5\cdot10^{-3} \pm 2.1\cdot10^{-3}$	$2.8\cdot10^{-4} \pm 2.2\cdot10^{-4}$	$8.1\cdot10^{-6} \pm 6.3\cdot10^{-6}$	$6.0\cdot10^{-7} \pm 1.9\cdot10^{-7}$	$2.0\cdot10^{-6} \pm 1.7\cdot10^{-6}$	0.0 ± 0.0
Resource use, fossils (MJ·tonne^{-1})	$8.7\cdot10^{1} \pm 4.4\cdot10^{1}$	$2.0\cdot10^{+2} \pm 1.4\cdot10^{+2}$	$4.1\cdot10^{1} \pm 3.1\cdot10^{1}$	$1.8\cdot10^{+2} \pm 5.7\cdot10^{1}$	$1.1 \pm 9.7\cdot10^{-1}$	0.0 ± 0.0
Photochemical ozone formation, human health (kg NMVOC eq.·tonne^{-1})	$3.7\cdot10^{-2} \pm 2.1\cdot10^{-2}$	$3.3\cdot10^{-2} \pm 2.5\cdot10^{-2}$	$3.0\cdot10^{-2} \pm 2.2\cdot10^{-2}$	$1.8\cdot10^{-1} \pm 5.7\cdot10^{-2}$	$7.8\cdot10^{-4} \pm 6.6\cdot10^{-4}$	$9.0\cdot10^{-2} \pm 6.8\cdot10^{-2}$
Ozone depletion (kg CFC-11 eq.·tonne^{-1})	$1.1\cdot10^{-6} \pm 7.9\cdot10^{-7}$	$8.4\cdot10^{-7} \pm 6.2\cdot10^{-7}$	$5.3\cdot10^{-7} \pm 4.1\cdot10^{-7}$	$4.0\cdot10^{-14} \pm 1.3\cdot10^{-14}$	$1.6\cdot10^{-8} \pm 1.4\cdot10^{-8}$	0.0 ± 0.0

Table 5.12. Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
2,4-D, dimethylamine salt	2008-39-1	ETP	$1.3\cdot10^{1}$	$3.6\cdot10^{-4}$	0.0	$9.9\cdot10^{-3}$	$5.6\cdot10^{1}$	$6.9\cdot10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Abamectin 1	65195-55-3	ETP	$7.0\cdot10^{1}$	$3.1\cdot10^{-5}$	0.0	$1.6\cdot10^{-4}$	$9.0\cdot10^{-1}$	$7.1\cdot10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$4.9\cdot10^{-7}$	$8.8\cdot10^{-11}$	0.0	$4.6\cdot10^{-13}$	$7.6\cdot10^{-9}$	$4.9\cdot10^{-7}$
		HTP	$4.9\cdot10^{-7}$	$8.8\cdot10^{-11}$	0.0	$4.6\cdot10^{-13}$	$7.6\cdot10^{-9}$	$4.9\cdot10^{-7}$
Abamectin 2	65195-55-3	ETP	$1.1\cdot10^{1}$	$4.9\cdot10^{-3}$	0.0	$2.6\cdot10^{-5}$	$1.4\cdot10^{-1}$	$1.1\cdot10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$7.8\cdot10^{-8}$	$1.4\cdot10^{-11}$	0.0	$7.4\cdot10^{-14}$	$1.2\cdot10^{-9}$	$8.0\cdot10^{-8}$
		HTP	$7.8\cdot10^{-8}$	$1.4\cdot10^{-11}$	0.0	$7.4\cdot10^{-14}$	$1.2\cdot10^{-9}$	$8.0\cdot10^{-8}$
Abamectin 3	65195-55-3	ETP	$3.5\cdot10^{1}$	$1.5\cdot10^{-5}$	0.0	$8.1\cdot10^{-5}$	$4.5\cdot10^{-1}$	$3.6\cdot10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$2.4\cdot10^{-7}$	$4.4\cdot10^{-11}$	0.0	$2.3\cdot10^{-13}$	$3.8\cdot10^{-9}$	$2.5\cdot10^{-7}$
		HTP	$2.4\cdot10^{-7}$	$4.4\cdot10^{-11}$	0.0	$2.3\cdot10^{-13}$	$3.8\cdot10^{-9}$	$2.5\cdot10^{-7}$
Abamectin 4	65195-55-3	ETP	$1.2\cdot10^{2}$	$5.1\cdot10^{-5}$	0.0	$2.7\cdot10^{-4}$	1.5	$1.2\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$8.1\cdot10^{-7}$	1.5·10-10	0.0	$7.7\cdot10^{-13}$	$1.3\cdot10^{-8}$	$8.3\cdot10^{-7}$
		HTP	$8.1\cdot10^{-7}$	1.5·10-10	0.0	$7.7\cdot10^{-13}$	$1.3\cdot10^{-8}$	$8.3\cdot10^{-7}$
Azoxystrobin 1	131860-33-8	ETP	$8.8\cdot10^{1}$	$4.7\cdot10^{-3}$	0.0	$6.2\cdot10^{-5}$	$3.5\cdot10^{2}$	$4.4\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Azoxystrobin 2	131860-33-8	ETP	$2.1\cdot10^{2}$	$1.1\cdot10^{-5}$	0.0	$1.5\cdot10^{-1}$	$8.2\cdot10^{2}$	$1.0\cdot10^{3}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0

Table 5.12. (cont.) Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Buprofezin	69327-76-0	ETP	$2.0\cdot10^{-1}$	$4.4\cdot10^{-4}$	0.0	$1.4\cdot10^{-4}$	$9.0\cdot10^{-1}$	1.1
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$1.2\cdot10^{-7}$	$5.6\cdot10^{-12}$	0.0	$1.8\cdot10^{-12}$	$9.5\cdot10^{-7}$	$1.1\cdot10^{-6}$
		HTP	$1.2\cdot10^{-7}$	$5.6\cdot10^{-12}$	0.0	$1.8\cdot10^{-12}$	$9.5\cdot10^{-7}$	$1.1\cdot10^{-6}$
Copper oxychloride	15158-11-9 (Cu(II))	ETP	$1.3\cdot10^{4}$	$3.3\cdot10^{-1}$	0.0	$1.1\cdot10^{1}$	$6.3\cdot10^{4}$	$7.7\cdot10^{4}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$2.2\cdot10^{-5}$	$7.9\cdot10^{-13}$	0.0	$2.7\cdot10^{-11}$	$2.4\cdot10^{-4}$	$2.6\cdot10^{-4}$
		HTP	$2.2\cdot10^{-5}$	$7.9\cdot10^{-13}$	0.0	$2.7\cdot10^{-11}$	$2.4\cdot10^{-4}$	$2.6\cdot10^{-4}$
Copper sulfate	15158-11-9 (Cu(II))	ETP	$4.8\cdot10^{3}$	$1.2\cdot10^{-1}$	0.0	4.0	$2.2\cdot10^{4}$	$2.7\cdot10^{4}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$7.9\cdot10^{-6}$	$2.8\cdot10^{-13}$	0.0	$9.7\cdot10^{-12}$	$8.6\cdot10^{-5}$	$9.4\cdot10^{-5}$
		HTP	$7.9\cdot10^{-6}$	$2.8\cdot10^{-13}$	0.0	$9.7\cdot10^{-12}$	$8.6\cdot10^{-5}$	$9.4\cdot10^{-5}$
Cuprous oxide	15158-11-9 (Cu(II))	ETP	$2.8\cdot10^{4}$	$6.7\cdot10^{-1}$	0.0	$2.3\cdot10^{1}$	$1.3\cdot10^{5}$	$1.6\cdot10^{5}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$4.6\cdot10^{-5}$	$1.6\cdot10^{-12}$	0.0	$5.6\cdot10^{-11}$	$5.0\cdot10^{-4}$	$5.4\cdot10^{-4}$
		HTP	$4.6\cdot10^{-5}$	$1.6\cdot10^{-12}$	0.0	$5.6\cdot10^{-11}$	$5.0\cdot10^{-4}$	$5.4\cdot10^{-4}$
Difenoconazole 1	119446-68-3	ETP	$6.4\cdot10^{1}$	$1.8\cdot10^{-5}$	0.0	$1.3\cdot10^{-5}$	$7.4\cdot10^{1}$	$1.4\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Difenoconazole 2	119446-68-3	ETP	$1.1\cdot10^{2}$	$3.1\cdot10^{-5}$	0.0	$2.3\cdot10^{-5}$	$1.3\cdot10^{2}$	$2.4\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Difenoconazole 3	119446-68-3	ETP	$1.7\cdot10^{1}$	$4.7\cdot10^{-3}$	0.0	$3.5\cdot10^{-3}$	$2.0\cdot10^{1}$	$3.6\cdot10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0

Table 5.12. (cont.) Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Diuron 1	330-54-1	ETP	$3.6\cdot10^{2}$	$3.6\cdot10^{-5}$	0.0	$1.8\cdot10^{-1}$	$1.0\cdot10^{3}$	$1.4\cdot10^{3}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$1.5\cdot10^{-7}$	$3.9\cdot10^{-12}$	0.0	$2.0\cdot10^{-11}$	$8.2\cdot10^{-7}$	$9.8\cdot10^{-7}$
		HTP	$1.5\cdot10^{-7}$	$3.9\cdot10^{-12}$	0.0	$2.0\cdot10^{-11}$	$8.2\cdot10^{-7}$	$9.8\cdot10^{-7}$
Diuron 2	330-54-1	ETP	$3.5\cdot10^{2}$	$3.4\cdot10^{-5}$	0.0	$1.7\cdot10^{-1}$	$9.8\cdot10^{2}$	$1.3\cdot10^{3}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$1.5\cdot10^{-7}$	$3.7\cdot10^{-12}$	0.0	$1.9\cdot10^{-11}$	$7.9\cdot10^{-7}$	$9.4\cdot10^{-7}$
		HTP	$1.5\cdot10^{-7}$	$3.7\cdot10^{-12}$	0.0	$1.9\cdot10^{-11}$	$7.9\cdot10^{-7}$	$9.4\cdot10^{-7}$
2,4-D isopropyl ester	94-75-7 (2-(2,4-dichlorophenoxy)acetic acid)	ETP	$1.5\cdot10^{-1}$	$2.5\cdot10^{-5}$	0.0	$5.2\cdot10^{-5}$	$2.9\cdot10^{-1}$	$4.4\cdot10^{-1}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$2.3\cdot10^{-9}$	$1.7\cdot10^{-13}$	0.0	$3.5\cdot10^{-13}$	$1.1\cdot10^{-8}$	$1.3\cdot10^{-8}$
		HTP	$2.3\cdot10^{-9}$	$1.7\cdot10^{-13}$	0.0	$3.5\cdot10^{-13}$	$1.1\cdot10^{-8}$	$1.3\cdot10^{-8}$
Flumioxazin 1	103361-09-7	ETP	$1.5\cdot10^{1}$	$3.3\cdot10^{-5}$	0.0	$6.8\cdot10^{-5}$	$3.8\cdot10^{2}$	$4.0\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Flumioxazin 2	103361-09-7	ETP	$1.3\cdot10^{1}$	$2.7\cdot10^{-5}$	0.0	$5.6\cdot10^{-5}$	$3.1\cdot10^{2}$	$3.3\cdot10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	n/a	n/a	n/a	n/a	n/a	0.0
Gibberellic acid	77-06-5	ETP	n/a	n/a	n/a	n/a	n/a	0.0
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		HTP	0.0	0.0	0.0	0.0	0.0	0.0

Table 5.12. (cont.) Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Glyphosate 1	1071-83-6	ETP	5.1	$2.4·10^{-4}$	0.0	$3.5·10^{-3}$	$2.0·10^{1}$	$2.5·10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$5.4·10^{-9}$	$1.2·10^{-13}$	0.0	$1.8·10^{-12}$	$3.2·10^{-8}$	$3.7·10^{-8}$
		HTP	$5.4·10^{-9}$	$1.2·10^{-13}$	0.0	$1.8·10^{-12}$	$3.2·10^{-8}$	$3.7·10^{-8}$
Glyphosate 2	1071-83-6	ETP	7.3	$3.5·10^{-4}$	0.0	$5.1·10^{-3}$	$2.8·10^{1}$	$3.6·10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$7.8·10^{-9}$	$1.7·10^{-13}$	0.0	$2.5·10^{-12}$	$4.6·10^{-8}$	$5.4·10^{-8}$
		HTP	$7.8·10^{-9}$	$1.7·10^{-13}$	0.0	$2.5·10^{-12}$	$4.6·10^{-8}$	$5.4·10^{-8}$
Glyphosate 3	1071-83-6	ETP	4.7	$2.2·10^{-4}$	0.0	$3.3·10^{-3}$	$1.8·10^{1}$	$2.3·10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$5.1·10^{-9}$	$1.1·10^{-13}$	0.0	$1.6·10^{-12}$	$3.0·10^{-8}$	$3.5·10^{-8}$
		HTP	$5.1·10^{-9}$	$1.1·10^{-13}$	0.0	$1.6·10^{-12}$	$3.0·10^{-8}$	$3.5·10^{-8}$
Glyphosate 4	1071-83-6	ETP	2.4	$1.1·10^{-4}$	0.0	$1.6·10^{-3}$	9.2	$1.2·10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$2.5·10^{-9}$	$5.6·10^{-14}$	0.0	$8.2·10^{-13}$	$1.5·10^{-8}$	$1.7·10^{-8}$
		HTP	$2.5·10^{-9}$	$5.6·10^{-14}$	0.0	$8.2·10^{-13}$	$1.5·10^{-8}$	$1.7·10^{-8}$
Glyphosate 5	1071-83-6	ETP	$1.8·10^{-1}$	$8.4·10^{-6}$	0.0	$1.2·10^{-4}$	$6.9·10^{-1}$	$8.7·10^{-1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$1.9·10^{-10}$	$4.2·10^{-15}$	0.0	$6.2·10^{-14}$	$1.1·10^{-9}$	$1.3·10^{-9}$
		HTP	1.9·10-10	$4.2·10^{-15}$	0.0	$6.2·10^{-14}$	$1.1·10^{-9}$	$1.3·10^{-9}$
Mancozeb 1	8018-1-7	ETP	$1.2·10^{3}$	$2.6·10^{-1}$	0.0	$6.3·10^{-1}$	$3.6·10^{3}$	$4.8·10^{3}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$8.7·10^{-8}$	$1.1·10^{-11}$	0.0	$2.6·10^{-11}$	$3.8·10^{-7}$	$4.6·10^{-7}$
		HTP	$8.7·10^{-8}$	$1.1·10^{-11}$	0.0	$2.6·10^{-11}$	$3.8·10^{-7}$	$4.6·10^{-7}$
Mancozeb 2	8018-1-7	ETP	$4.6·10^{2}$	$9.9·10^{-5}$	0.0	$2.4·10^{-1}$	$1.4·10^{3}$	$1.8·10^{3}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$3.3·10^{-8}$	$4.1·10^{-12}$	0.0	$9.9·10^{-12}$	$1.4·10^{-7}$	$1.8·10^{-7}$
		HTP	$3.3·10^{-8}$	$4.1·10^{-12}$	0.0	$9.9·10^{-12}$	$1.4·10^{-7}$	$1.8·10^{-7}$
Mancozeb 3	8018-1-7	ETP	$2.6·10^{2}$	$5.5·10^{-5}$	0.0	$1.4·10^{-1}$	$7.6·10^{2}$	$1.0·10^{3}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$1.9·10^{-8}$	$2.3·10^{-12}$	0.0	$5.6·10^{-12}$	$8.0·10^{-8}$	$9.9·10^{-8}$
		HTP	$1.9·10^{-8}$	$2.3·10^{-12}$	0.0	$5.6·10^{-12}$	$8.0·10^{-8}$	$9.9·10^{-8}$

Table 5.12. (cont.) Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Paraffinic oil	-	ETP	$2.6{\cdot}10^{-4}$	$2.3{\cdot}10^{-9}$	0.0	$1.5{\cdot}10^{-7}$	$8.6{\cdot}10^{-4}$	$1.1{\cdot}10^{-3}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$3.3{\cdot}10^{-8}$	$3.0{\cdot}10^{-13}$	0.0	$2.0{\cdot}10^{-11}$	$1.1{\cdot}10^{-7}$	$1.4{\cdot}10^{-7}$
		HTP	$3.3{\cdot}10^{-8}$	$3.0{\cdot}10^{-13}$	0.0	$2.0{\cdot}10^{-11}$	$1.1{\cdot}10^{-7}$	$1.4{\cdot}10^{-7}$
Paraquat 1	4685-14-7	ETP	$1.4{\cdot}10^{2}$	$2.1{\cdot}10^{-5}$	0.0	$6.1{\cdot}10^{-5}$	$3.4{\cdot}10^{2}$	$4.8{\cdot}10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$1.4{\cdot}10^{-8}$	$8.8{\cdot}10^{-13}$	0.0	$2.6{\cdot}10^{-12}$	$3.3{\cdot}10^{-8}$	$4.8{\cdot}10^{-8}$
		HTP	$1.4{\cdot}10^{-8}$	$8.8{\cdot}10^{-13}$	0.0	$2.6{\cdot}10^{-12}$	$3.3{\cdot}10^{-8}$	$4.8{\cdot}10^{-8}$
Paraquat 2	4685-14-7	ETP	$2.5{\cdot}10^{2}$	$3.5{\cdot}10^{-5}$	0.0	$1.0{\cdot}10^{-1}$	$5.8{\cdot}10^{2}$	$8.3{\cdot}10^{2}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$2.4{\cdot}10^{-8}$	$1.5{\cdot}10^{-12}$	0.0	$4.5{\cdot}10^{-12}$	$5.7{\cdot}10^{-8}$	$8.1{\cdot}10^{-8}$
		HTP	$2.4{\cdot}10^{-8}$	$1.5{\cdot}10^{-12}$	0.0	$4.5{\cdot}10^{-12}$	$5.7{\cdot}10^{-8}$	$8.1{\cdot}10^{-8}$
Paraquat 3	4685-14-7	ETP	$2.5{\cdot}10^{1}$	$3.6{\cdot}10^{-3}$	0.0	$1.1{\cdot}10^{-5}$	$5.9{\cdot}10^{1}$	$8.4{\cdot}10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$2.5{\cdot}10^{-9}$	$1.5{\cdot}10^{-13}$	0.0	$4.5{\cdot}10^{-13}$	$5.7{\cdot}10^{-9}$	$8.2{\cdot}10^{-9}$
		HTP	$2.5{\cdot}10^{-9}$	$1.5{\cdot}10^{-13}$	0.0	$4.5{\cdot}10^{-13}$	$5.7{\cdot}10^{-9}$	$8.2{\cdot}10^{-9}$
Phosmet	732-11-6	ETP	$3.0{\cdot}10^{1}$	$1.7{\cdot}10^{-5}$	0.0	$8.9{\cdot}10^{-3}$	$5.0{\cdot}10^{1}$	$8.0{\cdot}10^{1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	4.8·10-10	$9.9{\cdot}10^{-14}$	0.0	$5.2{\cdot}10^{-14}$	$2.2{\cdot}10^{-9}$	$2.7{\cdot}10^{-9}$
		HTP	4.8·10-10	$9.9{\cdot}10^{-14}$	0.0	$5.2{\cdot}10^{-14}$	$2.2{\cdot}10^{-9}$	$2.7{\cdot}10^{-9}$
Pyrachlostrobin 1	175013-18-0	ETP	$3.9{\cdot}10^{-7}$	$3.6{\cdot}10^{-12}$	0.0	2.3·10-10	$1.3{\cdot}10^{-6}$	$1.7{\cdot}10^{-6}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$1.4{\cdot}10^{-6}$	$1.3{\cdot}10^{-11}$	0.0	8.4·10-10	$4.7{\cdot}10^{-6}$	$6.1{\cdot}10^{-6}$
		HTP	$1.4{\cdot}10^{-6}$	$1.3{\cdot}10^{-11}$	0.0	8.4·10-10	$4.7{\cdot}10^{-6}$	$6.1{\cdot}10^{-6}$
Pyrachlostrobin 2	175013-18-0	ETP	$1.6{\cdot}10^{-7}$	$1.4{\cdot}10^{-12}$	0.0	$9.3{\cdot}10^{-11}$	$5.2{\cdot}10^{-7}$	$6.8{\cdot}10^{-7}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$5.6{\cdot}10^{-7}$	$5.1{\cdot}10^{-12}$	0.0	3.3·10-10	$1.9{\cdot}10^{-6}$	$2.4{\cdot}10^{-6}$
		HTP	$5.6{\cdot}10^{-7}$	$5.1{\cdot}10^{-12}$	0.0	3.3·10-10	$1.9{\cdot}10^{-6}$	$2.4{\cdot}10^{-6}$

Table 5.12. (cont.) Toxicity impacts of pesticides used in mandarin cultivation in Uruguay considering the amount of active principle applied

Substance Name	CAS No.	Type*	Initial emission compartment					Total
			Air	Fresh water	Sea water	Indust. soil	Agricul. soil	
Pyriproxyfen 1	95737-68-1	ETP	$3.2 \cdot 10^{-1}$	$1.4 \cdot 10^{-3}$	0.0	$1.9 \cdot 10^{-5}$	$1.1 \cdot 10^{-1}$	$4.3 \cdot 10^{-1}$
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$1.6 \cdot 10^{-10}$	$1.6 \cdot 10^{-14}$	0.0	$5.4 \cdot 10^{-16}$	$5.4 \cdot 10^{-11}$	$2.1 \cdot 10^{-10}$
		HTP	$1.6 \cdot 10^{-10}$	$1.6 \cdot 10^{-14}$	0.0	$5.4 \cdot 10^{-16}$	$5.4 \cdot 10^{-11}$	$2.1 \cdot 10^{-10}$
Pyriproxyfen 2	95737-68-1	ETP	1.6	$6.6 \cdot 10^{-3}$	0.0	$9.0 \cdot 10^{-5}$	$5.1 \cdot 10^{-1}$	2.1
		Carc.	n/a	n/a	n/a	n/a	n/a	0.0
		Non-Carc.	$7.6 \cdot 10^{-10}$	$7.5 \cdot 10^{-14}$	0.0	2.6·10-15	$2.6 \cdot 10^{-10}$	$1.0 \cdot 10^{-9}$
		HTP	$7.6 \cdot 10^{-10}$	$7.5 \cdot 10^{-14}$	0.0	2.6·10-15	$2.6 \cdot 10^{-10}$	$1.0 \cdot 10^{-9}$
Spinosad	168316-95-8	ETP	$8.1 \cdot 10^{-4}$	$7.4 \cdot 10^{-9}$	0.0	$4.8 \cdot 10^{-7}$	$2.7 \cdot 10^{-3}$	$3.5 \cdot 10^{-3}$
		Carc.	0.0	0.0	0.0	0.0	0.0	0.0
		Non-Carc.	$5.5 \cdot 10^{-8}$	$5.0 \cdot 10^{-13}$	0.0	$3.3 \cdot 10^{-11}$	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$
		HTP	$5.5 \cdot 10^{-8}$	$5.0 \cdot 10^{-13}$	0.0	$3.3 \cdot 10^{-11}$	$1.8 \cdot 10^{-7}$	$2.4 \cdot 10^{-7}$

*Ecotoxicity potential (ETP) is estimated in PAF.m^3.day. Human toxicity potential (HTP) is estimated in cases and is the sum of the carcinogenic (HTPc) and the noncarcinogenic (HTPnc) human toxicity potentials.
n/a: not available.

Table 5.13. Evaporation (Evap, mm), absorption (Abs, mm) and blue water consumption (BWC) calculated performing a water balance in the soil using LEACHM model (Hutson and Wagenet, 1992), for the six seasons of study

	2016-2017			2017-2018			2018-2019			2019-2020			2020-2021			2021-2022		
Month	Evap (mm)	Abs (mm)	BWC (mm)	Evap (mm)	Abs (mm)	BWC (mm)	Evap (mm)	Abs (mm)	BWC (mm)	Evap (mm)	Abs (mm)	BWC (mm)	Evap (mm)	Abs (mm)	BWC (mm)	Evap (mm)	Abs (mm)	BWC (mm)
Aug	34.34	24.86	59.2	33.7	24.4	58.1	29.24	21.16	50.4	30.5	22.04	52.54	16.7	23.1	39.8	31.32	26.48	57.8
Sept	41.9	35.18	77.08	49.22	34.82	84.04	44.72	32.26	76.98	40.62	34.54	75.16	43.14	35.4	78.54	45.58	33.42	79
Oct	42.54	42.82	85.36	51.38	42.72	94.1	59.7	50.38	110.08	55.12	40.64	95.76	12.3	42.76	55.06	42.2	51.84	94.04
Nov	56.26	53.96	110.22	52.48	55.58	108.06	43.32	56.44	99.76	68.42	56.82	125.24	16.08	55.36	71.44	30.94	62.2	93.14
Dec	77.98	60.32	138.3	13.66	60.98	74.64	45.2	58.2	103.4	60.24	59.78	120.02	40.34	63.36	103.7	14.7	71.46	86.16
Jan	62.02	57.58	119.6	30.84	58.1	88.94	64.7	49.94	114.64	75.98	62.84	138.82	32.84	56.46	89.3	86.96	68.12	155.08
Feb	58.54	44.72	103.26	25.28	44.34	69.62	44.94	46.46	91.4	52.84	55.82	108.66	62.24	57.12	119.36	50.7	55.12	105.82
Mar	59.16	45.54	104.7	27.58	46.34	73.92	47.04	40.44	87.48	18.06	46.6	64.66	41.52	33.66	75.18	55.16	39.94	95.1
Apr	34.02	28.8	62.82	21.92	28.1	50.02	21.78	22.7	44.48	18.44	28.84	47.28	40.36	29.18	69.54	30.28	28.4	58.68
May	21.82	15.84	37.66	21.22	15.66	36.88	20.82	15.12	35.94	26.62	19.28	45.9	22.56	16.38	38.94	23.94	17.34	41.28
Jun	18.62	13.48	32.1	18.62	13.48	32.1	17.7	12.76	30.46	16.02	11.64	27.66	18.28	13.22	31.5	16.24	11.72	27.96
Jul	26.86	18.44	45.3	26.86	18.38	45.24	20.22	13.78	34	18.62	13.52	32.14	26.8	18.4	45.2	23.62	16.12	39.74
Tot	**534.1**	**441.5**	**975.6**	**372.8**	**442.9**	**815.7**	**459.4**	**419.6**	**879.0**	**481.5**	**452.4**	**933.8**	**373.2**	**444.4**	**817.6**	**451.6**	**482.2**	**933.8**

Table 5.13. (cont.) Evaporation (Evap, mm), absorption (Abs, mm) and blue water consumption (BWC) calculated performing a water balance in the soil using LEACHM model (Hutson and Wagenet, 1992), for the six seasons of study

Year	Evaporation (mm)	Absorption (mm)	BWC (mm)
2016-2017	534.06	441.54	975.60
2017-2018	372.76	442.90	815.66
2018-2019	459.38	419.64	879.02
2019-2020	481.48	452.36	933.84
2020-2021	373.16	444.40	817.56
2021-2022	451.64	482.16	933.80

Table 5.14. Characterisation factors used for regionalisation of emitted flows and the corresponding non-regionalised ones

Impact category	Emitted flow	Global scale	Native resolution scale
MEu	NO_x	$2.11 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$
MEu	NH_3	$5.67 \cdot 10^{-2}$	$4.0 \cdot 10^{-2}$
FEu	Phosphate	$3.18 \cdot 10^{-1}$	$2.0 \cdot 10^{-2}$
TAc	NO_x	$9.82 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$
TAc	NH_3	$3.70 \cdot 10^{-3}$	$7.3 \cdot 10^{-4}$
FWAc	NO_x	$1.11 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$
FWAc	NH_3	$1.96 \cdot 10^{-6}$	$5.0 \cdot 10^{-7}$

Marine Eutrophication (MEu), Freshwater Eutrophication (FEu), Terrestrial Acidification (TAc), Freshwater Acidification (FWAc). The hyphen refers to the fact that there is no emission of the referred flow at that stage of the process.

Table 5.15. Information from Life Cycle Assessment studies of mandarin production in diverse locations, including yields, N and P_2O_5

							Methods for on-field emissions estimation					Impacts at farm gate per 1 kg citrus fruit				
Reference	Crop	Geographical location	Yield (tonne $\cdot ha^{-1}$)	N rate (kg $\cdot ha^{-1}$)	P_2O_5 rate (kg $\cdot ha^{-1}$)	Impact assessment method	N_2O	NH_3	NO_3^-	NOx	PO_4^{3-}	CC (kg CO_2 eq.)	FEu (kg P eq.)	MEu (kg N eq.)	TAc (kg SO_2 eq.)	WC related (m^3 eq.)
This study	Mandarin	Paysandú, Uruguay	35.8	68.3	1.8	EN 15804 +A2, Impact 2002+ v2.1., AWARE USEtox 2.0	LEACHN (Hutson and Wagenet 1992), IPCC (2006) + 2019 update	LEACHN (Hutson and Wagenet 1992)	LEACHN (Hutson and Wagenet 1992)	EEA (2019)	SALCA-P model (Nemecek et al. 2019)	0.05	$2.75 \cdot 10^{-5}$	$7.35 \cdot 10^{-4}$	$1.19 \cdot 10^{-2}$	0.11 (BWS)
Bessou et al. (2016)	Mandarin	Beni Mellal, Morocco	42.1	213.9	64.9	ReCiPe 2008	IPCC (2006) - direct Indirect not accounted for	Nemecek and Kägi (2007)	Brentrup et al. (2000)	Nemecek and Kägi (2007)	Nemecek and Kägi (2007)	0.40	$6.32 \cdot 10^{-5}$	$2.65 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$	0.25 (WD)
Cabot et al. (2023a)	Lemon	San José, Uruguay	56	203.1	8.5	EN 15804 +A2, AWARE USEtox 2.0	(IPCC 2006) + 2019 update	EEA (2019)	SQCB-NO_3 model (Emmenegger et al. 2009)	EEA (2019)	SALCA-P model (Nemecek et al. 2019)	0.09	$2.45 \cdot 10^{-5}$	$4.35 \cdot 10^{-3}$	***	0.12 (BWS)
Martin-Gorriz et al. (2020)	Mandarin	Murcia, Spain	22.5	214	43	CML 2001	IPCC (2006)	EEA (2016)	Martínez-Alcantara et al. (2012)	Sanz-Cobena et al. (2014)	Nemecek and Kägi (2007)	0.38	**		***	*
Ribal et al. (2017)	Citrus fruits	Comunitat Valenciana, Spain	33.4	164.8	51.8	CML 2001	IPCC (2006)	EEA (2013)	% of N input from nitrate balances for the region	-	Not considered	0.31	**		***	*

Table 5.15. (cont.) Information from Life Cycle Assessment studies of mandarin production in diverse locations, including yields, N and P_2O_5

							Methods for on-field emissions estimation					Impacts at farm gate per 1 kg citrus fruit				
Reference	Crop	Geographical location	Yield (tonne $\cdot ha^{-1}$)	N rate (kg $\cdot ha^{-1}$)	P_2O_5 rate (kg $\cdot ha^{-1}$)	Impact assessment method	N_2O	NH_3	NO_3^-	NOx	PO_4^{3-}	CC (kg CO_2 eq.)	FEu (kg P eq.)	MEu (kg N eq.)	TAc (kg SO_2 eq.)	WC related (m^3 eq.)
Yang et al. (2020)	Citrus fruits	Danling County, Sichuan, southwest China	24.4	847	443	Bibliography emission indexes	IPCC (2006)	Ti et. Al. (2005)	Zhao et. al. (2010)	Perrin et al. (2014)	Wang et. al. (2007) Chen et. al. (2011)	0.64	**		***	*

CC: climate change; FEu: freshwater eutrophication; MEu: Marine eutrophication; TAc: Terrestrial Acidification WC: Water Consumption related impact; BWS: Blue Water Scarcity; WD: Water Depletion

*: impact not estimated; **: authors do not discern between freshwater and marine eutrophication; ***: authors do not discern between terrestrial and aquatic acidification

Fig. 5.4. Boxplot representing the probability distribution of N on field emissions modelled with the five methods tested.

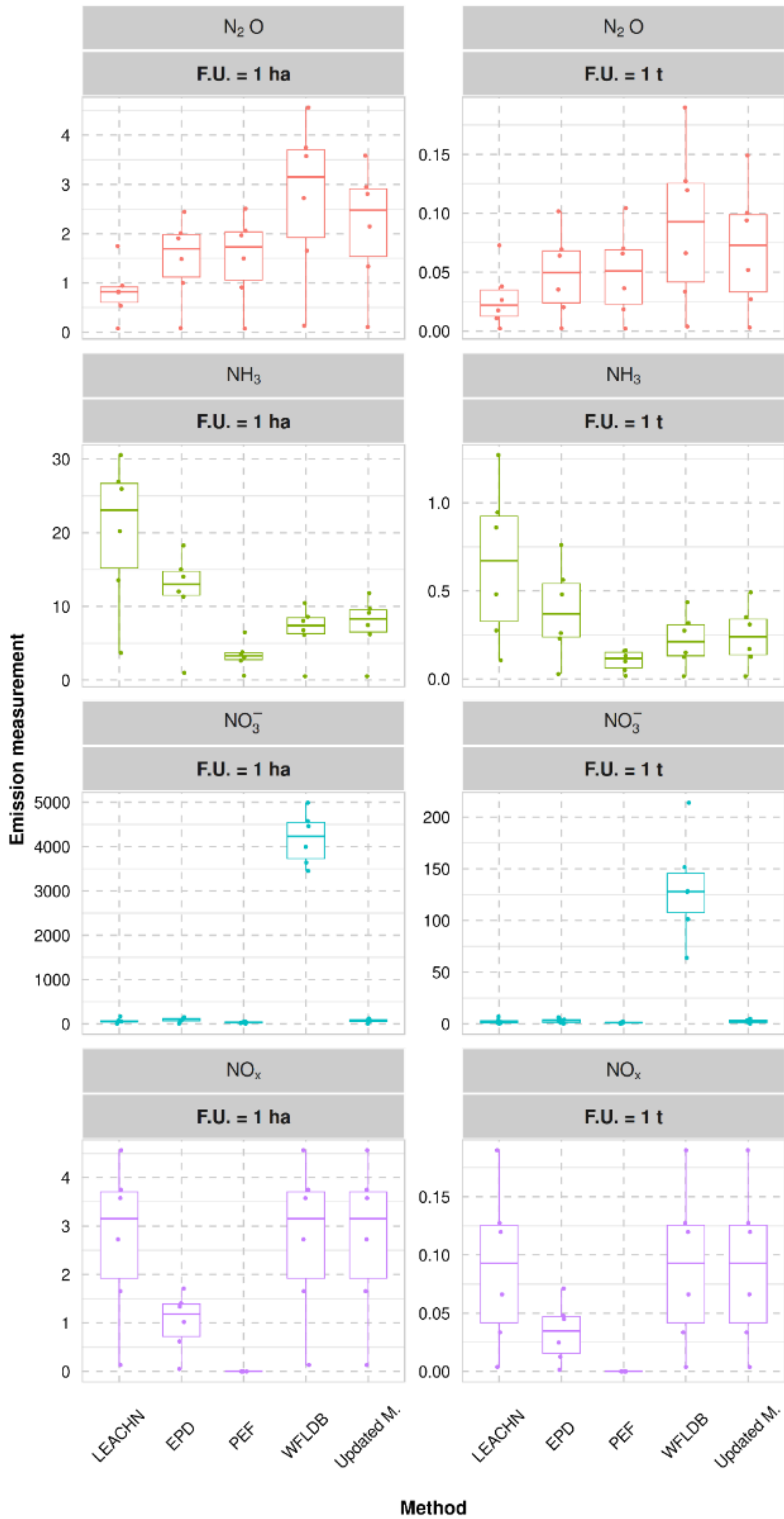
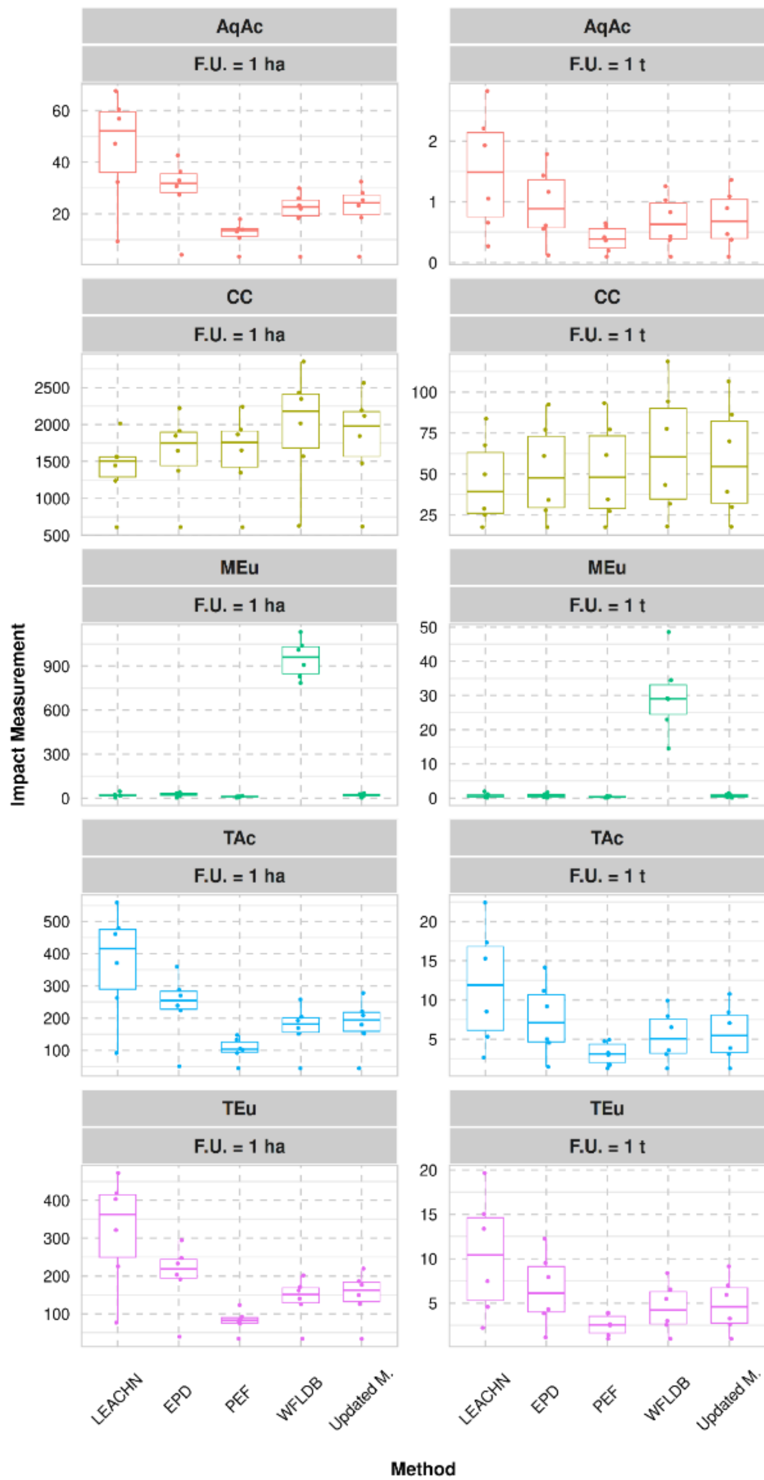


Fig. 5.5. Boxplot representing the probability distribution of LCA results for the six seasons of study for the selected impact categories considering the different modelling of N on field emissions.



Eq. 5.1. Supplementary Material S1 Penman-Monteith equation

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

ETo - reference evapotranspiration (mm·day^{-1})

R_n - net radiation at the crop surface (MJ·m^{-2}day^{-1})

G - soil heat flux density (MJ·m^{-2}day^{-1})

T - mean daily air temperature at 2 m height (°C)

u_2 - wind speed at 2 m height (m·s^{-1})

e_s - saturation vapour pressure(kPa)

e_a - actual vapour pressure (kPa)

e_s-e_a - saturation vapour pressure deficit (kPa)

Δ - slope vapour pressure curve (kPa·°C^{-1})

Eq. 5.2. Numerical integration of Richards' equation and convection-dispersion equation for solute transport

The Richards equation to calculate the flow of water in unsaturated soils is derived from Darcy's law and the continuity equation:

$$\frac{\delta\theta}{\delta t} = \frac{\delta(K(\theta)\frac{\delta H}{\delta z})}{\delta z} \quad - U_w(z,\ t)$$

H - hydraulic potential

K - hydraulic conductivity

z - depth

U_w - loss of water per unit of time due to transpiration

t - time

The resolution of this equation requires soil hydraulic parameters (θ-φ-K relationships), boundary conditions, evapotranspiration, irrigation and rainfall.

θ - volumetric moisture

φ - matrix potential

K - hydraulic conductivity

The relationship between moisture and matrix potential is given by the Campbell retentivity equation:

$$\varphi = a \cdot \frac{\theta}{\theta s} \ - b$$

θs - volumetric moisture at saturation

a, b - parameters related to pore size distribution

For hydraulic conductivity:

$$K(\theta) = Ks \cdot \frac{\theta}{\theta s}^{-2b+2+p}$$

Ks - hydraulic conductivity at saturation

b - constant

p - setting parameter (1 in the version used)

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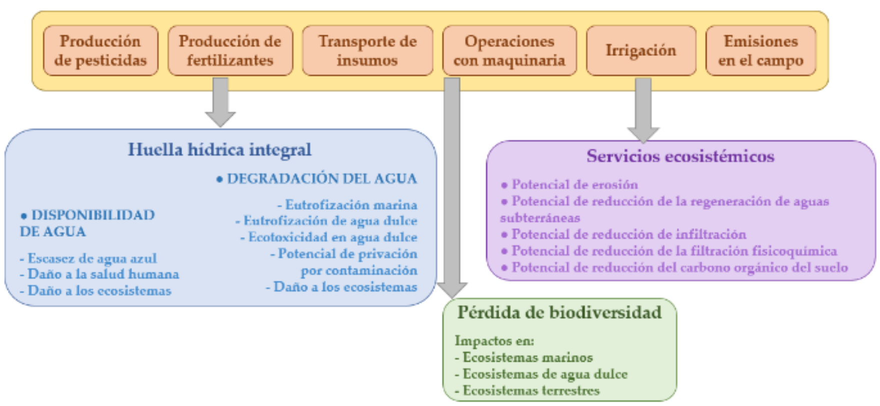
El **capítulo 6** se basa en el siguiente artículo:

Cabot MI, Lado J, Sanjuán N. Addressing water footprint, ecosystem services and biodiversity in citrus LCAs: a case study in Uruguay. Enviado a la revista *Ecological Indicators*.

6. HUELLA HÍDRICA, SERVICIOS ECOSISTÉMICOS Y BIODIVERSIDAD EN LOS ACV CITRÍCOLAS: UN CASO DE ESTUDIO EN URUGUAY

Resumen gráfico:

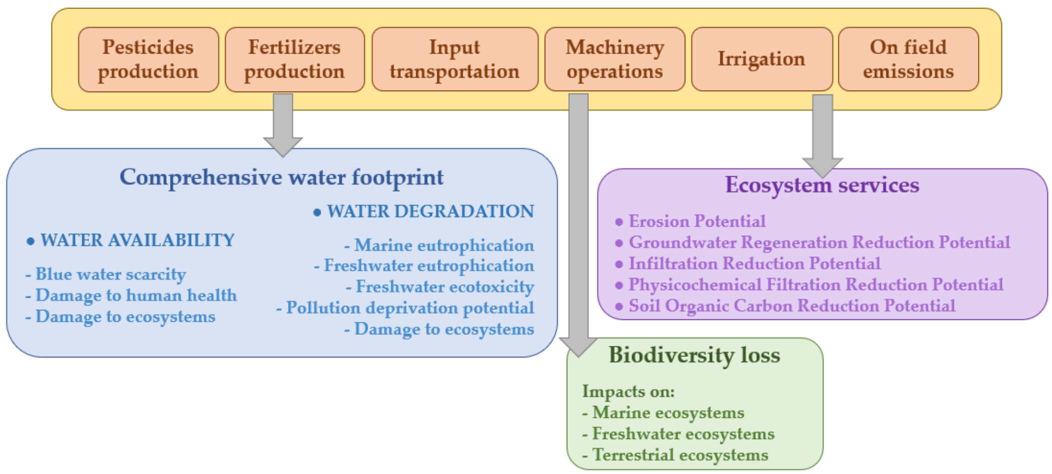


Resumen: algunos impactos ambientales reconocidos en los objetivos de desarrollo sostenible (ODS), como el uso y degradación del agua, la pérdida de biodiversidad y los efectos sobre los servicios ecosistémicos, a menudo no se consideran o se abordan parcialmente en los análisis de ciclo de vida agrícola (ACV) y, en particular, en aquellos de cítricos. Teniendo en cuenta que la naranja es el cítrico más importante del Uruguay en términos de toneladas producidas y superficie ocupada, este estudio tiene como objetivo cuantificar los impactos ambientales de la producción de naranja en Uruguay mediante ACV, con especial énfasis en los impactos antes mencionados. Con este objetivo, se han aplicado métodos actualizados basados en indicadores de punto medio y punto final bajo un enfoque de la cuna a la puerta del campo, utilizando unidades funcionales de masa y área. Los resultados muestran que el riego es el principal punto crítico detectado en el consumo de agua, tanto en cuanto a la escasez como al estrés hídrico, aunque en este último también destaca la producción de fertilizantes nitrogenados. Los principales puntos críticos detectados en la degradación del agua son las emisiones en el campo y la producción de pesticidas, especialmente el óxido de cobre. En cuanto a los impactos de punto final (es decir, el daño a los ecosistemas debido a la degradación del agua), destacan el transporte de insumos por barco y la producción de fertilizantes. La ocupación del suelo para la producción de naranja constituye la principal etapa crítica para la pérdida de servicios ecosistémicos, aunque afecta positivamente la regeneración de las aguas subterráneas. En cuanto a la pérdida de biodiversidad, el transporte de insumos es el principal impulsor detectado, principalmente por su contribución a la ecotoxicidad terrestre. Por lo tanto, dependiendo del impacto a minimizar, los esfuerzos deben enfocarse en diferentes etapas del proceso, para las cuales se proponen recomendaciones. Además, se destacan potenciales aspectos metodológicos para mejorar los métodos aplicados. Este estudio presenta la primera cuantificación de impactos ambientales no evaluados habitualmente en el cultivo de cítricos, con el objetivo de impulsar el desarrollo de ACV cítricolas más completos que consideren las diferentes áreas de la sostenibilidad ambiental.

Palabras clave: análisis de ciclo de vida; huella hídrica integral; servicios ecosistémicos; biodiversidad; frutas cítricas; sostenibilidad agrícola

6. ADDRESSING WATER FOOTPRINT, ECOSYSTEM SERVICES AND BIODIVERSITY IN CITRUS LCAS: A CASE STUDY IN URUGUAY

Graphical abstract:



Abstract: Some environmental impacts acknowledged in the Sustainable Development Goals (SDGs), such as water use and degradation, biodiversity loss, and the effects on ecosystem services, are often neglected or partially addressed in agricultural Life Cycle Assessments (LCAs) and, in particular, in those on citrus fruits. Taking into account that orange is Uruguay's most important citrus fruit in terms of tonnes produced and the area occupied, this study aims to quantify the environmental impacts of orange production in Uruguay using LCA, with a special focus on the aforementioned impacts. To this aim, updated methods based on both midpoint and endpoint indicators have been applied under a cradle-to-farm gate approach and using mass and area functional units. Results show that irrigation is the main hotspot detected in water consumption, both in water scarcity and water stress, although in the latter, the production of N fertilisers also stands out. The main hotspots detected in water degradation are on-field

emissions and pesticide production, especially copper oxide. At the endpoint level (i.e., ecosystem damage due to water degradation), input transportation by ship and fertiliser production stand out. Land occupation for orange production constitutes the main critical stage for ecosystem services loss, although it positively affects groundwater regeneration. As for biodiversity loss, input transportation is the main driver detected, mainly because of its contribution to terrestrial ecotoxicity. Therefore, depending on the impact to be minimised, efforts should be focused on different stages of the process for which recommendations are proposed. In addition, potential methodological aspects to improve the methods applied have been highlighted. This study presents the first quantification of environmental impacts not usually evaluated in citrus cultivation, with the aim to boost the development of more complete citrus LCAs which consider the different areas of environmental sustainability.

Keywords: Life Cycle Assessment; Comprehensive water footprint; Ecosystem services; Biodiversity; Citrus fruits; Agricultural sustainability

6.1. INTRODUCTION

Agriculture generates many widely recognised environmental impacts. Among the negative ones are those related to unsustainable use of vital resources, which cause air, water, and land pollution, degrading soil and threatening various species. These environmental problems are evident in intensive crop production, such as citrus fruit production, which has a high degree of interaction with natural resources. In particular, water constitutes a fundamental resource, and agriculture uses 70% of all water withdrawals globally (FAO, 2021), thereby contributing to the drying-up of water bodies and changing the distribution of soil moisture. Likewise, agriculture has an influence on water pollution due to its direct link with eutrophication and toxic emissions (Cabot et al., 2022). Agriculture affects another relevant resource, the soil, impacting on the ecosystem services provided. Land transformation and occupation for agricultural purposes, together with the indirect effects caused by the exchanges with the environment along the supply chain, also have a direct effect on biodiversity loss. These environmental pressures are expected to increase in the coming decades and represent a significant concern acknowledged by governments and economic stakeholders (WEF, 2023; UN, 2023a), highlighting the need to transition to sustainable agricultural systems.

The concept of sustainable agriculture makes it possible to define the main environmental effects of agriculture and the major environmental challenges facing its development (Pretty, 2005; Pretty, 2012). In this line, the 2030 Agenda for Sustainable Development sets indicators for assessing sustainability based on its three dimensions. Besides SDG 2, "Zero hunger", and SDG 13, "Climate action", which are the key goals to attain sustainable development in agriculture (Streimikis and Baležentis, 2020), SDG 6 and SDG 15 are linked to the environmental dimension of agriculture. SDG 6, “Clean water and sanitation”, is related to water management and, in particular, targets 6.3 and 6.4 (UN, 2023b) aim at improving water quality and availability. The former refers to improving water quality by reducing pollution, eliminating dumping, and minimising the release of hazardous chemicals and materials, and the latter to ensuring sustainable withdrawals and supply of freshwater to address water scarcity. SDG 15, "Life on land", focuses on the impacts related to land use. As to ecosystem services, target 15.1 reads, "Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services" (UN, 2023c). Within the different environmental compartments, the soil offers several ecosystem services, including regulating services such as water purification and erosion regulation (MEA, 2005); therefore, land use occupation and land use transformation for agricultural purposes have a direct influence on them. Target 15.5 copes with the prevention of biodiversity loss and refers to the importance of taking urgent and significant action to reduce the degradation of natural habitats and halt biodiversity loss (UN, 2023c).

Meeting the SDGs requires appropriate assessment tools to examine the environmental performance of agricultural systems, and Life Cycle Assessment (LCA) is a widely used methodology to assess these systems (see, for instance, Coltro and Karaski, 2019; Milà I Canals et al., 2006; Vázquez-Rowe et al., 2012). However, operational indicators for water use and degradation, soil quality impacts, and biodiversity loss have been recently developed and, at the moment, are not often applied in the LCA literature. Consequently, the information provided by many agricultural LCAs needs to be completed to be suitable for decision-making, as trade-offs among different environmental aspects should be better emphasised (van der Werf et al., 2020). Site-specific assessment methods are pertinent for quantifying these indicators, as this is a relevant aspect in agricultural systems whose impacts exhibit high dependency on the site (Cabot et al., 2023b).

To support decision-makers in achieving sustainable management of water resources, a holistic water use assessment is needed, and the water footprint (WF) concept (Hoekstra and Chapagain, 2011) has been designed to cope with this. As Boulay et al. (2013) state, there are two different, although complementary, approaches to estimating the WF, according to the Water Footprint Network (Hoekstra et al., 2012) and according to the ISO 14046 standard (ISO, 2014). The former is connected with a physical boundary represented by a hydrogeographic region, and the latter follows an LCA approach and thus focuses on a product system boundary (Lathuillière et al., 2018). A harmonised WF assessment that considers both approaches has been proposed by Lathuillière et al. (2018) and further developed by Pierrat et al. (2023). To account for all the environmental effects associated with water use, a comprehensive water footprint assessment must consider all environmentally relevant attributes or aspects of the natural environment, human health and resources related to water, including water availability and water degradation (ISO, 2014). Under the LCA approach, this implies the use of both midpoint and endpoint indicators since the consumptive use of water reduces water availability (calculated with midpoint indicators) but also leads to water stress, which causes damage to human health, wetlands, and terrestrial systems (Verones et al., 2017). As well, direct emissions to water generate water pollution, reducing water availability (both calculated with midpoint indicators) and leading to species loss too.

According to the Millennium Ecosystem Assessment Report (MEA, 2005), the main direct drivers of change in ecosystems are habitat change (e.g., due to land use change), overexploitation, invasive alien species, pollution, and climate change. The soil offers several ecosystem services, including regulating services such as water purification and erosion regulation (MEA, 2005). Therefore, land use occupation and transformation for agricultural purposes directly influence them. They also tend to be the main drivers of biodiversity loss (MEA, 2005), which is why, when assessing the impacts on biodiversity, the focus is generally on them. However, it is acknowledged that other impacts related to food production systems should also be considered as they drive biodiversity decline (Crenna et al., 2019; Sanyé-Mengual et al., 2022). To this aim, the usefulness of endpoint indicators stands out, as they reflect the environmental impacts at a further level of the cause-effect chain. By quantifying the effects of environmental impacts on ecosystem quality, the loss of species in terrestrial, freshwater, and marine ecosystems integrated over space and time is addressed (Huijbregts et al., 2017).

LCA has been widely used to quantify the environmental impacts of orange fruit (e.g., Alishah et al., 2019; Bell and Horvath, 2020; Bonales-Revuelta et al., 2022; Martin-Gorriz et al., 2020). However, none of these studies quantifies the water footprint considering the availability and degradation of the water used, nor the impacts on biodiversity or ecosystem services due to land use. This study aims to fulfil this gap, focusing on Uruguay's orange production as a case study. Specifically, orange is the main citrus crop in Uruguay, both in terms of the productive area occupied (5,675 ha in 2021, representing 44% of the total productive area) and tonnes produced (119,646 tonnes in 2021, 40% of the total citrus production) (MGAP, 2022). Between 2020 and 2021, a 35% increase in orange tonnes produced was observed (MGAP, 2022). The aim of the study is then to quantify the environmental impacts of orange production in Uruguay by using LCA, focusing on water footprint, soil ecosystem services and biodiversity. Hotspots are detected, measures to minimise them are proposed, and the temporal variability of the impacts is accounted for as six harvest seasons of orange trees in full production are studied. A comprehensive water footprint assessment is performed, quantifying the impacts of water consumption and degradation. The impacts of land occupation on ecosystem services are evaluated by quantifying five different potentials, and the impacts on biodiversity are assessed for marine, freshwater, and terrestrial ecosystems.

6.2. METHODS

This study follows the LCA methodology based on ISO standards (ISO, 2006a, 2006b; ISO, 2017; ISO, 2020a; 2020b) using LCA for experts (Sphera Solutions, Chicago, USA).

6.2.1. System description

A conventional orchard of Uruguayan orange production was selected as a case study. It has a surface of 272 ha with orange and mandarin trees. Of these, a plot of 5.43 ha was assessed, with 2132 trees of the 'Valencia' orange cultivar in full production; 74% were planted in 1999, and the remaining 26% in 1991. It must be noted that the Valencia cultivar is the country’s most important in terms of production, representing 54% of total orange production and area, accounting for 53% of the orange surface area (MGAP, 2022). The orchard is located in the north of Uruguay, where the production of oranges is concentrated, with 98% of total orange production (MGAP, 2022). The plot has an average yield of 19.9 $tonnes·ha^{-1}$ and a plant density of 393 $trees·ha^{-1}$, similar to the average values in the country (21.3 $tonnes·ha^{-1}$ and 423 $trees·ha^{-1}$ for this variety) (MGAP, 2022). These oranges are exported, like most of the Uruguayan citrus, with 52% of the oranges produced in the country being shipped in 2021 (MGAP, 2022). As well, the orchard belongs to one of the eight companies that concentrate 67% of citrus production in Uruguay (MGAP, 2022), and the agricultural practices follow the Global GAP certification system for exportation (GLOBALG.A.P., 2023), widely used by citrus exporting companies in the country. Further details on the climate and soil characteristics of the orchard are provided in Cabot et al. (2023b).

Different operations are performed during each cropping season (from October to September). Fertilisation is generally carried out from October to March via fertigation, foliar application, and direct application to the soil. The 2018-2019 season constitutes an exception, in which fertigation was not applied for economic reasons. Throughout the year, pesticides are applied via foliar to combat different pests and diseases, mainly anthracnose, melanosis, scabies, mites, citrus leaf miner and cochineal. A tractor (48.5 kW, 1700 rpm) is used for shredding pruning debris, transporting harvested orange bins and foliar input application, for which a fumigator is attached. Drip irrigation is mainly concentrated from October to April. Irrigation water is withdrawn from a nearby lake, property of the company, by using an electric pump. Valencia oranges for export are harvested between August and September; they are picked by hand and then transported to packinghouses, where the fruit is packaged according to the quality requirements at the destination.

6.2.2. Life cycle assessment

6.2.2.1. Functional unit and system boundaries

Two functional units (FUs) are adopted to observe the sensitivity of the impacts on this variable. A mass FU (1-tonne orange) to account for the function of food provision and an area FU (namely 1 ha) since agricultural systems also provide ecosystem services (Power, 2010; Swinton et al., 2007).

The system boundaries are set from cradle to farm gate. They include the production, transportation, and application of inputs (fertilisers and pesticides), the use of machinery, which involves the production and combustion of diesel, as well as irrigation, which implies the production of electricity for water pumping (Fig. 1). The impacts related to the production of capital goods for agriculture were not quantified since, according to Frischknecht et al. (2007), the production of capital goods for agriculture mainly contributes to resource use (mineral and metals) and land use impact categories. However, the authors used other land use indicators, different from those in this study. As well, considering that the life use of a tractor is around 12,000 h (MAGRAMA, 2023) and the average use per season in this case study is 23.9 h ha^{-1} (Table 6.1), only 1% of the impacts of tractor manufacturing would be allocated to the oranges produced per season. Regarding the temporal scope, one farming season is considered and, given the relevance of interseason variability, which is a critical issue in LCAs of perennial crops (Bessou et al., 2016; Cabot et al., 2023a; Cerutti et al., 2014), data from 6 seasons corresponding to trees in their full production phase are used, namely from 2016 to 2022.

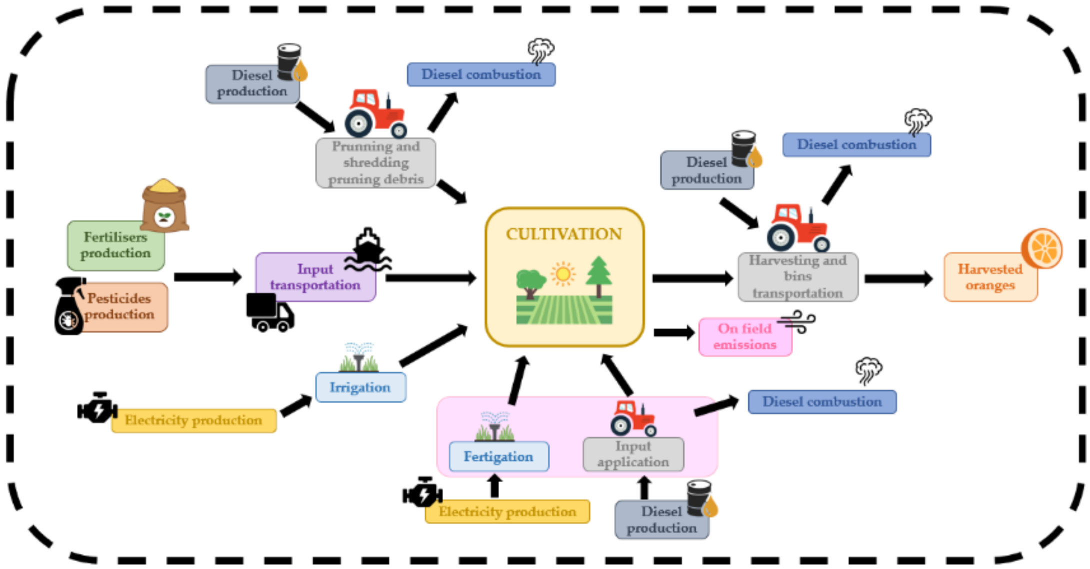


Fig. 6.1. System boundaries showing the life cycle stages included in the LCA of Uruguayan oranges.

6.2.2.2. Life cycle inventory (LCI)

The (LCI) was developed using different data sources, both primary and secondary, which are described below. Inventory data for the orange farming stage is shown in Table 6.1, and further details are presented in Table 6.3. In addition, to develop reference LCI datasets for the LCA model, relevant background processes were taken from Ecoinvent 3.9.1 database (Fitzgerald and Sonderegger, 2022; Wernet et al., 2016), which are detailed in Table 6.4.

Agricultural practices. Primary data on the farming practices were obtained from direct interviews with the agronomist responsible for the orchard. These data correspond to the yield, type and dose of inputs applied and their origin, amount of irrigation water, and fuel consumption for machinery per cropping season.

Table 6.1. Main inventory data for the orange cultivation stage of the assessed orchard in Uruguay

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Yield	tonne · ha^{-1}	16.8	20.0	21.3	9.7	34.9	16.7	19.9	8.4
Electricity for irrigation	kWh · ha^{-1}	287.5	284.7	65.2	114.5	148.2	237.4	189.6	93.5
Water withdrawal for irrigation	mm · $season^{-1}$	270.6	268.0	61.4	107.8	139.5	223.4	178.5	88.0
Rainfall water	mm · $season^{-1}$	1716.0	1388.0	1695.0	1364.0	1119.0	1053.0	1389.2	278.2
Rainfall + irrigation water	mm · $season^{-1}$	1986.6	1656.0	1756.4	1471.8	1258.5	1276.4	1567.6	285.8
Machinery use (input application)	h ·ha^{-1}	20.6	13.4	10.1	17.6	13.8	14.2	14.9	3.7
Machinery use (harvest and transport of bins)	h ·ha^{-1}	7.6	9.0	9.7	4.3	15.7	7.6	9.0	3.8
Diesel for machinery operations									
Application of inputs	L · ha^{-1}	165.0	106.8	80.7	140.7	110.5	113.4	119.5	29.4
Harvest and transport of bins	L · ha^{-1}	15.1	18.0	19.3	8.7	31.3	15.1	17.9	7.5
Fertilisers									
N	kg · ha^{-1}	25.0	60.0	6.4	133.2	175.2	104.1	84.0	65.1
P_2O_5	kg · ha^{-1}	2.1	3.3	0.2	1.9	2.7	1.4	1.9	1.1
K_2O	kg · ha^{-1}	21.0	25.4	1.8	38.9	37.9	40.7	27.6	15.0

Table 6.1. (cont) Main inventory data for the orange cultivation stage of the assessed orchard in Uruguay.

LCI data	Unit	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	Standard deviation
Pesticides									
Fungicides	$kg \cdot ha^{-1}$	26.5	13.9	11.1	14.7	14.3	14.5	15.8	5.4
Herbicides	$kg \cdot ha^{-1}$	3.5	3.8	1.1	2.2	1.2	0.9	2.1	1.3
Insecticides	$kg \cdot ha^{-1}$	25.7	6.1	30.6	28.7	24.9	24.5	23.4	8.8
Growth regulators	$kg \cdot ha^{-1}$	$2.5 \cdot 10^{-1}$	0.0	0.0	0.0	0.0	0.0	$4.2 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Dispersants	$kg \cdot ha^{-1}$	$8.8 \cdot 10^{-1}$	$3.7 \cdot 10^{-1}$	$4.2 \cdot 10^{-1}$	$7.5 \cdot 10^{-1}$	$6.7 \cdot 10^{-1}$	$4.8 \cdot 10^{-1}$	$5.9 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Nutrients	$kg \cdot ha^{-1}$	2.4	2.6	0.0	0.0	0.0	0.0	$8.4 \cdot 10^{-1}$	1.3
On-field emissions									
Direct N_2O	$kg \cdot ha^{-1}$	1.6	3.7	0.4	8.2	10.7	6.4	5.2	4.0
Indirect N_2O (from NO_3^-)	$kg \cdot ha^{-1}$	0.3	0.6	0.1	1.3	1.8	1.1	0.9	0.7
Indirect N_2O (from NH_3)	$kg \cdot ha^{-1}$	0.2	0.3	0.0	0.6	0.8	0.5	0.4	0.3
NH_3 volatilised	$kg \cdot ha^{-1}$	10.3	14.7	1.5	32.5	42.7	25.3	21.2	15.2
NO_2 volatilised	$kg \cdot ha^{-1}$	$5.3 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$	$9.8 \cdot 10^{-4}$	$4.5 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$
CO_2 volatilised	$kg \cdot ha^{-1}$	47.2	0.0	0.0	0.0	0.0	0.0	7.9	19.3
NO_3^- leached	$kg \cdot ha^{-1}$	69.6	156.9	16.4	344.9	453.5	269.4	218.5	167.7
PO_4^{3-} leached	$kg \cdot ha^{-1}$	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.0
PO_4^{3-} run-off	$kg \cdot ha^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-3}$

Irrigation and blue water consumption. The amounts of irrigated water and the irrigation hours are primary data the responsible for the orchard provided. The electricity consumption for irrigation was calculated using the volume of water withdrawn (Table 6.1) and considering a pressure of 30 m w.c. at the entrance of the irrigation head, as a drip irrigation system is used with water from a lake. The blue water consumption for irrigation was estimated according to Allen et al. (1998) by performing a soil balance in the root zone considering the evapotranspiration under water stress conditions. The parameters involved and the data sources used are presented in Eq. 6.1, while the values estimated for crop evapotranspiration and water consumption are shown in Table 6.5.

On-field emissions from fertilisers application. To model direct and indirect N_2O emissions and NO_3^- leaching, the Tier 1 IPCC Guidelines (IPCC, 2006) and the subsequent refinement (IPCC, 2019) were used, considering wet climate and synthetic fertilisers. CO_2 emissions from urea application were calculated under the Tier 1 approach of the IPCC (2006) guidelines, as the emission factor is not modified in the refinement. NH_3 and NO_x emissions were modelled following the EMEP/EEA guidebook (EEA, 2019). Precisely, NH_3 emissions were estimated following a Tier 2 approach, considering normal soil pH (7.0 or below) and temperate climate. A Tier 1 emission factor was used for NO_x emissions since the EMEP/EEA guidebook (EEA, 2019) does not propose a Tier 2 emission factor. Emissions from phosphorus application, namely PO_4^{3-} leaching and run-off to surface water, were estimated following the WFLDB guidelines (Nemecek et al., 2019) considering the P_2O_5 content of each fertiliser used, and the average quantities of P leached to groundwater and lost through run-off for arable land.

On-field emissions from pesticide application. PestLCI Consensus V.1.0 (Fantke et al., 2017) was used to calculate the primary emissions from pesticide application. It estimates the fraction of pesticide applied in the technosphere that crosses the technosphere-environment borders and becomes an environmental emission (Dijkman et al., 2012). Compartments considered are air, field soil surface, crop leaf surface and off-field surfaces.

Production of agricultural inputs. As commented at the beginning of this section, all the agricultural inputs were modelled using default processes from Ecoinvent 3.9.1. database (Fitzgerald and Sonderegger, 2022; Wernet et al., 2016); particularly concerning fertilisers, this means 11 compounds for the studied seasons (see Table 6.4). Potassium phosphate is unavailable in the database and was modelled as a standard PK fertiliser, considering its respective P_2O_5 and K_2O fertiliser units. The production of naphthaleneacetic acid (a growth regulator) was not modelled due to a lack of data, although it must be noted that only 0.25 $kg{\cdot}ha^{-1}$ was applied in 2016-2017.

Regarding pesticide manufacturing, 27 pesticides were modelled according to the following criteria. Firstly, the production process corresponding to the active principle of the pesticide was searched for in Ecoinvent 3.9.1. If it was unavailable in the database, the production of the corresponding chemical group was searched for. In the ultimate case this production was not found, it was modelled as a generic pesticide. The recommendations of Montemayor et al. (2022) were followed for Spinosad and copper oxychloride. The former was modelled considering glucose and electricity production in the country of origin, and the second as copper oxide. It must be noted that those compounds with the same active ingredient, but different origins were modelled separately (see Table 6.4) to differentiate the contribution of each one to the environmental impacts.

Input transportation. Agricultural inputs were transported by lorry or ship and lorry (Table 6.6). Transportation was modelled as one-way transport using the corresponding processes from Ecoinvent 3.9.1 (Fitzgerald and Sonderegger, 2022; Wernet et al., 2016), as shown in Table 6.4. Transport distances were retrieved from Searates (2023).

6.2.2.3. Impact categories and impact assessment methods

Different methods are selected for the impact assessment depending on the impact category and are detailed below.

Comprehensive water footprint. A comprehensive water footprint assessment implies considering the aspects concerning water availability and degradation, covering the impacts on the ecosystems (which includes the water itself) and human health (Fig. 6.2). In particular, to assess the impacts related to water consumption at the midpoint level, the AWARE method (Boulay et al., 2018) is used to quantify blue water scarcity (BWS, m^3eq.), using regionalised characterisation factors (CFs) for the basin studied in the foreground process (Google Earth, 2023) and CFs at the country level (WULCA, 2023), corresponding to the different origins of the inputs, for the background processes. The AWARE method was selected as it is the most up-to-date method, provides site-specific CFs, and is also recommended by the Life Cycle Initiative (UNEP, 2019a).

Impacts related to water consumption at the endpoint are assessed with LC-IMPACT 1.3 (Verones et al., 2020). This method was selected as it provides regionalised CFs to quantify damages to human health, ecosystem quality and mineral resources at four different spatial levels, native, country averages, continental averages, and a global average. In this manner, water stress due to water consumption was estimated, assessing damages to human health (WC-HH, DALY) and ecosystems (WC-Es, PDF) using the corresponding CFs (Verones, 2021).

As to water degradation, impacts at the midpoint level were quantified using indicators related to eutrophication and toxicity. Specifically, marine and freshwater eutrophication (MEu, kg N eq. and FWEu, kg P eq.) were evaluated following the EPD recommendations (EPD, 2023), which suggest using the CFs proposed in EN15804 A2+ that refer to the EUTREND model (Struijs et al., 2009). Regarding toxicity, the impacts on freshwater (FWET, CTUe) were quantified using USEtox 2.12 (Rosenbaum et al., 2008), an agreed and widely used methodology to quantify the impacts in agri-food LCAs (Cabot et al., 2022), which is endorsed by the UNEP/SETAC Life Cycle Initiative (UNEP, 2019b) and the recommended method by the ILCD Handbook (EC-JRC/IES, 2011). Impacts at the endpoint level were quantified using ReCiPe 2016 v1.1 (Huijbregts et al., 2017), a widely recognised method that quantifies impacts in the three areas of protection (human health, ecosystem quality and resource scarcity). Specifically, the endpoint impacts related to the 'ecosystem quality' protection area are contemplated, precisely those related to water quality, quantifying the impacts as local species loss integrated over time. The impacts corresponding to freshwater and marine ecotoxicity and eutrophication are then considered. Subsequently, the quantified impacts are added to determine a single indicator corresponding to species loss due to water degradation (WD-Es, species). This indicator represents a portion of the biodiversity loss indicator explained below; however, it is also calculated in the WF assessment to give an insight into the relevance of water degradation on the loss of biodiversity of water ecosystems. In addition, the pollution deprivation potential (PDP, m^3), a recently developed indicator by Pierrat et al. (2023), is used to explore the consequences of water pollution on water availability due to on-field emissions. Specifically, the PDP focuses on surface water resources since emission data and transport models are available, and it depends on the quality of the water present in the environment in such a way that water quality is insufficient when the environmental concentration of at least one pollutant exceeds the limit of the sectoral water quality requirement. For this case study, the indicator is quantified for phosphorus and nitrogen based on two main rationales. First, since, as stated by Boulay et al. (2011), the main reason why freshwater in Uruguay has an average quality level is due to the high microbial contamination, and second, because phosphorus and nitrogen are considered the most problematic nutrients for the environmental quality of surface waters in the country (MA, 2020). Details of the calculation of the PDP indicator are presented in Eq. 6.2.

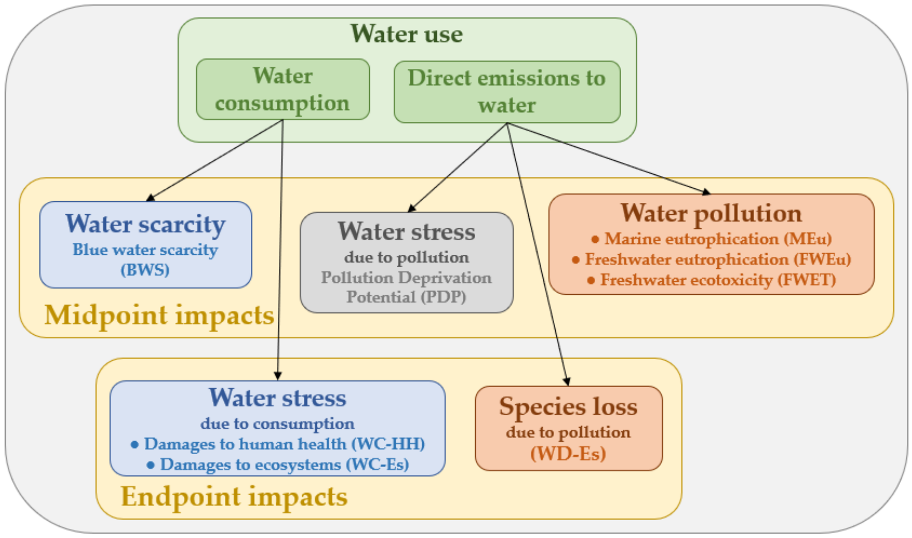


Fig. 6.2. Impact categories assessed in the comprehensive water footprint of Uruguayan oranges production.

Ecosystem services. To quantify land-use-related impacts on ecosystem services, the Land Use Indicator Value Calculation in Life Cycle Assessment - LANCA® v 2022.1 was used (Horn and Till, 2022). It is an internationally accepted and recognised method to integrate land use aspects into LCA (Horn, 2020), recommended for the European Union Product Environmental Footprint (PEF). In particular, the method enables the calculation of characterised indicators based on geoecological classification systems and uses site-specific input data (Fraunhofer IBP, 2023). For the present case study, only the impacts of land occupation on ecosystem services are evaluated as the land transformation for the main process (orange cultivation) took place more than 20 years ago (see Section 2.1). Occupation describes the land quality difference between the actual land use and a reference situation (Lindeijer, 2000). It must be noted that regionalised CFs corresponding to 'permanent crops, irrigated' for Uruguay were used for the orange cultivation stage (Horn et al., 2022). According to Horn (2020), the indicators cover the influence of land occupation on soil's ability to (indicator acronym and units into brackets): prevent erosion beyond the naturally occurring erosion (Erosion Potential - EP, kg), contribute to groundwater recharge (Groundwater Regeneration Reduction Potential - GWRRP, m^3), filter a suspension by mechanically binding pollutants to soil particles (Infiltration Reduction Potential - IRP, m^3), bind dissolved substances from the soil solution and thus prevent them from entering to the groundwater (Physicochemical Filtration Reduction Potential - PFRP, mol) and to store organic carbon (Soil Organic Carbon Reduction Potential - SOCRP, kg).

Biodiversity loss. To assess the impacts on biodiversity loss due to land occupation for the primary process (orange cultivation), the approach of Chaudhary and Brooks (2018) was followed. This method is based on the countryside spatial autoregressive (SAR) model and estimates the global species loss of five taxa (birds, mammals, reptiles, amphibians, and vascular plants) and five different land use types, with three intensity levels in 804 terrestrial ecoregions. This is particularly relevant since the species richness in different natural vegetation types can vary significantly, and CFs will vary accordingly (Huijbregts et al., 2017). For the case study, occupation CFs corresponding to cropland of intense use in the ecoregion 'Uruguayan savanna' were used. In addition, indirect impacts on biodiversity loss in marine, freshwater and terrestrial ecosystems driven by environmental pollution were assessed by applying ReCiPe 2016 v1.1 endpoint CFs (Huijbregts et al., 2017), bearing in mind that this methodology does not consider the loss of reptiles and amphibians and do consider arthropods loss. As the loss of the main taxonomic groups (birds, mammals, and vascular plants) is considered in the two methodologies used, the indicator corresponding to biodiversity loss (BL, species) is calculated as the sum of each impact category assessed. The impact categories included in the assessment are shown in Tables 6.7 and 6.8.

6.3. RESULTS

This section presents the average scores obtained for the impact categories assessed for the two FUs adopted. Furthermore, the main hotspots detected are analysed and discussed, as well as the interseasonal variation of the impacts, placing special emphasis on discussing the maximum and minimum values. The scores obtained by season for both FU expressed as the average of the six seasons assessed and the coefficient of variation (CV, %), are presented in Table 6.2. In Figs. 6.3a, 6.4a and 6.5a, the average contribution of the different stages to the total impact of the life cycle of oranges for each impact category is plotted, whereas the average contribution share of each stage and their standard deviation for both FUs are presented in Tables 6.7 and 6.8. Figs. 6.3b, 6.4b and 6.5b show the ratio "impact value in the season/mean impact value" for each category indicator and FU, allowing us to observe how the impact scores are distributed with respect to the mean. These graphs confirm what is obtained through the CV values and show the greater variability obtained when expressing the results per tonne (red) than per ha (blue).

Table 6.2. Impact scores per cropping season, average values, and coefficient of variation (CV) of cradle-to-farm gate orange cultivation in Uruguay

	FU = 1 ha								FU = 1 tonne							
Impact category	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	CV (%)	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	CV (%)
Water consumption-related midpoint impacts									Water consumption-related midpoint impacts							
BWS (m^3eq. · FU^{-1})	1030.7	1819.5	914.4	1614.3	2012.1	1880.2	1545.2	30	61.3	90.9	42.8	165.9	57.7	112.3	88.5	51
Water degradation-related midpoint impacts									Water degradation-related midpoint impacts							
WC-HH (DALY · FU^{-1})	$1.9\cdot10^{-5}$	$1.7\cdot10^{-5}$	$1.6\cdot10^{-5}$	$1.3\cdot10^{-5}$	$2.2\cdot10^{-5}$	$2.3\cdot10^{-5}$	$1.8\cdot10^{-5}$	21	$1.1\cdot10^{-6}$	$8.6\cdot10^{-7}$	$7.4\cdot10^{-7}$	$1.3\cdot10^{-6}$	$6.3\cdot10^{-7}$	$1.4\cdot10^{-6}$	$1.0\cdot10^{-6}$	30
WC-Es (PDF · FU^{-1})	$5.2\cdot10^{-12}$	$1.3\cdot10^{-11}$	$6.1\cdot10^{-12}$	$2.0\cdot10^{-11}$	$2.8\cdot10^{-11}$	$2.0\cdot10^{-11}$	$1.5\cdot10^{-11}$	58	$3.1\cdot10^{-13}$	$6.5\cdot10^{-13}$	$2.8\cdot10^{-13}$	$2.1\cdot10^{-12}$	$7.9\cdot10^{-13}$	$1.2\cdot10^{-12}$	$8.8\cdot10^{-13}$	76
Water degradation-related midpoint impacts									Water degradation-related midpoint impacts							
MEu (kg N eq. · FU^{-1})	17.8	38.0	4.4	82.7	108.4	64.7	52.7	76	1.1	1.9	0.2	8.5	3.1	3.9	3.1	95
FWEu (kg P eq. · FU^{-1})	1.3	1.1	0.8	1.1	1.1	1.0	1.0	14	$7.5\cdot10^{-2}$	$5.1\cdot10^{-2}$	$6.8\cdot10^{-2}$	$1.1\cdot10^{-1}$	$3.0\cdot10^{-2}$	$5.7\cdot10^{-2}$	$6.4\cdot10^{-2}$	40
FWET (CTUe · FU^{-1})	$5.0\cdot10^{+7}$	$3.5\cdot10^{+7}$	$1.9\cdot10^{+7}$	$3.2\cdot10^{+7}$	$3.3\cdot10^{+7}$	$2.9\cdot10^{+7}$	$3.3\cdot10^{+7}$	31	$3.0\cdot10^{+6}$	$1.7\cdot10^{+6}$	$9.0\cdot10^{+5}$	$3.3\cdot10^{+6}$	$9.4\cdot10^{+5}$	$1.7\cdot10^{+6}$	$1.9\cdot10^{+6}$	53
PDP (m^3 · FU^{-1}) (cultivation stage)	$2.7\cdot10^{-3}$	$7.2\cdot10^{-3}$	$9.5\cdot10^{-4}$	$1.2\cdot10^{-2}$	$2.5\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1.1\cdot10^{-2}$	84	$1.6\cdot10^{-4}$	$3.6\cdot10^{-4}$	$4.3\cdot10^{-5}$	$1.3\cdot10^{-3}$	$7.1\cdot10^{-4}$	$9.0\cdot10^{-4}$	$5.7\cdot10^{-4}$	82
Water degradation-related endpoint impacts									Water degradation-related endpoint impacts							
WD-Es (species · FU^{-1})	$3.0\cdot10^{-5}$	$3.7\cdot10^{-5}$	$1.4\cdot10^{-5}$	$5.6\cdot10^{-5}$	$6.7\cdot10^{-5}$	$4.8\cdot10^{-5}$	$4.2\cdot10^{-5}$	46	$1.8\cdot10^{-6}$	$1.9\cdot10^{-6}$	$6.5\cdot10^{-7}$	$5.8\cdot10^{-6}$	$1.9\cdot10^{-6}$	$2.9\cdot10^{-6}$	$2.5\cdot10^{-6}$	71

Table 6.2. (cont.) Impact scores per cropping season, average values, and coefficient of variation (CV) of cradle-to-farm gate orange cultivation in Uruguay

	FU = 1 ha								FU = 1 tonne							
Impact category	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	CV (%)	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022	Average	CV (%)
Impacts on ecosystem services									Impacts on ecosystem services							
EP ($kg \cdot FU^{-1}$)	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	$2.9 \cdot 10^3$	0	$1.7 \cdot 10^2$	$1.5 \cdot 10^2$	$1.4 \cdot 10^2$	$3.0 \cdot 10^2$	$8.4 \cdot 10^1$	$1.7 \cdot 10^2$	$1.7 \cdot 10^2$	43
GWRRP ($m^3 \cdot FU^{-1}$)	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	$-3.0 \cdot 10^2$	0	$-1.8 \cdot 10^1$	$-1.5 \cdot 10^1$	$-1.4 \cdot 10^1$	$-3.1 \cdot 10^1$	-8.6	$-1.8 \cdot 10^1$	$-1.7 \cdot 10^1$	43
IRP ($m^3 \cdot FU^{-1}$)	$1.2 \cdot 10^3$	$1.2 \cdot 10^3$	$8.5 \cdot 10^2$	$1.3 \cdot 10^3$	$1.4 \cdot 10^3$	$1.3 \cdot 10^3$	$1.2 \cdot 10^3$	16	$7.4 \cdot 10^1$	$5.9 \cdot 10^1$	$4.0 \cdot 10^1$	$1.4 \cdot 10^2$	$4.0 \cdot 10^1$	$7.5 \cdot 10^1$	$7.1 \cdot 10^1$	50
PFRP ($mol \cdot FU^{-1}$)	$1.8 \cdot 10^6$	$1.8 \cdot 10^6$	$1.7 \cdot 10^6$	$1.8 \cdot 10^6$	$1.9 \cdot 10^6$	$1.8 \cdot 10^6$	$1.8 \cdot 10^6$	3	$1.1 \cdot 10^5$	$9.0 \cdot 10^4$	$7.9 \cdot 10^4$	$1.9 \cdot 10^5$	$5.4 \cdot 10^4$	$1.1 \cdot 10^5$	$1.0 \cdot 10^5$	44
SOCRP ($kg \cdot FU^{-1}$)	$1.3 \cdot 10^4$	$1.3 \cdot 10^4$	$1.2 \cdot 10^4$	$1.3 \cdot 10^4$	$1.3 \cdot 10^4$	$1.3 \cdot 10^4$	$1.3 \cdot 10^4$	2	$7.8 \cdot 10^2$	$6.5 \cdot 10^2$	$5.8 \cdot 10^2$	$1.3 \cdot 10^3$	$3.8 \cdot 10^2$	$7.7 \cdot 10^2$	$7.5 \cdot 10^2$	43
Impacts on biodiversity									Impacts on biodiversity							
BL ($species \cdot FU^{-1}$)	$2.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$	$3.9 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$	45	$1.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$	$5.3 \cdot 10^{-6}$	$4.7 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$	$2.3 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	71

BWS: blue water scarcity - WC-HH: damage to human health due to water consumption - WC-Es: damage to ecosystems due to water consumption - MEu: marine eutrophication - FWEu: freshwater eutrophication - FWET: freshwater ecotoxicity - PDP: pollution deprivation potential - WD-Es: damage to ecosystems due to water degradation - EP: erosion potential - GWRRP: groundwater regeneration reduction potential - IRP: infiltration reduction potential - PFRP: physicochemical filtration reduction potential - SOCRP: soil organic carbon reduction potential - BL: biodiversity loss
DALY: disability-adjusted life year - PDF: potentially disappeared fraction of species - CTUe: comparative toxic unit (ecotoxicity potential)

6.3.1. Comprehensive water footprint

Water consumption. The scores obtained for the environmental indicators related to water consumption are 1545.2 m^3 eq.·ha^{-1} and 88.5 m^3 eq.·$tonne^{-1}$ for BWS, $1.8 \cdot 10^{-5}$ DALY·ha^{-1} and $1.0 \cdot 10^{-6}$ DALY·$tonne^{-1}$ for WC-HH and $1.5 \cdot 10^{-11}$ PDF·ha^{-1} and $8.8 \cdot 10^{-13}$ PDF·$tonne^{-1}$ for WC-Es (Table 6.2). As expected, the hotspot that stands out in the three indicators is the irrigation provided to meet the crop water demand, representing 76%, 82% and 40% on average, respectively (Fig. 6.3a). Although the Uruguayan CFs for these indicators present low values, the high water consumption of the crop compared to that of the other life cycle stages evaluated makes this a hotspot. Likewise, for the WC-Es, fertiliser production is also a hotspot (59% on average in the six seasons) (Fig. 6.3a). Specifically, urea ammonium nitrate production stands out, as it is one of the inputs with a greater application dose, which implies a greater water consumption for its production. In addition, this product is imported from the United States, which is the country, among those involved in this study, with the highest CF for this impact category.

When analysing the temporal variability of the three indicators related to water consumption, it can be observed that the highest scores per ha were obtained for the 2020-2021 and 2021-2022 seasons, which are the ones with the lower rainfall values recorded in the orchard (Table 6.1) and the highest water consumption from the basin. The lowest values were obtained for the seasons 2016-2017 for WC-Es, 2018-2019 for BWS and 2019-2020 for WC-HH, coinciding with the crop's lowest water consumption (Table 6.5). The seasons 2016-2017 and 2018-2019 are the ones with the highest rainfall, and thus, part of the water necessary for crop growth was supplied by green water (rain). As commented above, fertiliser production also represents a hotspot for the WC-Es category, contributing to the low values obtained in 2016-2017 as it is the season with the second lowest fertiliser application and therefore produced (Table 6.1). As for BWS, the minimum presented in 2018-2019 is also related to the fact that, in that season, most of the rainfall (47%) was concentrated in the months of highest scarcity in the basin (December to March), easing its burden and lowering the score. The season 2019-2020 does not present a relatively high rainfall value; therefore, what weighs in the WC-HH score is the second hotspot detected: pesticide production (18% on average). In that season, although the amount of pesticides applied was not the lowest, it was when fewer pesticides from the countries with the highest CFs (China and India) were used and produced, thus lowering the impact.

Regarding the scores per tonne, maximum and minimum for BWS and WC-Es are observed in 2019-2020 and 2018-2019, respectively. The former is the season with the lowest yield (Table 6.1), which is the factor that makes the score the highest. The latter is a season with high yield and low water consumption (Table 6.5), both responsible for the low score obtained. As to the WC-HH category, the maximum was obtained in 2021-2022, a season with a low yield and a high water consumption (Tables 6.1 and A22). The minimum score was obtained in 2020-2021, which coincides with the crop's highest yield, which weighs more than the water consumption in the results, as the latter presents a high value for this season.

Water degradation. The average scores obtained for MEu are 52.7 kg N eq.$\cdot$ha^{-1} and 3.1 kg N eq.$\cdot$tonne^{-1} (Table 6.2). The hotspot detected is on-field emissions, which dominate the impact category along the assessed seasons with 97% on average (Fig. 6.3a); specifically, nitrate emissions, which are minimum in 2018-2019 and maximum in 2020-2021 due to the dose of N applied. This is aligned with the maximum and minimum observed when expressing the results per ha. When expressing the results per tonne, the minimum is still in 2018-2019 (due to the almost no fertilisation), but the maximum is in 2019-2020 due to the crop yield, which is the lowest in this season and weighs more in the results than on-field emissions.

Regarding FWEu, the average scores obtained are 1.0 kg P eq.$\cdot$ha^{-1} and $6.6\cdot10^{-2}$ kg P eq.$\cdot$tonne^{-1} (Table 6.2). Two main hotspots are detected (Fig. 6.3a), on-field emissions (53% on average), specifically phosphate leaching and run-off to surface water, and pesticide production (36% on average), mainly that of copper oxides. The maximum score obtained per ha in 2016-2017 responds to the 'pesticide production' hotspot as in that season the maximum amount of copper oxides is added (Table 6.3). The minimum, obtained in 2018-2019, corresponds to the minimum amount of copper oxides applied but also to the lowest phosphate emission to water (Table 6.1). Thus, both have their contribution to the impact score in this case. As for the extreme values obtained per tonne, these respond to the yield, specifically to the seasons with the lowest and highest crop yield.

The FWET impact category presents average scores of $3.3\cdot10^{7}$ CTUe$\cdot$ha^{-1} and $1.9\cdot10^{6}$ CTUe$\cdot$tonne^{-1}. It is dominated by the production of agricultural inputs, mainly pesticides (83% on average), and again due to copper oxides production (Fig. 6.3a). Along these lines, the highest impacts per ha were obtained in 2016-2017, and the lowest in 2018-2019, coinciding with the highest and lowest application of copper oxides, as previously mentioned. Per tonne, the maximum was obtained in 2019-2020, the season with the lowest yield, and the minimum for 2018-2019, the season with a high yield and a low quantity of copper oxides added.

The average score for PDP per ha is $1.1·10^{-2}$ $m^3·ha^{-1}$, with a maximum in 2020-2021 and a minimum in 2018-2019, which are the seasons with the highest and lowest NO_3^- leaching, whereas PO_4^{3-} values are mostly constant (Table 6.1). The average score per tonne is $5.7E·10^{-4}$ m^3, with a maximum in 2019-2020 (due to low yield) and a minimum in 2018-2019 due to high yield and the low values of the above-discussed emissions.

The average scores of WD-Es are $4.2·10^{-5}$ species·ha^{-1} and $2.5·10^{-6}$ species·$tonne^{-1}$, and it presents two main hotspots (Fig. 6.3a): transportation (49% on average) and fertilisers production (20% on average). This is due to the relevance of toxicity-related impacts in WD-Es, in which ship transportation and urea ammonium nitrate production stand out. The highest value of WD-Es per ha was obtained in 2020-2021 and the lowest in 2018-2019, seasons where the highest and lowest inputs were applied, respectively (Table 6.1), consequently generating a greater and lower impact due to production and transportation. The highest value per tonne was obtained in 2019-2020 due to the lowest yield of the crop, and the lowest score in 2018-2019, the season in which a high yield was obtained and a low amount of inputs was used, which reduced the impact of its production and transportation, thus making the impact score minimum.

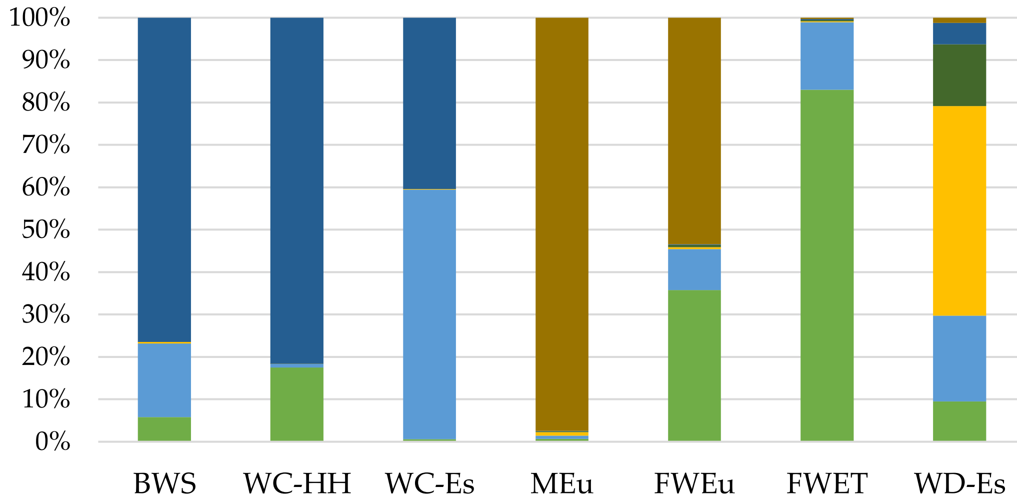


Fig. 6.3. (a) Average percentual contribution of the life cycle stages to the water footprint of Uruguayan oranges per tonne and ha. ■ Pesticides production, ■ Fertilisers production, ■ Transport, ■ Machinery operations, ■ Irrigation, ■ On-field emissions + occupation. BWS: blue water scarcity - WC-HH: damage to human health due to water consumption - WC-Es: damage to ecosystems due to water consumption - MEu: marine eutrophication - FWEu: freshwater eutrophication - FWET: freshwater ecotoxicity - WD-Es: damage to ecosystems due to water degradation.

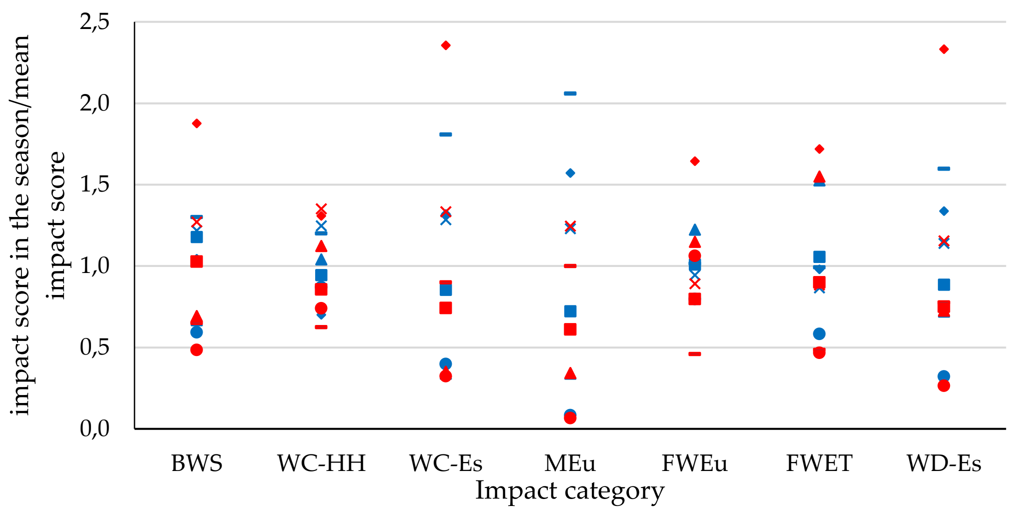


Fig. 6.3. (b) Relative variability of the values of the water footprint of Uruguayan oranges with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per ha of the orchard. ▲ 2016-2017, ■ 2017-2018, ● 2018-2019, ◆ 2019-2020, – 2020-2021, × 2021-2022. BWS: blue water scarcity - WC-HH: damage to human health due to water consumption - WC-Es: damage to ecosystems due to water consumption - MEu: marine eutrophication - FWEu: freshwater eutrophication - FWET: freshwater ecotoxicity - WD-Es: damage to ecosystems due to water degradation

6.3.2. Ecosystem services

The EP shows that the loss of soil amounts to $2.9\cdot10^3$ kg·ha^{-1} and $1.7\cdot10^2$ kg·tonne^{-1} (Table 6.2), and the use of land for oranges cultivation is the main hotspot detected (Fig. 6.4a), which makes the CV per ha equal to 0%, as the area and land use type remain the same in the studied years. The negative scores of GWRRP mean that infiltrated water due to orange cultivation contributes to groundwater recharge, with scores of $-3.0\cdot10^2$ m^3·ha^{-1} and $-1.7\cdot10^1$ m^3·tonne^{-1}. Land use for cultivation is also the leading cause of this positive impact. As the area occupied by citrus is constant during all the seasons assessed (5.43 ha, section 2.1), this indicator does not exhibit variability per ha (0% CV, Table 6.2). The negative scores obtained for this indicator (positive impacts on the environment) arise from the fact that for Uruguay, and specifically for certain land use types such as agriculture, forest and permanent crops, the values of the CFs are negative, implying that land occupation to produce oranges has a positive effect. The decrease of the infiltration potential of soil is described by IRP and PFRP, with scores per ha of $1.2 \cdot 10^{3}$ m^{3} and $1.8 \cdot 10^{6}$ mol^{-1}, and per kg of orange of $7.1 \cdot 10^{1}$ m^{3} and $1.0 \cdot 10^{5}$ mol, respectively. The main hotspot detected is also the land use for orange cultivation; thus, the CV per ha is low (16% and 3%, respectively, Table 6.2) but higher than 0% since the production of inputs (especially copper oxides and urea ammonium nitrate production) and their transport by truck slightly weight in the final score. SOCRP shows that $1.3 \cdot 10^{4}$ kg of soil organic carbon are lost per ha and $7.5 \cdot 10^{2}$ kg per tonne, being again orange cultivation the main hotspot detected (Fig. 6.4a), whereby it also presents a low CV per ha (2%, Table 6.2). When expressing the results per tonne, the yield increases the CVs, and the maximum and minimum results respond to the lowest and highest crop yields, respectively, except for GWRRP, for which the opposite happens, as the values obtained are negative.

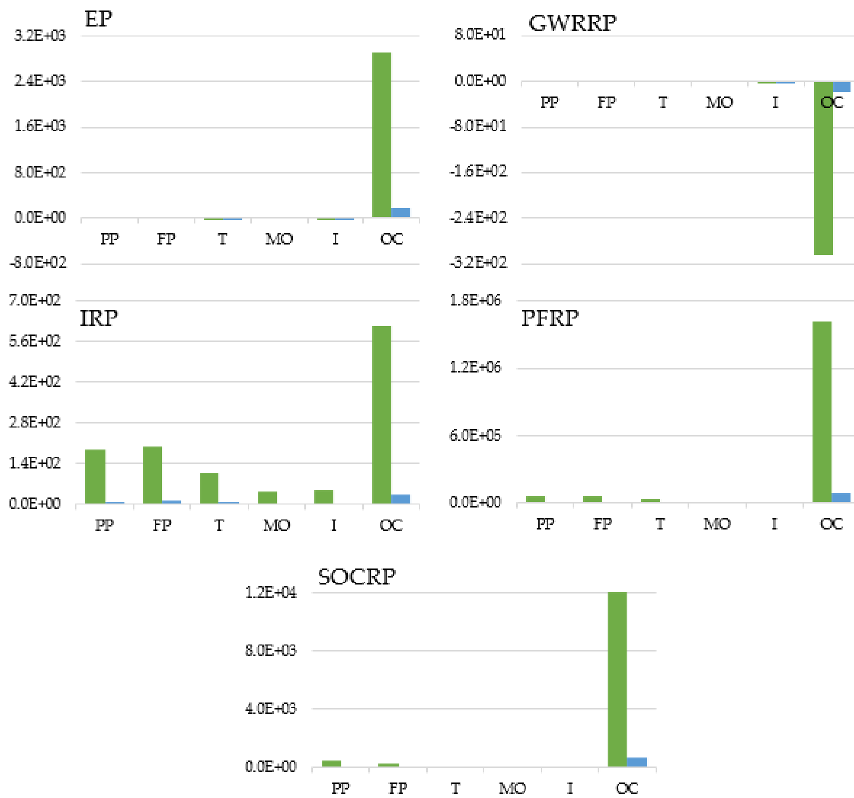


Fig. 6.4. (a) Average contribution of the life cycle stages to the loss of ecosystem services due to Uruguayan oranges cultivation per tonne (blue) and ha (green). PP: Pesticides production - FP: Fertilisers production - T: Transport - MO: Machinery operations - I: Irrigation - OC: Orange cultivation - EP: erosion potential - GWRRP: groundwater regeneration reduction potential - IRP: infiltration reduction potential - PFRP: physicochemical filtration reduction potential - SOCRP: soil organic carbon reduction potential

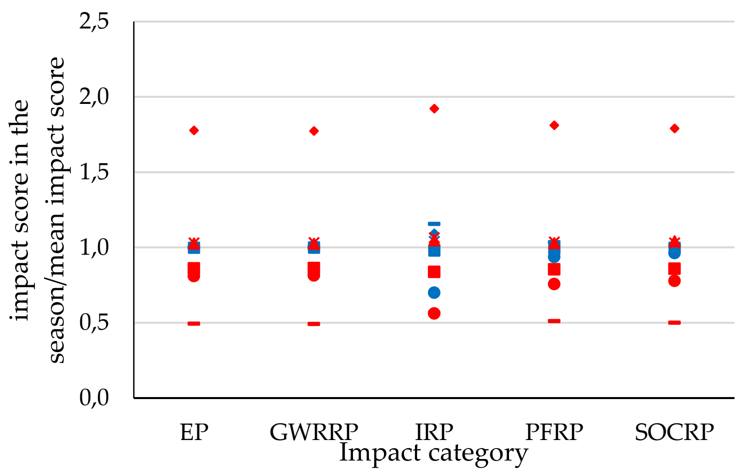


Fig. 6.4. (b) Relative variability of the impact values of ecosystem services losses in Uruguayan oranges cultivation with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per ha of the orchard. ▲ 2016-2017, ■ 2017-2018, ● 2018-2019, ◆ 2019-2020, – 2020-2021, × 2021-2022. EP: erosion potential - GWRRP: groundwater regeneration reduction potential - IRP: infiltration reduction potential - PFRP: physicochemical filtration reduction potential - SOCRP: soil organic carbon reduction potential

6.3.3. Biodiversity loss

The scores obtained in BL were $3.5{\cdot}10^{-4}$ species·ha^{-1} and $2.0{\cdot}10^{-5}$ species·tonne^{-1} and, contrary to what the reader might intuitively think, land use for orange cultivation is not the main driver of this impact, but pollution, mainly that caused by the transportation of inputs to the orchard due to the long distances travelled, which imply significant diesel combustion (Fig. 6.5a). Specifically, due to its contribution to the ecotoxicity-related categories, especially terrestrial ecotoxicity, which, of all the endpoint impact categories that contribute to BL, has the highest share (Tables 6.7 and 6.8).

It is interesting to analyse the polluting endpoint impacts that contribute to BL. Within them, impacts of climate change on freshwater and terrestrial ecosystems (CC FWEs and CC TEs), freshwater and marine eutrophication (FWEu and MEu) and terrestrial acidification (TAc) present on-field emissions as hotspots. As to the LU, the hotspot detected is the land occupation by the crop, where the loss of species is led by plants with 37% of the total species loss, followed by birds, mammals, and amphibians with 21, 20 and 20% of species loss, respectively, and reptiles, with 2% of the total species lost.

Regarding the variability of this impact category, CV values are high (Table 6.2), both per ha (45% on average) and per tonne (71% on average). The highest and lowest values obtained per ha correspond to the 2020-2021 and 2018-2019 seasons, which are those with the highest and lowest input applications, implying the highest and lowest impact of transport. Regarding the values per tonne, the highest value was obtained in the season of lowest yield (2019-2020) and the lowest value in 2018-2019, coinciding with a high yield and the lowest amount of transported inputs.

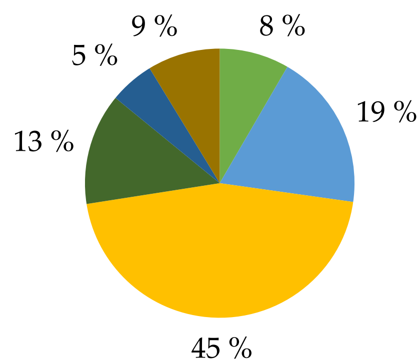


Fig. 6.5. (a) Average percentual contribution of the life cycle stages to Biodiversity Loss (BL) of Uruguayan oranges production per tonne and ha. ■ Pesticides production, ■ Fertilisers production, ■ Transport, ■ Machinery operations, ■ Irrigation, ■ On-field emissions + occupation.

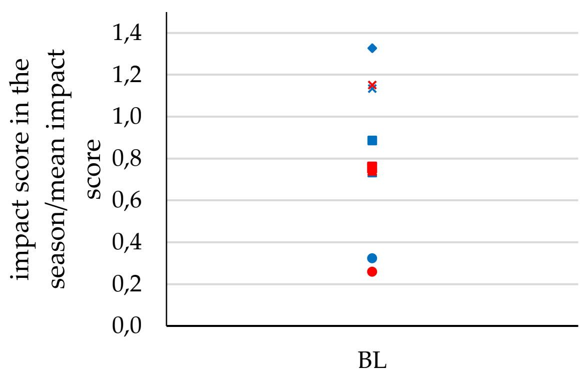


Fig. 6.5. (b) Relative variability of the impact values of Biodiversity Loss (BL) due to Uruguayan oranges cultivation with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per ha of the orchard. ▲ 2016-2017, ■ 2017-2018, ● 2018-2019, ◆ 2019-2020, – 2020-2021, × 2021-2022.

6.4. DISCUSSION

6.4.1. Comparison with other Uruguayan studies and alternatives for improvement

Results show different hotspots depending on the impact assessed, but when it comes to understanding their magnitude, comparisons with other citrus LCAs developed in the country become relevant. Nevertheless, comparisons are performed for the water use-related impact categories, as no studies regarding ecosystem services or biodiversity loss have been found in the literature reviewed. BWS values are in the same order of magnitude but lower than those obtained for lemons and mandarin. The scores obtained for lemon production in the south of the country are 6400 m^3eq.·ha^{-1} and 116.8 m^3eq.·$tonne^{-1}$ (Cabot et al., 2023a), and for mandarin production in the north, 3656.3 m^3eq.·ha^{-1} and 113.9 m^3eq.·$tonne^{-1}$ (Cabot et al., 2023b). The amount of water consumed by the crop in the latter was quantified using LEACHN (Hutson and Wagenet, 1992) and the results obtained are slightly lower. Regarding the former, the climatic region, soil type, and basin from which the water is extracted differ. Nonetheless, as expected, irrigation was the main hotspot detected in BWS in the three studies. Similar values to the obtained in the present study are reported for FWEu in Uruguayan mandarin production, 0.9 kg P eq.·ha^{-1} and $2.7 \cdot 10^{-2}$ kg P eq.·$tonne^{-1}$ (Cabot et al., 2023b), and Uruguayan lemon production, 1.3 kg P eq.·ha^{-1} and $2.4 \cdot 10^{-2}$ kg P eq.·$tonne^{-1}$ (Cabot et al., 2023a). The hotspots detected also coincide, highlighting copper compounds' production and PO_4^{3-} run-off. Regarding FWET, copper compounds' production was detected as hotspot too, and similar results were obtained for Uruguayan citrus production in previous works; $3.1 \cdot 10^7$ CTUe·ha^{-1}

and $1.0 \cdot 10^6$ CTUe·tonne^{-1} for mandarins (Cabot et al., 2023b) and $8.2 \cdot 10^7$ CTUe·ha^{-1} and $1.5 \cdot 10^6$ CTUe·tonne^{-1} for lemons (Cabot et al., 2023a). As for MEu, nitrate emissions are also a hotspot in other studies performed in citrus orchards in the country. However, direct numerical comparisons would not be entirely fair as these emissions were quantified using different methodologies, LEACHN (Hutson and Wagenet, 1992) in Cabot et al. (2023b) and the SQCB-NO_3 model (Emmenegger et al., 2009) in Cabot et al. (2023a).

To reduce the main hotspots detected, different measures or tools could be implemented. Irrigation is the main hotspot for BWS, WC-HH and WC-Es, and they could be minimised by optimising the irrigation regime (i.e., quantity, moment, and irrigation technique). As drip irrigation is already applied in the orchard, subsurface drip irrigation, advanced irrigation scheduling, or deficit irrigation come up as interesting ideas that could be implemented (García-Tejero et al., 2012). As well, the search for rootstocks with lower water requirements, the use of nets to cover the crops to reduce water demand, and the choice of citrus varieties with a higher water use efficiency due to leaf characteristics or grown habits could be useful (Wachsmann et al., 2014).

Fertiliser production and transportation is another relevant hotspot in the present study, especially that of urea ammonium nitrate, as it is used in a significant proportion and transported a long distance by ship and truck. Decreasing its use would directly reduce WC-Es, WD-Es and BL impact categories. This could be achieved through the optimisation of the N cycle. As commented by Cabot et al. (2023a), several options can be considered, for example, the use of tools to optimise N application such as the Normalized

Difference Vegetative Index (Pettorelli, 2013) and the use of Site-Specific Nutrient Management (Buresh and Witt, 2007). As well, the selection of fertilisers with slow-release forms of N or covered with low permeability materials (Cayuela et al., 2017; Mahmud et al., 2021; Skiba et al., 1997). Selecting rootstocks that absorb N more efficiently could be another interesting option (Morales Alfaro et al., 2021). These measures would also positively affect MEu, as N on-field emissions were detected as a hotspot.

The production of copper oxide compounds was detected as a hotspot in FWEu and FWET. As input production is not a direct responsibility of the citrus producers, practices oriented to reduce pathogen inoculum in the orchard, such as pruning and remotion of old twigs, organic mulches, and combinations with other species between rows could represent a good alternative to reduce the use of this input and minimise the environmental impacts (Cabot et al., 2023a). New formulations based on different active principles (e.g., chitosan, phosphites, hexanoic acid) could also help to mitigate pathogen attacks improving plant resistance and contributing to a lower use of copper compounds (Caccalano et al., 2021; Garganese et al., 2019; Lombardo et al., 2023).

6.4.2. Limitations and future research needs

Regarding the limitations of this study, some relevant aspects related to the methodologies applied arise. Firstly, it is relevant to highlight that LANCA® is a useful methodology since it covers a need in LCA, to assess ecosystem services loss due to land use considering different aspects of soil quality. It also covers a wide range of countries and agricultural practices, distinguishing between intensive and extensive productions. However, some improvements can be proposed considering the characteristics of the parameters evaluated. Firstly, the spatial resolution of the CFs should be increased since, even within the same country, soil properties show great spatial variability. This could be achieved using a fully integrated geographic information system (GIS) approach instead of an average at the country level (De Laurentiis et al., 2019). In addition, CFs could also be refined considering the specific management practices where the land use activity is taking place (or is most likely to take place). It is worth to be mentioned that efforts are being carried out in that line. In particular, Maier (2022, submitted) propose a multiscale framework offering CFs at three levels of detail (country average, georeferenced average and the local level) (Horn and Till, 2022). However, these three levels are not yet available in the database used. Regarding ecosystem services in general, it would also be interesting to quantify the capacity to generate them (that is, the "positive" environmental impacts) and not just demand them. This could be addressed in future studies using, for example, the cascade framework proposed by Rugani et al. (2019).

As to biodiversity loss assessment, although the development of the CFs for species richness by Chaudhary and Brooks (2018) and previous studies (Chaudhary et al., 2015; Curran et al., 2016; De Baan et al., 2015, 2013) represent a significant advance in this regard, several aspects can be improved. On the one hand, the existing methods that assess direct and indirect impacts on biodiversity show differences concerning key aspects such as the impact categories included, the scope of the method, the coverage of elementary flows and the consideration of ecosystem compartments (Sanyé-Mengual et al., 2022). In this sense, both the method used to assess direct biodiversity loss and the method to assess indirect loss due to pollution should have the same spatial resolution and evaluate the same taxa, including insects, whose decline due to intensive agriculture is recognised as a great concern (Sánchez-Bayo and Wyckhuys, 2019). These methods should also cover all the drivers of biodiversity loss as they do not include, for example, impact pathways for the introduction of invasive species or for the overexploitation of resources (Crenna et al., 2020). On the other hand, the method used to assess biodiversity loss due to land occupation and transformation does not consider the variety of existing agricultural practices, such as organic agriculture, biodynamic etc. (van der Werf et al., 2020). However, efforts are being carried out in this direction. For example, Knudsen et al. (2017) provide midpoint occupation CFs to estimate land use impacts on biodiversity in the 'Temperate Broadleaf and Mixed Forest' biome in Europe based on direct measures of plant species richness and considering four land use types and two management practices (organic and conventional). The authors found an overall effect of land use (type of crop) across countries and management within the crops, obtaining higher CFs for arable crops and conventional management. In this line, more studies considering other taxa and different biomes worldwide are encouraged. Another aspect that should be remarked is that the CFs applied in the present study only consider species richness, while other biodiversity indicators could be used, such as species abundance, endemicity and species composition, as acknowledged by the developers of the CFs (Chaudhary and Brooks, 2018). As land use is a driver of ecosystem services loss too, as Jeswani et al. (2018) propose, the ideal would be to build a single indicator for land use that includes all relevant aspects for biodiversity and ecosystem services loss or otherwise to generate an aggregated indicator for the loss of ecosystem services, similar to that of biodiversity proposed by Chaudhary and Brooks (2018).

Regarding the quantification of the water footprint, the importance of adding regionalised methods to existing LCA software is highlighted. Although in the present study the AWARE and the LC-IMPACT methods are used to quantify the impacts at the basin and country level, the impacts of water depletion (MEu, FWEu, FWET, and WD-Es) are calculated using non-regionalized methods. This is because, although methods that present regionalised CFs for these indicators are available, these have not yet been incorporated into the software used in this study (LCA for experts). The need to develop global geospatial models that dynamically estimate environmental concentrations in freshwater (surface and groundwater) in order to refine water pollution assessment is also highlighted for this impact category (Pierrat et al., 2023).

Despite the need to deepen the improvement of some aspects of the methods, several aspects come out of this study regarding decision-making. As to water use, results can help decision-makers manage water resources, as they reveal if water consumption or water pollution is more relevant regarding water availability and their effect on species loss. The study could also be helpful in building sustainable agriculture guidelines, as it addresses soil health and biodiversity, key aspects when comparing conventional and organic systems. Likewise, the fact that many aspects affecting biodiversity (apart from land use) are considered in this study opens the gate to new solutions (apart from land-sparing or changes in agricultural practices) for halting biodiversity loss associated with agriculture.

6.5. CONCLUSIONS

The environmental performance of orange production in Uruguay was assessed by performing an LCA, focusing on water use and degradation, ecosystem services loss due to land use, and biodiversity loss. Irrigation constitutes the primary hotspot for water consumption both at a midpoint and at an endpoint level, although when quantifying the damage to ecosystems, fertiliser production also stands out. Regarding water degradation at the midpoint level, on-field emissions from fertiliser application are the main hotspots detected in marine and freshwater eutrophication. In the freshwater ecotoxicity impact category, pesticide production stands out. At the endpoint level, water degradation-related impacts are led by ship input transportation and urea ammonium nitrate production, as they dominate freshwater and marine ecotoxicity, which are the principal drivers in this category. Regarding the impacts on ecosystem services due to land use, land occupation for orange production plays a double role, as it is detected as a hotspot for erosion, infiltration reduction, physicochemical filtration reduction and soil organic carbon reduction, but it has positive impacts on groundwater regeneration. As for biodiversity loss, the hotspot detected was not land use but input transportation to the orchard.

The relevance of including several seasons in the analysis is confirmed, as high coefficients of variation were obtained for almost all impact categories per ha and tonne. Exceptions are the impacts on ecosystem services when the FU is 1 hectare since land use is the main hotspot detected, and the principal variable considered for their quantification in LANCA® is the area occupied by the crop, which is constant for all the seasons assessed.

The present study provides scientific and quantitative evidence to make decisions to increase the environmental performance of Uruguayan orange production in line with the SDGs, focusing especially on SDG 6 and SDG 15. Indicators commonly not included in LCAs are evaluated, which allows the fulfilment of more complete environmental assessments. However, the methods to assess these impacts can still be improved to better address the SDGs related to agricultural activity.

CRediT authorship contribution statement

María Inés Cabot: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Investigation.

Joanna Lado: Conceptualization, Methodology, Writing – review & editing.

Neus Sanjuán: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing,

Funding

Maria Inés Cabot is the recipient of a PhD scholarship (POS_EXT_2018_1_154319) from the National Agency for Research and Innovation (ANII, Uruguay) and received a support scholarship for the completion of postgraduate studies (BFPD_2023_1#46477920) from the Postgraduate Academic Commission (CAP, University of the Republic).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors particularly acknowledge UPEFRUY-Uruguay fruits (http://uruguayfruits.com.uy/en) for their sincere collaboration and for sharing their data for this study.

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6.6. MATERIAL COMPLEMENTARIO DEL CAPÍTULO 6

La presente sección se divide en los siguientes apartados:

- Inventario ambiental detallado del cultivo de naranja
- Metadatos del modelado del proceso de cultivo de naranja
- Consumo de agua azul para las seis temporadas de estudio
- Distancias de transporte de los insumos utilizados
- Resultados promedio de los impactos ambientales y desviación estándar por etapa del cultivo de naranja, por hectárea y por tonelada
- Descripción de las ecuaciones utilizadas

Table 6.3. Detailed inventory of the orange cultivation stage

LCI data	Unit	2016 2017	2017 2018	2018 2019	2019 2020	2020 2021	2021 2022	Avg	Strd dev
Yield	tonne·ha^{-1}	16.8	20.0	21.3	9.7	34.9	16.7	19.9	8.4
Electricity for irrigation	kWh·ha^{-1}	287.5	284.7	65.2	114.5	148.2	237.4	189.6	93.5
Water withdrawal for irrigation	mm·season^{-1}	270.6	268.0	61.4	107.8	139.5	223.4	178.5	88.0
Rainfall water	mm·season^{-1}	1716.0	1388.0	1695.0	1364.0	1119.0	1053.0	1389.2	278.2
Rainfall + irrigation water	mm·season^{-1}	1986.6	1656.0	1756.4	1471.8	1258.5	1276.4	1567.6	285.8
Machinery use (input application)	h·ha^{-1}	20.6	13.4	10.1	17.6	13.8	14.2	14.9	3.7
Machinery use (harvest and transport of bins)	h·ha^{-1}	7.6	9.0	9.7	4.3	15.7	7.6	9.0	3.8
Diesel for machinery operations									
Application of inputs	L·ha^{-1}	165.0	106.8	80.7	140.7	110.5	113.4	119.5	29.4
Harvest and transport of bins	L·ha^{-1}	15.1	18.0	19.3	8.7	31.3	15.1	17.9	7.5
Fertilisers									
N	kg·ha^{-1}	25.0	60.0	6.4	133.2	175.2	104.1	84.0	65.1
P_2O_5	kg·ha^{-1}	2.1	3.3	0.2	1.9	2.7	1.4	1.9	1.1
K_2O	kg·ha^{-1}	21.0	25.4	1.8	38.9	37.9	40.7	27.6	15.0
Fungicides									
Azoxystrobin	kg·ha^{-1}	0.0	0.0	$3.1·10^{-1}$	0.0	0.0	0.0	$5.2·10^{-2}$	$1.3·10^{-1}$
Carbendazim	kg·ha^{-1}	0.0	0.0	0.0	$8.0·10^{-1}$	$8.9·10^{-1}$	$8.7·10^{-1}$	$4.3·10^{-1}$	$4.7·10^{-1}$
Copper oxychloride	kg·ha^{-1}	8.8	8.6	0.0	0.0	0.0	0.0	2.9	4.5
Cuprous oxide 1	kg·ha^{-1}	5.9	1.8	5.5	8.6	8.4	6.4	6.1	2.5
Cuprous oxide 2	kg·ha^{-1}	0.0	0.0	0.0	0.0	0.0	1.3	$2.1·10^{-1}$	$5.1·10^{-1}$
Difenoconazole 1	kg·ha^{-1}	0.0	0.0	0.0	0.0	$1.3·10^{-1}$	$1.3·10^{-1}$	$4.4·10^{-2}$	$6.8·10^{-2}$
Difenoconazole 2	kg·ha^{-1}	$1.3·10^{-1}$	$1.3·10^{-1}$	$1.5·10^{-1}$	$1.2·10^{-1}$	0.0	0.0	$8.7·10^{-2}$	$6.8·10^{-2}$
Mancozeb 1	kg·ha^{-1}	0.0	0.0	0.0	4.8	0.0	0.0	$8.1·10^{-1}$	2.0
Mancozeb 2	kg·ha^{-1}	$1.2·10^{1}$	3.2	5.1	0.0	4.5	5.7	5.0	3.8
Pyraclostrobin 1	kg·ha^{-1}	0.0	0.0	0.0	$3.2·10^{-1}$	$3.0·10^{-1}$	$1.4·10^{-1}$	$1.3·10^{-1}$	$1.5·10^{-1}$
Pyraclostrobin 2	kg·ha^{-1}	0.0	$7.5·10^{-2}$	0.0	0.0	0.0	0.0	$1.2·10^{-2}$	$3.0·10^{-2}$
Herbicides									
2,4-D dimethyl amine salt 1	kg·ha^{-1}	0.0	0.0	0.0	$3.5·10^{-1}$	0.0	0.0	$5.9·10^{-2}$	$1.4·10^{-1}$

Table 6.3. (cont.) Detailed inventory of the orange cultivation stage

LCI data	Unit	2016 2017	2017 2018	2018 2019	2019 2020	2020 2021	2021 2022	Avg	Strd dev
2,4-D dimethyl amine salt 2	$kg \cdot ha^{-1}$	0.0	$7.8 \cdot 10^{-1}$	0.0	0.0	$1.9 \cdot 10^{-1}$	0.0	$1.6 \cdot 10^{-1}$	$3.1 \cdot 10^{-1}$
Diuron 1	$kg \cdot ha^{-1}$	1.9	0.0	0.0	0.0	0.0	0.0	$3.2 \cdot 10^{-1}$	$7.7 \cdot 10^{-1}$
Diuron 2	$kg \cdot ha^{-1}$	0.0	2.2	0.0	0.0	0.0	0.0	$3.7 \cdot 10^{-1}$	$9.0 \cdot 10^{-1}$
Flumioxazin	$kg \cdot ha^{-1}$	0.0	0.0	0.0	$9.0 \cdot 10^{-2}$	0.0	$3.1 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$
Glyphosate	$kg \cdot ha^{-1}$	1.7	$8.4 \cdot 10^{-1}$	1.1	1.8	$9.7 \cdot 10^{-1}$	$8.8 \cdot 10^{-1}$	1.2	$4.0 \cdot 10^{-1}$
Insecticides									
Abamectin 2	$kg \cdot ha^{-1}$	$6.8 \cdot 10^{-3}$	0.0	$8.5 \cdot 10^{-3}$	$3.4 \cdot 10^{-2}$	0.0	0.0	$8.2 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$
Abamectin 1	$kg \cdot ha^{-1}$	$2.5 \cdot 10^{-2}$	$1.4 \cdot 10^{-2}$	$2.9 \cdot 10^{-2}$	0.0	$4.1 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$
Mineral oil	$kg \cdot ha^{-1}$	$2.5 \cdot 10^{1}$	5.1	$3.0 \cdot 10^{1}$	$2.8 \cdot 10^{1}$	$2.5 \cdot 10^{1}$	$2.4 \cdot 10^{1}$	$2.3 \cdot 10^{1}$	9.0
Bifenthrin	$kg \cdot ha^{-1}$	0.0	0.0	0.0	0.0	$3.6 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$	$1.2 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$
Buprofezin	$kg \cdot ha^{-1}$	0.0	$6.5 \cdot 10^{-1}$	0.0	$7.0 \cdot 10^{-1}$	0.0	0.0	$2.3 \cdot 10^{-1}$	$3.5 \cdot 10^{-1}$
Phosmet	$kg \cdot ha^{-1}$	$4.7 \cdot 10^{-2}$	$4.7 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	$1.6 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$
Pyriproxyfen	$kg \cdot ha^{-1}$	0.0	$2.1 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$	$2.9 \cdot 10^{-1}$	$2.8 \cdot 10^{-1}$	$1.9 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$
Spinosad	$kg \cdot ha^{-1}$	0.0	$6.8 \cdot 10^{-2}$	0.0	0.0	0.0	0.0	$1.1 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$
Tau-fluvalinate	$kg \cdot ha^{-1}$	$5.1 \cdot 10^{-1}$	0.0	0.0	0.0	0.0	0.0	$8.4 \cdot 10^{-2}$	$2.1 \cdot 10^{-1}$
Growth regulators									
Naphthaleneacetic acid	$kg \cdot ha^{-1}$	$2.5 \cdot 10^{-1}$	0.0	0.0	0.0	0.0	0.0	$4.2 \cdot 10^{-2}$	$1.0 \cdot 10^{-1}$
Dispersants									
Polyether silicone copolymer	$kg \cdot ha^{-1}$	$8.8 \cdot 10^{-1}$	$3.7 \cdot 10^{-1}$	$4.2 \cdot 10^{-1}$	$7.5 \cdot 10^{-1}$	$6.7 \cdot 10^{-1}$	$4.8 \cdot 10^{-1}$	$5.9 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$
Nutrient									
Molasses	$kg \cdot ha^{-1}$	2.4	2.6	0.0	0.0	0.0	0.0	$8.4 \cdot 10^{-1}$	1.3
On-field emissions									
Direct N_2O	$kg \cdot ha^{-1}$	1.6	3.7	$3.9 \cdot 10^{-1}$	8.2	$1.1 \cdot 10^{1}$	6.4	5.2	4.0
Indirect N_2O (from NO_3-)	$kg \cdot ha^{-1}$	$2.7 \cdot 10^{-1}$	$6.1 \cdot 10^{-1}$	$6.4 \cdot 10^{-2}$	1.3	1.8	1.1	$8.5 \cdot 10^{-1}$	$6.5 \cdot 10^{-1}$
Indirect N_2O (from NH_3)	$kg \cdot ha^{-1}$	$1.9 \cdot 10^{-1}$	$2.7 \cdot 10^{-1}$	$2.8 \cdot 10^{-2}$	$5.9 \cdot 10^{-1}$	$7.7 \cdot 10^{-1}$	$4.6 \cdot 10^{-1}$	$3.8 \cdot 10^{-1}$	$2.8 \cdot 10^{-1}$
NH_3 volatilised	$kg \cdot ha^{-1}$	$1.0 \cdot 10^{1}$	$1.5 \cdot 10^{1}$	1.5	$3.2 \cdot 10^{1}$	$4.3 \cdot 10^{1}$	$2.5 \cdot 10^{1}$	$2.1 \cdot 10^{1}$	$1.5 \cdot 10^{1}$
NO_2 volatilised	$kg \cdot ha^{-1}$	$5.3 \cdot 10^{-3}$	$1.0 \cdot 10^{-2}$	$9.8 \cdot 10^{-4}$	$4.5 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	$2.1 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$
CO_2 volatilised	$kg \cdot ha^{-1}$	$4.7 \cdot 10^{1}$	0.0	0.0	0.0	0.0	0.0	7.9	$1.9 \cdot 10^{1}$
NO_3^- leached	$kg \cdot ha^{-1}$	$7.0 \cdot 10^{1}$	$1.6 \cdot 10^{2}$	$1.6 \cdot 10^{1}$	$3.4 \cdot 10^{2}$	$4.5 \cdot 10^{2}$	$2.7 \cdot 10^{2}$	$2.2 \cdot 10^{2}$	$1.7 \cdot 10^{2}$
PO_4^{3-} leached	$kg \cdot ha^{-1}$	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.0
PO_4^{3}- run-off	$kg \cdot ha^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$5.4 \cdot 10^{-1}$	$1.4 \cdot 10^{-3}$

Table 6.4. Life cycle inventory metadata for Uruguayan orange production

Input	LCI Name	Type of process	Source
2,4-D dimethyl amine salt 1	RoW: phenoxy-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
2,4-D dimethyl amine salt 2	RoW: phenoxy-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Abamectin 1	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Abamectin 2	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Azoxystrobin	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Bifenthrin	RoW: pyrethroid-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Buprofezin	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Carbendazim	RoW: benzimidazole-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Copper oxychloride	RoW: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Copper sulphate	GLO: copper sulfate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Cuprous oxide 1	RER: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Cuprous oxide 2	RoW: copper oxide production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diesel combustion (harvest and transport of bins)	GLO: diesel, burned in agricultural machinery	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diesel combustion (input application)	GLO: diesel, burned in agricultural machinery	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diesel production (harvest and transport of bins)	RoW: diesel production, petroleum refinery operation	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diesel production (input application)	RoW: diesel production, petroleum refinery operation	agg LCI result, cut-off method	Ecoinvent 3.9.1
Difenoconazole 1	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Difenoconazole 2	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diuron 1	RoW: urea production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Diuron 2	RoW: urea production	agg LCI result, cut-off method	Ecoinvent 3.9.1

Table 6.4. (cont.) Life cycle inventory metadata for uruguayan orange production

Input	LCI Name	Type of process	Source
Electricity production for irrigation	UY: market for electricity, medium voltage	agg LCI result, cut-off method	Ecoinvent 3.9.1
Flumioxazin	RoW: phthalimide-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Glyphosate	RoW: glyphosate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Liquid urea	RoW: urea production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Magnesium sulphate	RoW: magnesium sulfate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Mancozeb 1	RoW: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Mancozeb 2	RoW: mancozeb production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Manganese sulphate	GLO: manganese sulfate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Mineral oil	RoW: paraffin production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Molasses	GLO: market for molasses, from sugar beet	agg LCI result, cut-off method	Ecoinvent 3.9.1
Monoammonium phosphate	RoW: monoammonium phosphate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Phosmet	RoW: organophosphorus-compound production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Phosphoric acid	RoW: phosphoric acid production, dihydrate process	agg LCI result, cut-off method	Ecoinvent 3.9.1
Polyether silicone copolymer	RoW: silicone product production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Potassium chloride	RoW: potassium chloride production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Potassium phosphite	RoW: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.9.1
Potassium phosphite	RoW: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.9.1
Potassium sulphate	RER: potassium sulfate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Pyraclostrobin 1	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Pyraclostrobin 2	RER: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.9.1
Pyriproxyfen	RoW: pyridine-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1

Table 6.4. (cont.) Life cycle inventory metadata for Uruguayan orange production

Input	LCI Name	Type of process	Source
Spinosad	US-RFC: electricity, high voltage, production mix	agg LCI result, cut-off method	Ecoinvent 3.9.1
Spinosad	RoW: Glucose production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Tau-fluvalinate	RoW: pyrethroid-compound production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Transportation by lorry	RoW: transport, freight, lorry 16-32 metric ton, EURO3	agg LCI result, cut-off method	Ecoinvent 3.9.1
Transportation by ship	GLO: transport, freight, sea, container ship	agg LCI result, cut-off method	Ecoinvent 3.9.1
Urea ammonium nitrate	RNA: urea ammonium nitrate production	agg LCI result, cut-off method	Ecoinvent 3.9.1
Zinc sulphate	RoW: zinc monosulfate production	agg LCI result, cut-off method	Ecoinvent 3.9.1

Table 6.5. Reference evapotranspiration (ETo), crop evapotranspiration (ETc) and blue water consumption (BWC), estimated following Allen et al. (1998) (see Eq. 6.1 for details) for the six seasons of study

	2016-2017			2017-2018			2018-2019			2019-2020			2020-2021			2021-2022		
Month	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)
Aug	56.1	48.9	0.0	54.9	47.9	0.0	52.9	46.2	0.0	63.2	55.2	0.0	64.1	55.9	25.7	56.0	48.8	26.6
Sept	69.9	59.4	27.8	79.7	67.7	0.0	84.0	71.4	47.9	76.2	64.8	24.2	79.1	67.2	27.5	0.0	0.0	0.0
Oct	105.4	85.3	26.9	107.2	86.7	25.0	120.1	97.2	51.4	100.4	81.3	0.0	128.9	104.4	74.8	125.9	101.9	71.6
Nov	137.7	103.3	49.5	150.9	113.3	69.8	136.4	102.4	47.5	138.5	103.9	50.5	158.4	118.9	99.0	153.4	115.1	48.7
Dec	152.3	102.5	52.0	163.7	110.2	75.2	144.8	97.5	49.2	147.5	99.3	49.8	156.8	105.5	51.8	187.0	125.8	125.4
Jan	144.5	74.2	27.0	166.9	85.7	52.1	117.2	60.2	0.0	148.8	76.4	0.0	155.1	79.6	52.2	172.2	88.4	26.0
Feb	113.2	70.2	0.0	141.0	87.4	23.8	123.5	76.6	25.6	135.3	83.9	25.6	123.3	76.5	26.5	138.3	85.7	53.9
Mar	109.0	77.2	52.4	126.3	89.4	52.1	103.5	73.3	27.3	116.2	82.3	84.9	104.2	73.7	48.1	96.3	68.2	0.0
Apr	69.1	53.8	25.5	82.2	64.0	27.0	64.9	50.5	27.2	72.4	56.3	26.7	76.3	59.3	0.0	67.7	52.7	26.5
May	39.0	32.3	0.0	41.7	34.6	0.0	36.4	30.2	0.0	46.6	38.7	0.0	45.7	37.9	0.0	41.6	34.5	27.7
Jun	31.8	27.4	0.0	31.3	27.0	0.0	31.1	26.8	0.0	27.3	23.5	0.0	29.7	25.6	0.0	27.2	23.5	0.0
Jul	44.9	39.3	0.0	33.3	29.2	0.0	34.2	29.9	0.0	33.4	29.3	0.0	43.2	37.9	0.0	40.1	35.1	0.0
Tot (mm)	1073.0	773.9	261.2	1179.1	843.0	325.0	1049.1	762.1	276.1	1106.0	794.8	261.7	1164.8	842.4	405.6	1105.7	779.8	406.5

Table 6.5. (cont.) Reference evapotranspiration (ETo), crop evapotranspiration (ETc) and blue water consumption (BWC), estimated following Allen et al. (1998) (see Ec. A3 for details) for the six seasons of study.

Year	$ET_{0,m}$ (mm)	$ET_{c,m}$ (mm)	BWC (mm)
2016-2017	1072.96	773.92	261.20
2017-2018	1179.13	843.01	325.01
2018-2019	1049.07	762.06	276.11
2019-2020	1105.96	794.79	261.71
2020-2021	1164.79	842.39	405.65
2021-2022	1105.69	779.77	406.45

Table 6.6. Transport distances for the inputs used in Uruguayan orange cultivation (Searates, 2023)

Input	Use	Distance by ship (km)	Distance by truck (km)
2,4-D dimethyl amine salt 1	Herbicide	0.0	300.0
2,4-D dimethyl amine salt 2	Herbicide	23142.2	483.2
Abamectin 1	Insecticide	0.0	300.0
Abamectin 2	Insecticide	23142.2	483.2
Azoxystrobin	Fungicide	23142.2	483.2
Bifenthrin	Insecticide	13279.9	540.7
Buprofezin	Insecticide	23142.2	483.2
Carbendazim	Fungicide	23142.2	483.2
Copper oxychloride	Fungicide	0.0	300.0
Copper sulphate	Fertiliser	0.0	300.0
Cuprous oxide 1	Fungicide	12547.5	524.8
Cuprous oxide 2	Fungicide	0.0	3083.2
Difenoconazole 1	Fungicide	0.0	300.0
Difenoconazole 2	Fungicide	23142.2	483.2
Diuron 1	Herbicide	0.0	300.0
Diuron 2	Herbicide	13279.9	540.7
Flumioxazin	Herbicide	23142.2	483.2
Glyphosate	Herbicide	23142.2	483.2
Liquid urea	Fertiliser	0.0	300.0
Magnesium sulphate	Fertiliser	23142.2	483.2
Mancozeb 1	Fungicide	0.0	2600.0
Mancozeb 2	Fungicide	15617.8	913.9
Manganese sulphate	Fertiliser	23142.2	483.2
Mineral oil	Insecticide	0.0	1100.0
Molasses	Nutrient	0.0	300.0
Monoammonium phosphate	Fertiliser	13279.9	540.7
Naphthaleneacetic acid	Growth regulator	0.0	300.0
Phosmet	Insecticide	12340.7	560.9
Phosphoric acid	Fertiliser	23142.2	483.2
Polyether silicone copolymer	Dispersant	12340.7	560.9
Potassium chloride	Fertiliser	0.0	300.0
Potassium phosphite	Fertiliser	0.0	300.0
Potassium sulphate	Fertiliser	13054.1	443.4
Pyraclostrobin 1	Fungicide	17041.7	444.4
Pyraclostrobin 2	Fungicide	10864.0	439.8

Table 6.6. (cont.) Transport distances for the inputs used in Uruguayan orange cultivation (Searates, 2023)

Input	Use	Distance by ship (km)	Distance by truck (km)
Pyriproxyfen	Insecticide	23142.2	483.2
Spinosad	Insecticide	12340.7	560.9
Tau-fluvalinate	Insecticide	13279.9	540.7
Urea ammonium nitrate	Fertiliser	12340.7	560.9
Zinc sulphate	Fertiliser	23142.2	483.2
Considering the size of the country, the average distance for Uruguayan products is established at 300km			

Table 6.7. Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 ha

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
Water consumption-related impacts							
BWS (m^3eq. · ha^{-1})	AWARE (Boulay et al., 2018)	$9.0\cdot10^{1} \pm 4.1\cdot10^{1}$	$2.7\cdot10^{2} \pm 2.3\cdot10^{2}$	5.4 ± 3.3	$1.4\cdot10^{-1} \pm 2.7\cdot10^{-2}$	$1.2\cdot10^{3} \pm 2.7\cdot10^{2}$	0.0 ± 0.0
WC-HH (DALY · ha^{-1})	LC-IMPACT1.3 (Verones et al., 2020)	$3.2\cdot10^{-6} \pm 2.1\cdot10^{-6}$	$1.6\cdot10^{-7} \pm 1.1\cdot10^{-7}$	$5.8\cdot10^{-10} \pm 3.6\cdot10^{-10}$	$1.2\cdot10^{-9} \pm 2.3\cdot10^{-10}$	$1.5\cdot10^{-5} \pm 3.2\cdot10^{-6}$	0.0 ± 0.0
WC-Es (PDF · ha^{-1})	LC-IMPACT1.3 (Verones et al., 2020)	$9.5\cdot10^{-14} \pm 2.9\cdot10^{-14}$	$9.0\cdot10^{-12} \pm 7.9\cdot10^{-12}$	$2.1\cdot10^{-14} \pm 1.3\cdot10^{-14}$	$4.8\cdot10^{-16} \pm 9.5\cdot10^{-17}$	$6.2\cdot10^{-12} \pm 1.3\cdot10^{-12}$	0.0 ± 0.0
Water degradation-related impacts							
MEu (kg N eq. · ha^{-1})	EN15804 A2+	$3.8\cdot10^{-1} \pm 1.1\cdot10^{-1}$	$4.0\cdot10^{-1} \pm 2.5\cdot10^{-1}$	$4.2\cdot10^{-1} \pm 2.8\cdot10^{-1}$	$1.2\cdot10^{-1} \pm 2.4\cdot10^{-2}$	$1.8\cdot10^{-2} \pm 9.1\cdot10^{-3}$	$5.1\cdot10^{1} \pm 3.9\cdot10^{1}$
FWEu (kg P eq. · ha^{-1})	EN15804 A2+	$3.8\cdot10^{-1} \pm 1.2\cdot10^{-1}$	$1.0\cdot10^{-1} \pm 4.1\cdot10^{-2}$	$4.9\cdot10^{-3} \pm 3.0\cdot10^{-3}$	$5.5\cdot10^{-3} \pm 1.1\cdot10^{-3}$	$1.5\cdot10^{-3} \pm 7.4\cdot10^{-4}$	$5.6\cdot10^{-1} \pm 4.7\cdot10^{-4}$
FWET (CTUe · ha^{-1})	USEtox 2.12 (Rosenbaum et al., 2008)	$2.7\cdot10^{7} \pm 9.2\cdot10^{6}$	$5.2\cdot10^{6} \pm 5.1\cdot10^{6}$	$8.2\cdot10^{4} \pm 4.3\cdot10^{3}$	$9.7\cdot10^{4} \pm 2.2\cdot10^{4}$	$6.7\cdot10^{4} \pm 9.2\cdot10^{3}$	$1.0\cdot10^{5} \pm 3.3\cdot10^{4}$
WD-Es (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$4.0\cdot10^{-6} \pm 1.2\cdot10^{-6}$	$8.5\cdot10^{-6} \pm 5.3\cdot10^{-6}$	$2.1\cdot10^{-5} \pm 1.4\cdot10^{-5}$	$6.1\cdot10^{-6} \pm 1.2\cdot10^{-6}$	$2.1\cdot10^{-6} \pm 1.0\cdot10^{-6}$	$5.2\cdot10^{-7} \pm 6.3\cdot10^{-8}$
PDP (m^3 · ha^{-1})	(Pierrat et al., 2023)	n.q.	n.q.	n.q.	n.q.	n.q.	$1.1\cdot10^{-2} \pm 8.9\cdot10^{-3}$
Impacts on ecosystem services							
EP (kg · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	4.5 ± 1.7	2.0 ± 1.1	$-1.1\cdot10^{-1} \pm 6.0\cdot10^{-2}$	$3.3\cdot10^{-1} \pm 6.4\cdot10^{-2}$	-8.8 ± 4.3	$2.9\cdot10^{3} \pm 0.0$
GWRRP (m^3 · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$1.6 \pm 5.1\cdot10^{-1}$	$8.7\cdot10^{-1} \pm 4.2\cdot10^{-1}$	$3.3\cdot10^{-1} \pm 1.9\cdot10^{-1}$	$1.7\cdot10^{-1} \pm 3.3\cdot10^{-2}$	$-6.3\cdot10^{-2} \pm 3.1\cdot10^{-2}$	$-3.0\cdot10^{2} \pm 0.0$
IRP (m^3 · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$1.9\cdot10^{2} \pm 6.0\cdot10^{1}$	$2.0\cdot10^{2} \pm 1.1\cdot10^{2}$	$1.1\cdot10^{2} \pm 6.5\cdot10^{1}$	$4.5\cdot10^{1} \pm 8.9$	$5.1\cdot10^{1} \pm 2.5\cdot10^{1}$	$6.2\cdot10^{2} \pm 2.6\cdot10^{-10}$
PFRP (mol · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$6.3\cdot10^{4} \pm 2.0\cdot10^{4}$	$6.5\cdot10^{4} \pm 3.6\cdot10^{4}$	$3.8\cdot10^{4} \pm 2.3\cdot10^{4}$	$1.5\cdot10^{4} \pm 2.9\cdot10^{3}$	$6.5\cdot10^{3} \pm 3.2\cdot10^{3}$	$1.6\cdot10^{6} \pm 0.0$
SOCRP (kg · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$4.9\cdot10^{2} \pm 1.6\cdot10^{2}$	$2.9\cdot10^{2} \pm 1.4\cdot10^{2}$	$8.8\cdot10^{1} \pm 5.2\cdot10^{1}$	$4.6\cdot10^{1} \pm 9.1$	9.0 ± 4.5	$1.2\cdot10^{4} \pm 0.0$

Table 6.7. (cont.) Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 ha

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
Impacts on biodiversity							
MET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$4.7·10^{-7} ± 1.4·10^{-7}$	$1.1·10^{-6} ± 6.6·10^{-7}$	$2.6·10^{-6} ± 1.7·10^{-6}$	$7.6·10^{-7} ± 1.5·10^{-7}$	$2.6·10^{-7} ± 1.3·10^{-7}$	$4.9·10^{-8} ± 1.6·10^{-8}$
MEu (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$5.0·10^{-11} ± 1.6·10^{-11}$	$6.1·10^{-11} ± 4.1·10^{-11}$	$3.3·10^{-12} ± 2.1·10^{-12}$	$1.3·10^{-11} ± 2.6·10^{-12}$	$4.3·10^{-13} ± 2.1·10^{-13}$	$8.4·10^{-8} ± 6.4·10^{-8}$
CC FWEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$1.1·10^{-11} ± 3.2·10^{-12}$	$3.2·10^{-11} ± 2.2·10^{-11}$	$6.6·10^{-12} ± 4.2·10^{-12}$	$7.4·10^{-12} ± 1.4·10^{-12}$	$5.9·10^{-13} ± 2.9·10^{-13}$	$1.5·10^{-10} ± 1.1·10^{-10}$
FWC FWEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$5.4·10^{-12} ± 1.5·10^{-12}$	$1.7·10^{-11} ± 1.1·10^{-11}$	$2.2·10^{-13} ± 1.4·10^{-13}$	$4.4·10^{-13} ± 8.6·10^{-14}$	$4.7·10^{-14} ± 2.3·10^{-14}$	0.0± 0.0
FWET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$3.3·10^{-6} ± 9.8·10^{-7}$	$7.4·10^{-6} ± 4.6·10^{-6}$	$1.8·10^{-5} ± 1.2·10^{-5}$	$5.4·10^{-6} ± 1.0·10^{-6}$	$1.9·10^{-6} ± 9.2·10^{-7}$	$1.4·10^{-8} ± 8.1·10^{-9}$
FWEu (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.5·10^{-7} ± 8.1·10^{-8}$	$6.8·10^{-8} ± 2.7·10^{-8}$	$3.3·10^{-9} ± 2.0·10^{-9}$	$3.7·10^{-9} ± 7.2·10^{-10}$	$1.0·10^{-9} ± 5.0·10^{-10}$	$3.8·10^{-7} ± 3.1·10^{-10}$
CC TEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$4.2·10^{-7} ± 1.2·10^{-7}$	$1.2·10^{-6} ± 8.1·10^{-7}$	$2.4·10^{-7} ± 1.5·10^{-7}$	$2.7·10^{-7} ± 5.3·10^{-8}$	$2.1·10^{-8} ± 1.1·10^{-8}$	$5.4·10^{-6} ± 4.1·10^{-6}$
FWC TEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$4.2·10^{-8} ± 1.2·10^{-8}$	$1.3·10^{-7} ± 8.4·10^{-8}$	$1.7·10^{-9} ± 1.1·10^{-9}$	$3.4·10^{-9} ± 6.7·10^{-10}$	$2.5·10^{-6} ± 5.3·10^{-7}$	0.0± 0.0
TAc (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$9.6·10^{-7} ± 3.0·10^{-7}$	$3.4·10^{-7} ± 1.8·10^{-7}$	$2.0·10^{-7} ± 1.4·10^{-7}$	$7.4·10^{-8} ± 1.5·10^{-8}$	$8.3·10^{-9} ± 4.1·10^{-9}$	$8.8·10^{-6} ± 6.3·10^{-6}$
TET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.3·10^{-5} ± 6.9·10^{-6}$	$5.5·10^{-5} ± 3.4·10^{-5}$	$1.4·10\text{-}04 ± 9.0·10^{-5}$	$4.0·10^{-5} ± 7.8·10^{-6}$	$1.4·10^{-5} ± 6.8·10^{-6}$	$1.2·10^{-5} ± 4.2·10^{-6}$
POF Es (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$9.9·10^{-8} ± 2.8·10^{-8}$	$1.0·10^{-7} ± 6.0·10^{-8}$	$1.4·10^{-7} ± 9.6·10^{-8}$	$5.5·10^{-8} ± 1.1·10^{-8}$	$6.2·10^{-9} ± 3.1·10^{-9}$	$2.1·10^{-9} ± 2.0·10^{-9}$
LU (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017) Chaudhary and Brooks (2018)	$9.5·10^{-8} ± 2.9·10^{-8}$	$7.2·10^{-8} ± 3.8·10^{-8}$	$1.5·10^{-8} ± 9.2·10^{-9}$	$1.6·10^{-8} ± 3.1·10^{-9}$	$7.1·10^{-8} ± 3.5·10^{-8}$	$4.4·10^{-7} ± 0.0$

Table 6.7. (cont.) Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 ha

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
BL (species · ha^{-1})	**ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)**	**$2.9 \cdot 10^{-5} \pm 8.6 \cdot 10^{-6}$**	**$6.5 \cdot 10^{-5} \pm 4.1 \cdot 10^{-5}$**	**1.6·10-04 ± 1.0·10-04**	**$4.6 \cdot 10^{-5} \pm 9.1 \cdot 10^{-6}$**	**$1.9 \cdot 10^{-5} \pm 8.0 \cdot 10^{-6}$**	**$3.0 \cdot 10^{-5} \pm 1.1 \cdot 10^{-5}$**

BWS: blue water scarcity - WC HH: damage to human health due to water consumption - WC Es: damage to ecosystems due to water consumption - MEu: marine eutrophication - FWEu: freshwater eutrophication - FWET: freshwater ecotoxicity - WD Es: damage to ecosystems due to water degradation - PDP: pollution deprivation potential - EP: erosion potential - GWRRP: groundwater regeneration reduction potential - IRP: infiltration reduction potential - PFRP: physicochemical filtration reduction potential - MET: marine ecotoxicity - CC FWEs: impacts of climate change on freshwater ecosystems - FWC FWEs: impacts of freshwater consumption on freshwater ecosystems - CC TEs: impacts of climate change on terrestrial ecosystems - FWC TEs: impacts of freshwater consumption on terrestrial ecosystems - TAc: terrestrial acidification - TET: terrestrial ecotoxicity - POF Es: impacts of photochemical ozone formation on (terrestrial) ecosystems - LU: land use - BL: biodiversity loss. DALY: disability-adjusted life year - PDF: potentially disappeared fraction of species - CTUe: comparative toxic unit (ecotoxicity potential) - n.q.: not quantified

Table 6.8. Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 tonne

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
Water consumption-related impacts							
BWS (m^3eq. · ha^{-1})	AWARE (Boulay et al., 2018)	4.9 ± 2.2	$1.6\cdot10^{1} \pm 1.7\cdot10^{1}$	$3.2\cdot10^{-1} \pm 2.7\cdot10^{-1}$	$8.1\cdot10^{-3} \pm 4.3\cdot10^{-3}$	$6.7\cdot10^{1} \pm 3.0\cdot10^{1}$	0.0 ± 0.0
WC-HH (DALY · ha^{-1})	LC-IMPACT1.3 (Verones et al., 2020)	$1.7\cdot10^{-7} \pm 1.3\cdot10^{-7}$	$9.6\cdot10^{-9} \pm 8.3\cdot10^{-9}$	$3.4\cdot10^{-11} \pm 3.0\cdot10^{-11}$	$6.9\cdot10^{-11} \pm 3.6\cdot10^{-11}$	$8.3\cdot10^{-7} \pm 2.9\cdot10^{-7}$	0.0 ± 0.0
WC-Es (PDF · ha^{-1})	LC-IMPACT1.3 (Verones et al., 2020)	$5.7\cdot10^{-15} \pm 3.3\cdot10^{-15}$	$5.3\cdot10^{-13} \pm 5.7\cdot10^{-13}$	$1.2\cdot10^{-15} \pm 1.1\cdot10^{-15}$	$2.9\cdot10^{-17} \pm 1.5\cdot10^{-17}$	$3.4\cdot10^{-13} \pm 1.2\cdot10^{-13}$	0.0 ± 0.0
Water degradation-related impacts							
MEu (kg N eq. · ha^{-1})	EN15804 A2+	$2.2\cdot10^{-2} \pm 1.2\cdot10^{-2}$	$2.3\cdot10^{-2} \pm 1.9\cdot10^{-2}$	$2.5\cdot10^{-2} \pm 2.2\cdot10^{-2}$	$7.3\cdot10^{-3} \pm 3.8\cdot10^{-3}$	$1.0\cdot10^{-3} \pm 5.6\cdot10^{-4}$	$3.0 \pm 3.9\cdot10^{1}$
FWEu (kg P eq. · ha^{-1})	EN15804 A2+	$2.2\cdot10^{-2} \pm 1.2\cdot10^{-2}$	$6.0\cdot10^{-3} \pm 3.8\cdot10^{-3}$	$2.9\cdot10^{-4} \pm 2.5\cdot10^{-4}$	$3.2\cdot10^{-4} \pm 1.7\cdot10^{-4}$	$8.5\cdot10^{-5} \pm 4.5\cdot10^{-5}$	$3.8\cdot10^{-2} \pm 4.7\cdot10^{-4}$
FWET (CTUe · ha^{-1})	USEtox 2.12 (Rosenbaum et al., 2008)	$1.6\cdot10^{6} \pm 8.4\cdot10^{5}$	$3.1\cdot10^{5} \pm 7.7\cdot10^{5}$	$4.9\cdot10^{3} \pm 3.1\cdot10^{2}$	$5.8\cdot10^{3} \pm 3.7\cdot10^{3}$	$3.8\cdot10^{3} \pm 8.1\cdot10^{2}$	$6.1\cdot10^{3} \pm 3.3\cdot10^{4}$
WD-Es (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.4\cdot10^{-7} \pm 1.3\cdot10^{-7}$	$5.0\cdot10^{-7} \pm 4.2\cdot10^{-7}$	$1.2\cdot10^{-6} \pm 1.1\cdot10^{-6}$	$3.6\cdot10^{-7} \pm 1.9\cdot10^{-7}$	$1.2\cdot10^{-7} \pm 6.5\cdot10^{-8}$	$3.4\cdot10^{-8} \pm 1.4\cdot10^{-8}$
PDP (m^3 · ha^{-1})	(Pierrat et al., 2023)	n.q.	n.q.	n.q.	n.q.	n.q.	$5.7\cdot10^{-4} \pm 4.7\cdot10^{-4}$
Impacts on ecosystem services							
EP (kg · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$2.6\cdot10^{-1} \pm 1.4\cdot10^{-1}$	$1.1\cdot10^{-1} \pm 8.4\cdot10^{-2}$	$-6.5\cdot10^{-3} \pm 5.4\cdot10^{-3}$	$1.9\cdot10^{-2} \pm 1.0\cdot10^{-2}$	$-5.0\cdot10^{-1} \pm 2.7\cdot10^{-1}$	$1.7\cdot10^{2} \pm 7.5$
GWRRP (m^3 · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$9.2\cdot10^{-2} \pm 4.9\cdot10^{-2}$	$5.2\cdot10^{-2} \pm 3.8\cdot10^{-2}$	$2.0\cdot10^{-2} \pm 1.7\cdot10^{-2}$	$9.9\cdot10^{-3} \pm 5.2\cdot10^{-3}$	$-3.6\cdot10^{-3} \pm 1.9\cdot10^{-3}$	$-1.8\cdot10^{1} \pm 1.5\cdot10^{1}$
IRP (m^3 · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$1.1\cdot10^{1} \pm 6.0$	$1.2\cdot10^{1} \pm 9.3$	6.6 ± 5.6	2.7 ± 1.4	2.9 ± 1.6	$3.6\cdot10^{1} \pm 4.0\cdot10^{4}$
PFRP (mol · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$3.7\cdot10^{3} \pm 2.0\cdot10^{3}$	$3.9\cdot10^{3} \pm 3.0\cdot10^{3}$	$2.3\cdot10^{3} \pm 1.9\cdot10^{3}$	$8.6\cdot10^{2} \pm 4.5\cdot10^{2}$	$3.7\cdot10^{2} \pm 2.0\cdot10^{2}$	$9.4\cdot10^{4} \pm 0.0$
SOCRP (kg · ha^{-1})	LANCA® v 2022.1 (Horn and Till, 2022)	$2.9\cdot10^{1} \pm 1.5\cdot10^{1}$	$1.7\cdot10^{1} \pm 1.3\cdot10^{1}$	5.3 ± 4.4	2.7 ± 1.4	$5.1\cdot10^{-1} \pm 2.7\cdot10^{-1}$	$7.0\cdot10^{2} \pm 0.0$

Table 6.8. (cont.) Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 tonne

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
Impacts on biodiversity							
MET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.8\cdot10^{-8} \pm 1.5\cdot10^{-8}$	$6.2\cdot10^{-8} \pm 5.2\cdot10^{-8}$	$1.5\cdot10^{-7} \pm 1.4\cdot10^{-7}$	$4.5\cdot10^{-8} \pm 2.4\cdot10^{-8}$	$1.5\cdot10^{-8} \pm 8.1\cdot10^{-9}$	$2.9\cdot10^{-9} \pm 1.5\cdot10^{-9}$
MEu (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$3.0\cdot10^{-12} \pm 1.7\cdot10^{-12}$	$3.6\cdot10^{-12} \pm 3.1\cdot10^{-12}$	$2.0\cdot10^{-13} \pm 1.7\cdot10^{-13}$	$7.8\cdot10^{-13} \pm 4.1\cdot10^{-13}$	$2.4\cdot10^{-14} \pm 1.3\cdot10^{-14}$	$4.9\cdot10^{-9} \pm 4.8\cdot10^{-9}$
CC FWEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$6.8\cdot10^{-13} \pm 3.8\cdot10^{-13}$	$1.9\cdot10^{-12} \pm 1.7\cdot10^{-12}$	$3.9\cdot10^{-13} \pm 3.4\cdot10^{-13}$	$4.4\cdot10^{-13} \pm 2.3\cdot10^{-13}$	$3.3\cdot10^{-14} \pm 1.8\cdot10^{-14}$	$8.6\cdot10^{-12} \pm 8.2\cdot10^{-12}$
FWC FWEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$3.2\cdot10^{-13} \pm 1.7\cdot10^{-13}$	$9.9\cdot10^{-13} \pm 8.3\cdot10^{-13}$	$1.3\cdot10^{-14} \pm 1.1\cdot10^{-14}$	$2.6\cdot10^{-14} \pm 1.4\cdot10^{-14}$	$2.7\cdot10^{-15} \pm 1.4\cdot10^{-15}$	0.0 ± 0.0
FWET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$1.9\cdot10^{-7} \pm 1.1\cdot10^{-7}$	$4.4\cdot10^{-7} \pm 3.7\cdot10^{-7}$	$1.1\cdot10^{-6} \pm 9.5\cdot10^{-7}$	$3.2\cdot10^{-7} \pm 1.7\cdot10^{-7}$	$1.1\cdot10^{-7} \pm 5.7\cdot10^{-8}$	$8.2\cdot10^{-10} \pm 5.1\cdot10^{-10}$
FWEu (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$1.5\cdot10^{-8} \pm 7.9\cdot10^{-9}$	$4.0\cdot10^{-9} \pm 2.6\cdot10^{-9}$	$1.9\cdot10^{-10} \pm 1.7\cdot10^{-10}$	$2.2\cdot10^{-10} \pm 1.1\cdot10^{-10}$	$5.7\cdot10^{-11} \pm 3.1\cdot10^{-11}$	$2.5\cdot10^{-8} \pm 1.1\cdot10^{-8}$
CC TEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.5\cdot10^{-8} \pm 1.4\cdot10^{-8}$	$6.9\cdot10^{-8} \pm 6.2\cdot10^{-8}$	$1.4\cdot10^{-8} \pm 1.2\cdot10^{-8}$	$1.6\cdot10^{-8} \pm 8.4\cdot10^{-9}$	$1.2\cdot10^{-9} \pm 6.5\cdot10^{-10}$	$3.2\cdot10^{-7} \pm 3.0\cdot10^{-7}$
FWC TEs (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$2.5\cdot10^{-9} \pm 1.3\cdot10^{-9}$	$7.7\cdot10^{-9} \pm 6.5\cdot10^{-9}$	$1.0\cdot10^{-10} \pm 8.6\cdot10^{-11}$	$2.0\cdot10^{-10} \pm 1.1\cdot10^{-10}$	$1.4\cdot10^{-7} \pm 4.8\cdot10^{-8}$	0.0 ± 0.0
TAc (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$5.6\cdot10^{-8} \pm 3.0\cdot10^{-8}$	$2.0\cdot10^{-8} \pm 1.5\cdot10^{-8}$	$1.2\cdot10^{-8} \pm 1.0\cdot10^{-8}$	$4.4\cdot10^{-9} \pm 2.3\cdot10^{-9}$	$4.7\cdot10^{-10} \pm 2.5\cdot10^{-10}$	$5.2\cdot10^{-7} \pm 4.7\cdot10^{-7}$
TET (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$1.4\cdot10^{-6} \pm 7.6\cdot10^{-7}$	$3.2\cdot10^{-6} \pm 2.7\cdot10^{-6}$	$8.0\cdot10^{-6} \pm 7.1\cdot10^{-6}$	$2.3\cdot10^{-6} \pm 1.2\cdot10^{-6}$	$7.8\cdot10^{-7} \pm 4.2\cdot10^{-7}$	$7.3\cdot10^{-7} \pm 3.8\cdot10^{-7}$
POF Es (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)	$5.8\cdot10^{-9} \pm 3.1\cdot10^{-9}$	$5.9\cdot10^{-9} \pm 4.8\cdot10^{-9}$	$8.5\cdot10^{-9} \pm 7.5\cdot10^{-9}$	$3.2\cdot10^{-9} \pm 1.7\cdot10^{-9}$	$3.5\cdot10^{-10} \pm 1.9\cdot10^{-10}$	$1.6\cdot10^{-10} \pm 2.2\cdot10^{-10}$
LU (species · ha^{-1})	ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017) Chaudhary and Brooks (2018)	$5.6\cdot10^{-9} \pm 3.0\cdot10^{-9}$	$4.2\cdot10^{-9} \pm 3.2\cdot10^{-9}$	$9.2\cdot10^{-10} \pm 7.8\cdot10^{-10}$	$9.2\cdot10^{-10} \pm 4.9\cdot10^{-10}$	$4.0\cdot10^{-9} \pm 2.2\cdot10^{-9}$	$2.6\cdot10^{-8} \pm 1.1\cdot10^{-8}$

Table 6.8. (cont.) Average impact results per stage and standard deviation of cradle to farm gate cultivation of orange in Uruguay. FU = 1 tonne

	Impact assessment method	Pesticides production	Fertilizers production	Transport	Machinery operations	Irrigation	Field emissions + land occupation
BL (species · ha^{-1})	**ReCiPe 2016 v1.1 Endpoint (H) (Huijbregts et al., 2017)**	**$1.7 \cdot 10^{-6} \pm 9.4 \cdot 10^{-7}$**	**$3.9 \cdot 10^{-6} \pm 3.2 \cdot 10^{-6}$**	**$9.2 \cdot 10^{-6} \pm 8.2 \cdot 10^{-6}$**	**$2.7 \cdot 10^{-6} \pm 1.4 \cdot 10^{-6}$**	**$1.0 \cdot 10^{-6} \pm 5.1 \cdot 10^{-7}$**	**$1.8 \cdot 10^{-6} \pm 1.1 \cdot 10^{-6}$**

BWS: blue water scarcity - WC HH: damage to human health due to water consumption - WC Es: damage to ecosystems due to water consumption - MEu: marine eutrophication - FWEu: freshwater eutrophication - FWET: freshwater ecotoxicity - WD Es: damage to ecosystems due to water degradation - PDP: pollution deprivation potential - EP: erosion potential - GWRRP: groundwater regeneration reduction potential - IRP: infiltration reduction potential - PFRP: physicochemical filtration reduction potential - MET: marine ecotoxicity - CC FWEs: impacts of climate change on freshwater ecosystems - FWC FWEs: impacts of freshwater consumption on freshwater ecosystems - CC TEs: impacts of climate change on terrestrial ecosystems - FWC TEs: impacts of freshwater consumption on terrestrial ecosystems - TAc: terrestrial acidification - TET: terrestrial ecotoxicity - POF Es: impacts of photochemical ozone formation on (terrestrial) ecosystems - LU: land use - BL: biodiversity loss. DALY: disability-adjuCsted life year - PDF: potentially disappeared fraction of species - CTUe: comparative toxic unit (ecotoxicity potential) - n.q.: not quantified

Eq. 6.1. Equations and data sources for calculation of blue water consumption for irrigation

$$\mathbf{D_{r,i} = D_{r,i-1} - P_{eff,i} - I_i - CR_i + ET_{c,i} + DP_i} \qquad \text{(equation 1)}$$

The subscript "i" refers to daily values.

$\mathbf{D_{r,i}}$ and $\mathbf{D_{r,i-1}}$ refer to moisture depletion in the root zone (mm) - the amount of water missing with respect to the field capacity.

Initial $\mathbf{D_{r,i-1}}$ was considered zero since it is assumed that the analysis starts after heavy rain or irrigation which means that, according to Allen et al. (1998), the moisture content in the root zone is close to field capacity and $\mathbf{D_{r,i-1}} \approx 0$.

$\mathbf{P_{eff,i}}$: effective precipitation (mm). Retrieved from INIA Salto Grande meteorological station (INIA-GRAS, 2023).

$\mathbf{I_i}$: net layer of irrigation on the day i that infiltrates the soil (mm)

Taking as a premise that irrigation is not necessary as long as the crop has readily available water in the soil to consume, the following assumption is made; in the event that the value of the initial moisture depletion in the root zone minus the effective precipitation of that day (which is considered to occur at the beginning of the period) is greater than the RAW value, the dose of irrigation water ($\mathbf{I_i}$) needed to reach the field capacity is ($\mathbf{D_{r,i-1} - P_{eff,i}}$) is applied. Otherwise, the crop is not irrigated.

RAW: the readily available (extractable) water from the soil root zone (mm). The maximum fraction of the total available water that the crop can extract from the root zone without experiencing water stress.

$RAW_i = p_i \cdot TAW$ (equation 2)

TAW: total water available in the root zone of the soil (mm)

$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r$ (equation 3)

θ_{FC}: moisture content at field capacity ($m^3 \cdot m^{-3}$). Retrieved from INIA-GESIR (2023) for CONEAT 9.3 soils.

θ_{WP}: moisture content at permanent wilting point ($m^3 \cdot m^{-3}$). Retrieved from INIA-GESIR (2023) for CONEAT 9.3 soils.

Z_r: root depth (m). Retrieved from Goñi and Otero (2009).

p_i: average fraction of the total water available in the soil that can be depleted from the root zone before moisture stress (dimensionless). This value for citrus fruits was calculated according to Allen et al. (1998) as:

$p_i = 0.4 + 0.04 \cdot (5 - \mathbf{ET_{c,i}})$ (equation 4)

$\mathbf{ET_{c,i}}$: crop evapotranspiration on the day i (mm). It was estimated by following FAO guidelines (Allen et al., 1998):

$\mathbf{ET_{c,i}} = K_c \cdot ET_{0,i}$ (equation 5)

K_c: crop coefficient (dimensionless)

$ET_{0,i}$: reference crop evapotranspiration ($mm \cdot day^{-1}$). To obtain daily $ET_{0,i}$, climate data for the studied seasons from INIA Salto Grande meteorological station (INIA-GRAS, 2023) was used as an input for the Penman-Monteith equation (Allen et al., 1998). Then, by adding up those daily values, the monthly $ET_{0,m}$ ($mm \cdot month^{-1}$) values were calculated, which were subsequently multiplied by the monthly K_c for Uruguayan citrus fruits obtained from García Petillo and Castel (2007) to obtain $ET_{c,m}$ (mm · month^{-1}). Finally, the monthly $ET_{c,m}$ (mm · month^{-1}) values were added up to obtain the $ET_{c,s}$ of the studied seasons (mm · season^{-1}), reported in Table 6.5.

CR_i: capillary rise from the groundwater table on the day i (mm). It is assumed to be zero since the water table in Uruguay is more than 1 m below the root zone (Allen et al., 1998; Fan et al., 2013)

DP_i: water loss from the root zone by deep percolation on the day i (mm) after heavy rain or irrigation. It was calculated using equation 1, considering that the values of Dr,i and CRi are zero; this means that there is no moisture depletion in the soil root zone or capillary rise from the groundwater table after heavy rain or irrigation, thus equation (1) becomes:

$$\mathbf{DP_i = P_{eff,i} + I_i - ET_{c,i} - D_{r,i-1}} \qquad \text{(equation 6)}$$

If the system is below its field capacity, this value is null.

Eq. 6.2. Equations and data sources for calculation of pollution deprivation potential due to on-field emissions. Adapted from Pierrat et al. (2023).

$PDP_j^s = q_j^s \cdot s^s \cdot \sum_k WC_j^{s,k}$

$\boldsymbol{PDP_j^s}$= pollution deprivation potential of sector j in season s for the river basin

$\boldsymbol{q_j^s}$= Boolean water quality assessment for sector j in season s (equals one if water quality is insufficient) = **1**

$\boldsymbol{s^s}$= ratio of water availability to demand in season s (ratio between 0 and 1) = **1**

$s^s = \frac{A^s}{\sum_{k,j} WC_j^{s,k}}$ *for* $0 \leq \frac{A^s}{\sum_{k,j} WC_j^{s,k}} \leq 1$ $\quad$ $s^s = 1$ *otherwise*

$\boldsymbol{A^s}$ = season water availability (m^3) = $5.06 \cdot 10^{10}$ - Uruguay river hydrographic region (MVOTMA, 2020)

$\boldsymbol{WC_j^{s,k}}$ = water consumption of j user k in sector j in season s

2016-2017	$1.42 \cdot 10^4$	
2017-2018	$1.76 \cdot 10^4$	
2018-2019	$1.50 \cdot 10^4$	
2019-2020	$1.42 \cdot 10^4$	
2020-2021	$2.20 \cdot 10^4$	
2021-2022	$2.21 \cdot 10^4$	(From Table 6.5)

$PDP_j^{s,k} = wp_j^{s,k} \cdot PDP_j^s$

$\boldsymbol{PDP_j^{s,k}}$= contribution of user k to PDP

$\boldsymbol{wp_j^{s,k}}$= pollution weighting factor of user k

$$wp_j^{s,k} = \sum_n \left(\frac{r_n^{s,k}}{\sum_k r_n^{s,k}} \cdot \frac{q_{j,n}^s \cdot \left(1 - \frac{c_{lim,j,n}}{c_{j,n}^s}\right)}{\sum_n q_{j,n}^s \cdot \left(1 - \frac{c_{lim,j,n}}{c_{j,n}^s}\right)}\right)$$

$\boldsymbol{r_n^{s,k}}$ = emission of substance n from user k in season s (in kg/season)

	N	P
2016-2017	$8.54 \cdot 10^1$	3.02
2017-2018	$1.92 \cdot 10^2$	3.02
2018-2019	$2.02 \cdot 10^1$	3.01
2019-2020	$4.23 \cdot 10^2$	3.02
2020-2021	$5.56 \cdot 10^2$	3.02
2021-2022	$3.30 \cdot 10^2$	3.02

(From Table 1)

$\boldsymbol{\sum_k r_n^{s,k}}$

N	P
$4.76 \cdot 10^7$	$1.17 \cdot 10^7$

(Ministerio de Ambiente [MA], 2020)

$\boldsymbol{q_{j,n}^s}$=water functionality for quality parameter n of sector j. It is a Boolean equal to 1

if $c_n^s \geq c_{lim\ j,n}$ and 0 otherwise = **1**

$\boldsymbol{c_{lim,j,n}}$ = concentration limit for pollutant n in the quality requirement for sector j

N (mg/L)	P (mg/L)
10	0.025

(IMPO, 2023)

$\boldsymbol{c_{j,n}^s}$= environmental concentration of pollutant n included in the quality requirement for sector j

N (mg/L)	P (mg/L)	
50	0.10	(Boulay et al. , 2011)

$wp_j^{s,k}$	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022
wp N	$9.25 \cdot 10^{-7}$	$2.08 \cdot 10^{-6}$	$2.18 \cdot 10^{-7}$	$4.58 \cdot 10^{-6}$	$6.03 \cdot 10^{-6}$	$3.58 \cdot 10^{-6}$
wp P	$1.25 \cdot 10^{-7}$	$1.25 \cdot 10^{-7}$	$1.24 \cdot 10^{-7}$	$1.25 \cdot 10^{-7}$	$1.25 \cdot 10^{-7}$	$1.25 \cdot 10^{-7}$
wp TOTAL	$1.05 \cdot 10^{-6}$	$2.21 \cdot 10^{-6}$	$3.43 \cdot 10^{-7}$	$4.71 \cdot 10^{-6}$	$6.15 \cdot 10^{-6}$	$3.70 \cdot 10^{-6}$

	2016-2017	2017-2018	2018-2019	2019-2020	2020-2021	2021-2022
$PDP_j^{s,k}$/ha	$2.74 \cdot 10^{-3}$	$7.18 \cdot 10^{-3}$	$9.47 \cdot 10^{-4}$	$1.23 \cdot 10^{-2}$	$2.49 \cdot 10^{-2}$	$1.51 \cdot 10^{-2}$
$PDP_j^{s,k}$/ton	$1.63 \cdot 10^{-4}$	$3.59 \cdot 10^{-4}$	$4.44 \cdot 10^{-5}$	$1.27 \cdot 10^{-3}$	$7.15 \cdot 10^{-4}$	$8.99 \cdot 10^{-4}$

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El **capítulo 7** se basa en el siguiente artículo:

Cabot MI, Lado J, Manzi M, Sanjuán N. Life cycle assessment of citrus nursery: are its environmental impacts relevant? Enviado a la revista *Environmental Impact Assessment Review.*

7. ANÁLISIS DE CICLO DE VIDA DE VIVEROS CITRÍCOLAS: ¿SON RELEVANTES SUS IMPACTOS AMBIENTALES

Resumen: La producción de frutas perennes a escala comercial, como los cítricos, comienza con la producción de plantones en un vivero. En Uruguay, esta etapa puede durar hasta 28-32 meses y comprende tres fases principales: cultivo en semillero, cultivo en maceta e injerto. Como el plantón no produce frutos, pero sí consume insumos y necesita una infraestructura, el estudio de los impactos ambientales asociados a esta etapa se vuelve relevante para comprender su contribución al impacto total del ciclo del cultivo. Sin embargo, no se encuentran en la literatura estudios del análisis del ciclo de vida (ACV) de frutas cítricas que utilicen datos primarios y se centren en esta etapa. El objetivo principal de este estudio es cuantificar los impactos de los viveros utilizando ACV y establecer un punto de referencia para este proceso. Asimismo, este estudio tiene como objetivo identificar los puntos críticos del proceso, analizar alternativas para su reducción y evaluar la relevancia de los impactos ambientales de esta etapa en el ciclo citrícola. Se estudió un vivero de cítricos representativo de Uruguay que produce plantones de limón y mandarina, del cual se obtuvieron datos primarios. Las emisiones de fertilizantes y pesticidas se modelaron siguiendo las recomendaciones de ACV con respecto al cultivo en invernaderos. Se utilizó la evaluación de impacto EN 15804+A2 y se cuantificó la ecotoxicidad humana y de agua dulce mediante USEtox. Los resultados muestran que los principales puntos críticos de la etapa de vivero son la producción de infraestructura y el transporte del sustrato. Extender la vida útil de las estructuras de acero galvanizado puede reducir los impactos entre un 39 % en la toxicidad humana-efectos cancerígenos (THC) y un 28 % en la eutrofización de agua dulce (EAD) y en el uso de recursos de minerales y metales (UR, MM). Una disminución del 20 % en las distancias de transporte de turba reduce los impactos entre un 13-14 % en la acidificación (AC), eutrofización terrestre (ET) y en los impactos en la salud humana debido a la formación de ozono fotoquímico (FOF, SH) y de 6 a 7 % en el cambio climático (CC) y agotamiento del ozono (AO). La contribución de la etapa de vivero al ciclo de producción de cítricos es insignificante para casi todas las categorías de impacto evaluadas excepto THC, ya que representa del 0 al 3,6 % de los impactos según la categoría de impacto. El presente estudio aporta evidencia científica y cuantitativa que demuestra que las medidas para minimizar el impacto ambiental de la producción citrícola uruguaya, en línea con el objetivo de desarrollo sostenible 12, «Producción y Consumo Responsable», deben enfocarse en la etapa de plena producción.

Palabras clave: análisis de ciclo de vida; vivero; frutas cítricas; ciclo de cultivo; cultivo perenne; impactos ambientales

7. LIFE CYCLE ASSESSMENT OF CITRUS NURSERY: ARE ITS ENVIRONMENTAL IMPACTS RELEVANT?

Abstract: Perennial fruit production at the commercial scale, such as citrus fruits, begins with seedlings production in a nursery. In Uruguay, this stage can last up to 28-32 months and involves three main phases: cultivation in seedbeds, pot cultivation, and grafting. As the seedling does not produce fruit but does consume inputs and needs an infrastructure, the study of the environmental impacts associated with this stage becomes relevant to understand its contribution to the total impact of the crop cycle. However, life cycle assessment (LCA) studies of citrus fruits using primary data and focused on this stage are not found in the literature. The main goal of this study is to quantify nursery impacts using LCA and set a benchmark for this process. This study aims to identify the hotspots of the process, analyse alternatives for their reduction and evaluate the relevance of the environmental impacts of this stage in the whole citrus production cycle. A representative Uruguayan citrus nursery producing lemon and mandarin seedlings was studied, from which primary data was obtained. Fertiliser and pesticide emissions were modelled following recommendations for LCAs regarding cultivation in greenhouses. The EN 15804 +A2 impact assessment was used, and human and freshwater ecotoxicity were quantified using USEtox. Results show that the main hotspots of the nursery stage are infrastructure production and peat transportation. Extending the lifespan of the galvanised steel structures can reduce the impacts between 39% in human toxicity–cancer effects (HTc) to 28% in freshwater eutrophication (FEu) and resource use of minerals and

metals (RUm). A 20% decrease in peat transport distances reduces impacts between 13-14% in acidification (Ac), terrestrial eutrophication (TEu) and impacts on human health due to photochemical ozone formation (POFhh) to 6-7% in climate change (CC) and ozone depletion (OD). The contribution of the nursery stage to the citrus production cycle is negligible for almost all the impact categories assessed except HTc, as it accounts for 0-3.6% of the impacts depending on the impact category. The present study provides scientific and quantitative evidence showing that measures to minimise the environmental impact of Uruguayan citrus fruit production, in line with Sustainable Development Goal 12, "Responsible Consumption and Production", should be focused on the full production stage.

Keywords: Life Cycle Assessment; Nursery; Citrus fruits; Crop cycle; Perennial crop; Environmental impacts

7.1. INTRODUCTION

Citrus fruit is the most relevant fruit crop in Uruguay both in terms of tonnes and area, with 299,100 t and 14,392 ha in 2021, in comparison to other fruits grown in the country, such as grapes, apples, peaches, and pears, which added up a total of 171,900 t and 9,472 ha in 2021 (MGAP, 2022a). Whether its destination is export, industry, or domestic consumption, citrus fruit production entails a nursery stage, where the plant does not produce fruit but consumes inputs. In particular, between 2017 and 2019, an average of 541,916 citrus plants were produced annually, of which 50% corresponded to lemons and 39% to mandarins (Fontán

2023, personal communication). Nurseries are concentrated in the south of the country (62% of the total nurseries), mainly to minimise the spread of diseases, as opposed to the concentration of citrus orchards, mostly located in the north (91%) (MGAP, 2022b).

Three main technological factors determine the productivity and quality of citrus fruits and, therefore, their competitiveness in the market: farm management, plant quality, and genetics (Procitrus, 2019), being the latter two intrinsically linked to the nursery stage. For this reason, in Uruguay, the National Seed Institute (INASE) strictly controls the production of seedlings in nurseries based on a specific production standard (INASE, 2021) where the requirements for the production and commercialisation of certified citrus propagation materials are established. Certification is mandatory at the national level; therefore, all nurseries must be inscribed in the General Seed Registry (INASE, 2023) and comply with the standard. The citrus nursery stage differs from the rest of the tree cycle because it is a soilless activity that needs a structure, the greenhouse, and it involves three steps: sowing in seedbeds, transplanting into pots, and grafting.

Previous studies on the environmental impacts of perennial crops highlight the importance of considering the impacts associated with this stage due to the long time from sowing until the plant is ready to be transplanted in the orchard and the intensive use of inputs that it can entail (Bessou et al., 2013; Cerutti et al., 2014). Nevertheless, only a few studies consider this stage, and those that do, analyse it as secondary data using processes already modelled from databases (Bessou et al., 2016; Martin-Gorriz et al., 2020). According to Perrin et al. (2014), this stage should be included unless it can be demonstrated that its contribution to the impacts is negligible; hence, studies focused on the nursery stage using primary data and with a detailed description of the inventory used are needed (Cabot et al., 2022).

Life cycle assessment (LCA) is a valuable tool to quantify the environmental impacts associated with this stage, as it considers the whole production system. Published LCAs for food production in nurseries are centred on horticultural products, especially tomatoes in European countries, such as those in the Mediterranean region (Boulard et al., 2011; Torrellas et al., 2012a), Hungary and the Netherlands (Torrellas et al., 2012b), and also in Colombia (Bojacá et al., 2014). Other studies are found for peppers, melons, zucchini, and green beans (Cellura et al., 2012; Romero-Gámez et al., 2012). Regarding perennial trees, studies have been carried out for cashew in Brazil (Brito De Figueirêdo et al., 2016), walnut in Italy (Cambria and Pierangeli, 2011) and apples in France (Alaphilippe et al., 2016). However, to the best of the authors' knowledge, no LCA studies on citrus fruit nurseries using primary data have been published yet.

Previous LCA studies of Uruguayan citrus have assessed temporal variability in the high-productive stage of lemons (Cabot et al., 2023a), as well as the relevance of considering site specificity and temporal variability in mandarin production (Cabot et al., 2023b). Still, there are no studies that analyse the nursery stage. To fill this gap detected in the LCA literature on citrus fruits, and to contribute to a more accurate evaluation of citrus production in Uruguay, this study aims to quantify the impacts associated with the production of citrus seedlings in the nursery using primary data from a representative citrus nursery producing lemon and mandarin seedlings in the south of Uruguay. In this way, we seek to set a benchmark for this process, analyse the hotspots detected, propose alternatives for their reduction, and, in addition, assess the potential relevance of this stage's environmental impacts with respect to the whole production cycle.

7.2. MATERIALS AND METHODS

This study follows the LCA methodology based on ISO standards (ISO, 2006a, 2006b; ISO 2017; ISO, 2020a; ISO, 2020b) using GaBi software (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany). PCRs for fruits (EPD, 2019) state that if the nursery stage is under the organisation's direct control, operations providing seedlings should be modelled using primary data. However, they do not provide specific guidelines for this modelling.

7.2.1. System description

The studied citrus nursery is located in Villa Rodríguez, San José Department, south of Uruguay. It comprises 31 greenhouses of approximately 450 m^2 each. Two of them are used for growing seedlings in seedbeds, one has the grafting material, another one has the mother plants, which constitute the company's germplasm bank with a collection of plants from 15 to 20 years old, and the remaining 27 greenhouses are used for growing seedlings in pots. The selected nursery can be considered representative for several reasons; firstly, as in all the citrus nurseries in the country, the seedlings produced are certified and comply with the specific standard (INASE, 2021). Secondly, because the species produced are lemon and mandarin, the most grown in Uruguayan citrus nurseries (Gabriel Fontán 2023, personal communication). Lastly, the proposed production scheme allows for 100,000 annual seedlings to be produced, representing 19% of the citrus seedlings in the country and 21% of the specific production of lemons and mandarins.

The cultivation process in the citrus nursery consists of different steps that last up to 28-32 months. Firstly, the rootstocks are sown in seedbeds, usually during the first winter months of the 1st year. The seedlings develop throughout the winter and spring of that year, and in the first months of summer, which correspond to the end of the 1st year and the beginning of the 2nd, young seedlings are transplanted into pots, while in autumn of the 2nd year, the seedlings are grafted with the corresponding citrus variety ('autumn graft'). Occasionally, in that year, the so-called “spring graft” is carried out for seedlings that were not grafted before. In the spring of the 3rd year, the seedlings are ready to be transplanted in the orchard. In some cases, ready-to-go seedlings grafted in autumn can be transplanted in the orchard by the early summer of the 2nd year (usually lemon seedlings, as they tend to grow faster). These seedlings typically reach less than 30% of the total seedlings in the greenhouse.

As mentioned, the rootstocks are sown in the seedbeds manually, in grooves, with a separation of 5 cm between rows, using black peat as substrate mixed with a slow-release NPK fertiliser. The seedlings are sprayed with a fungicide once a week from July to September. Irrigation is applied on demand by controlling the pH, electrical conductivity, and amount of drainage with high-density micro-sprinklers placed on the roof. Subsequently, when the seedling reaches 25 cm high or more, approximately seven months after sowing, they are transplanted into pots. Only the best seedlings are transplanted, that is, erect seedlings, not branched, with straight and tap roots, involving around 20% discards.

Pot cultivation is carried out in 5 L pots specifically designed for this use, made from recycled polyethene (HDPE) from disused orchard pipes, whose shape is an inverted truncated pyramid with a large drainage opening and internal ribs to direct the roots. Substrate composition is relevant in nursery cultivation, and each company has its recipe according to its needs and availability. In the studied nursery, the substrate used consists of 65% white peat, 25% black peat and 10% perlite. Different pesticides and fertilisers are applied during this stage, as detailed in Table 7.4 Slow-release NPK fertilisers are initially mixed with the substrate, and the rest are applied by fertigation and broadcast fertilisation. At the same time, some (especially those which correct mineral deficiencies) are sprayed on the seedling by foliar application. Pesticides are sprayed, except for imidacloprid, which is applied with the irrigation water. Insecticides, acaricides and fungicides are applied to fight pests or diseases, mainly *Tetranychus urticae* and *Phytophthora*. Drip irrigation is carried out with 4-way pressure-compensated drippers with a flow rate of 2L/h to obtain drainage, electrical conductivity, and pH values within the established ranges.

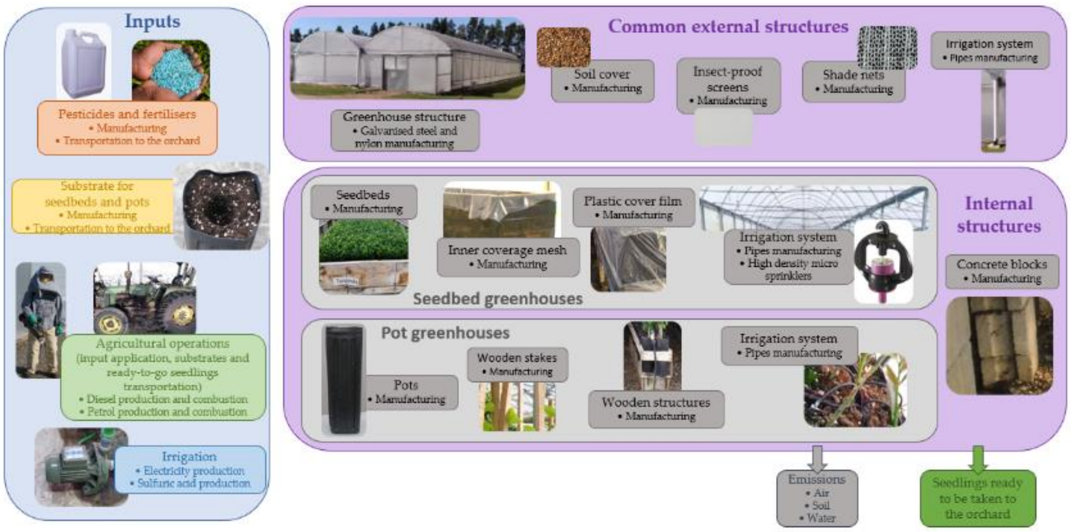
Irrigation water for seedbeds and pot cultivation is pumped from a well approximately 30 m deep with an electric pump. A particularity of the water in the area is its high pH (about 9); sulfuric acid is thus added to lower it to 5.5-6, which is recommended for citrus seedlings. The amount of sulfuric acid added is approximately 2.4 L per 10 m^3 of water. The irrigation system is an open loop without recirculation of the drained water. A John Deere 50D tractor fuelled by diesel transports the substrates and the ready-to-go seedlings to the nursery gate. A backpack sprayer with a wind turbine and a petrol engine is used to apply pesticides.

7.2.2. Life cycle assessment

7.2.2.1. Functional unit and system boundaries

Since the primary function of nurseries is supplying seedlings to the orchards, the functional unit considered is one seedling 28-32 month-old at the nursery gate ready to be transplanted. As the treatment given to mandarin seedlings does not differ from that given to lemon seedlings, both species are considered jointly in the analysis. At the studied nursery, a finished seedling must have well-branched secondary and tertiary roots distributed throughout the substrate volume without presenting coils. In addition, the graft must show erect growth and be located 10 - 20 cm from the base. The stem must be lignified without gum exudation, and the leaves must not show symptoms of nutritional deficiencies or diseases. As mentioned in section 2.1, this is achieved approximately 28-32 months after sowing, except for early seedlings, which are ready after 17-19 months.

The system boundaries are set from cradle to nursery gate, and the stages considered are the production and transportation of inputs and substrates, agricultural operations, irrigation, infrastructure production, and on-field emissions (Fig. 7.1), which are detailed in section 2.2.2. As to the temporal system boundaries, data was obtained for 2017, 2018 and 2019. To follow the entire cycle in detail by month, all the greenhouses in which the complete in-pot cycle was carried out in those years were included in the study, as this stage exhibits the greatest variability in agricultural practices. This involved analysing a total of 15



greenhouses.

Fig. 7.1. System boundaries showing the life cycle stages included in the LCA of Uruguayan lemon and mandarin nursery production.

7.2.2.2. Life cycle inventory (LCI)

For the LCI development, primary data provided by the nursery managers was essential, as the inventory is detailed by month for each of the 15 greenhouses studied. The primary information provided involved the description of the agricultural practices, the number of seedlings transplanted to the orchard from each greenhouse, the type, dose, and form of application of fertilisers and pesticides, the quantity and composition of the substrate, the amount of water applied for irrigation, the quantity of fuel used for both the tractor and the backpack sprayers, as well as all the materials used for the external and internal structures of the greenhouses. Inventory data for the citrus nursery stage is shown in Table 7.1, and further details are provided in Tables 7.4 and 7.5. Relevant background data was taken from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016). As explained below, this data was then used to develop reference LCI datasets for the LCA models. The metadata for these reference LCIs is described in Table 7.6.

Table 7.1. Average inventory data for citrus seedlings production

LCI data	Unit	Average	Standard deviation
Production	seedling · $cycle^{-1}$	6882.3	190.6
Water withdrawal for irrigation	m^3 · $seedling^{-1}$ · $cycle^{-1}$	$7.5 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
Electricity for irrigation	kWh · $seedling^{-1}$ · $cycle^{-1}$	$1.6 \cdot 10^{-2}$	$2.2 \cdot 10^{-3}$
Diesel for transporting substrates and finished seedlings	L · $seedling^{-1}$ · $cycle^{-1}$	$1.2 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$
Petrol for the application of phytosanitary products with backpack sprayers	L · $seedling^{-1}$ · $cycle^{-1}$	$5.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
Substrates			
Peat, seedbeds stage	m^3 · $seedling^{-1}$ · $cycle^{-1}$	$3.9 \cdot 10^{-4}$	$1.1 \cdot 10^{-5}$
Peat, pots stage	m^3 · $seedling^{-1}$ · $cycle^{-1}$	$4.7 \cdot 10^{-3}$	$4.5 \cdot 10^{-5}$
Perlite, pots stage	kg · $seedling^{-1}$ · $cycle^{-1}$	$4.7 \cdot 10^{-2}$	$4.5 \cdot 10^{-4}$
Fertilisers			
N	kg · $seedling^{-1}$ · $cycle^{-1}$	$5.2 \cdot 10^{-3}$	$7.1 \cdot 10^{-4}$
P_2O_5	kg · $seedling^{-1}$ · $cycle^{-1}$	$2.8 \cdot 10^{-3}$	$4.5 \cdot 10^{-4}$
K_2O	kg · $seedling^{-1}$ · $cycle^{-1}$	$3.7 \cdot 10^{-3}$	$6.4 \cdot 10^{-4}$
Fungicides	kg · $seedling^{-1}$ · $cycle^{-1}$	$8.3 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$

Table 7.1. (cont.) Average inventory data for citrus seedlings production

LCI data	Unit	Average	Standard deviation
Insecticides	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
Acaricide	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.2 \cdot 10^{-6}$	$6.6 \cdot 10^{-7}$
On-field emissions			
N_2O volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.5 \cdot 10^{-4}$	$3.1 \cdot 10^{-5}$
NH_3 volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.7 \cdot 10^{-4}$	$4.7 \cdot 10^{-5}$
NO_2 volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.2 \cdot 10^{-4}$	$2.8 \cdot 10^{-5}$
NO_3^- leached	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$1.2 \cdot 10^{-2}$	$4.1 \cdot 10^{-3}$
PO_4^{3-} leached	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.0 \cdot 10^{-7}$	0.0
Greenhouse materials (allocated to 1 seedling)			
Concrete	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	446.2	-
Crushed stone	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	1636.3	-
High-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	3.4	-
Low-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	6.9	-
Nylon 150µm	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	5.7	-
Planed softwood	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	0.0	-
Polyvinylchloride	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	11.5	-
Raw softwood	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	0.7	-
Recycled High-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	0.2	-
Steel	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	1981.1	-
Zinc coating	$m^2 \cdot seedling^{-1} \cdot cycle^{-1}$	12.9	-

External greenhouse structures. The structure of the 31 greenhouses is a multi-tunnel made up of 2 tunnels with lateral and upper-frontal ventilation openings and a double-door antechamber (Fig. 7.2a). The frame is made of galvanised steel, the walls and ceilings are covered with 150μm nylon, and the floor is covered with crushed stones. The highest height of the greenhouse (the ridge) is 3.5 m, and the lowest is 2 m, which coincides with the antechamber's height. The span width of the tunnel is 7 m, and the length is 32 m. The antechamber's length and width are 3.5 m and 2.3 m, respectively. All the ventilation openings have anti-aphid meshes, and, in the hottest months, a shade mesh is unfolded under the roof, which allows the temperature to drop by up to 10 ºC. The common external irrigation system for all the greenhouses comprises aerial and underground PVC pipes. A summary of the quantity of materials used, along with their life spans, is gathered in Table 7.5.

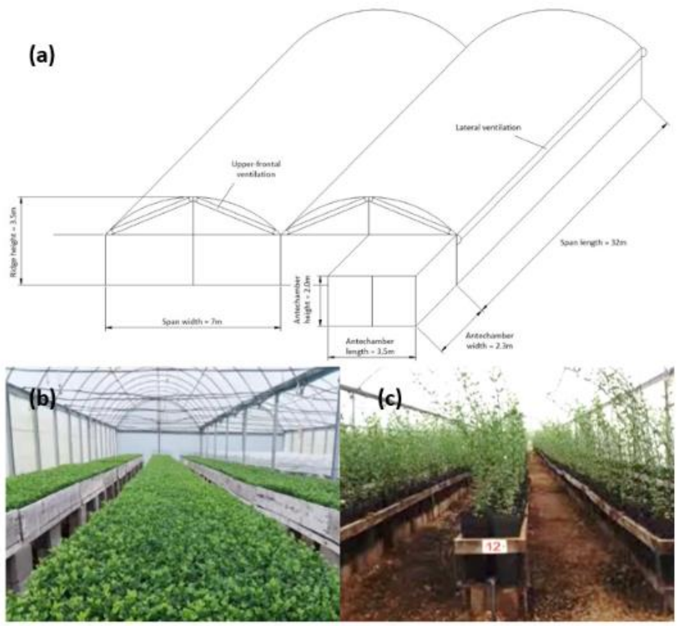


Fig. 7.2. (a) external greenhouse structure, (b) internal structures for seedbed greenhouses, (c) internal structures for pot greenhouses. Photographs were provided by the responsible for the nursery.

Internal structures of the seedbed greenhouses. As commented in section 2.1, two of the 31 greenhouses of the nursery contain seedbeds. Each seedbed greenhouse has 66 wooden boxes (seedbeds) 2.3 m long, 1.5 m wide and 0.2 m high, supported by cement blocks and with an inner cover of an HDPE shade mesh. After sowing, an LDPE plastic film is added to maintain the microclimate required for plant emergence. Irrigation is carried out by sprinkling on demand through LDPE aerial pipes with high-density micro-sprinklers (Fig. 7.2b).

Internal structures of the pot greenhouses. 27 of the 31 greenhouses are intended for pot growing. Each pot greenhouse has a capacity of 7,224 pots, placed in 14 wooden structures with two rows of 258 pots each (Fig. 7.2c). These wooden structures are made up of strips of wood and metal beams to support them, and the pots are placed on top of cement blocks. Each seedling is placed in an HDPE pot recycled from disused field pipes, and a wooden stake is added to guide its growth. Irrigation is carried out with pressure-compensated drippers of LDPE with four outlets.

Substrate production. Substrate composition is a critical factor in soilless cultivation. In the studied nursery, the substrate used for the seedbeds is fine peat to enhance the contact between the seeds and the peat. For pot cultivation, the substrate is a mixture of black and white peat and expanded perlite (see section 2.1). Data on peat and perlite production were obtained from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016).

Fertilisers production. Fertiliser production data was also obtained from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016). Most fertilisers are NPK and were modelled considering their respective fertiliser units, as N, P_2O_5 and K_2O. According to the development of the seedlings, fertilisers with micronutrients are also used, which were modelled considering the compounds with the highest proportion. The production of fertilisers used as iron and calcium sources could not be modelled due to a lack of data in the databases.

Pesticides production. Data on pesticide manufacturing was taken from Ecoinvent 3.8. (Moreno Ruiz et al., 2021; Wernet et al., 2016). Captan and fosetyl-Al were modelled using their active principle, while alphacypermethrin, benomyl and chlorpyrifos were modelled according to their chemical group. The production of the rest of the pesticides was modelled using the generic "pesticide production" process (Table 7.6).

Input transportation. Input transportation (substrate, fertilisers, and pesticides) was modelled considering the quantities and distances transported (Table 7.7) using the corresponding Ecoinvent 3.8 processes (Moreno Ruiz et al., 2021; Wernet et al., 2016). A lorry with a 16-32 metric tonne payload was chosen, and for ship transport, a container ship (Table 7.6).

Fertiliser emissions. In the case study, fertilisers are applied in several ways. Slow-release granular fertilisers are added with the substrate at the beginning of both phases (seedbeds and pots). Then, depending on the crop requirements, fertilisers are applied by fertigation, foliar application, and broadcast fertilisation. For the case of slow-release fertilisers, and based on the supplier's specifications, the nutrient release was modelled linearly for five months after its application for the seedbed phase (as it begins in winter when the release of nutrients is slow due to the low temperature) and for three months for the pot phase (which starts in summer, when nutrient release is faster). Following Antón et al. (2019) recommendations, a monthly balance of N and P_2O_5 was performed considering the nutrients provided by fertilisers and irrigation, N and P_2O_5 seedling uptake, leaching, and air emissions. To model N and P_2O_5 absorption by the seedling, the monthly distribution of nutrients proposed by Quiñones et al. (2010) was adapted to the climatic seasons in Uruguay. In this way, the monthly quantity of nutrients consumed by the seedlings was calculated as fractions of their net annual requirements.

To model N_2O emissions in soilless substrate systems, the emission factor proposed by Pitton et al. (2021) was used. In that study, the authors analyse the emissions of a Douglas fir (*Pseudotsuga menziesii*) grown in a bark-based substrate that incorporates a controlled-release fertiliser where different doses of fertiliser are applied. The authors observed that N_2O is the major greenhouse gas from a soilless substrate. Although the product system is not the same as the one in this case study, it is also a perennial tree with an organic substrate with slow-release fertilisers incorporated, to which broadcast fertilisation is applied. As the average N used by broadcast fertilisation in this study is low (2.31 g N·seedling^{-1}, on average), the emission factor corresponding to the treatment with 5 g of fertiliser added to the surface of the substrate was used, which corresponds to 2.84% N-N_2O·N applied^{-1}.

NH_3 and NO_x were modelled following the EMEP/EEA guidebook (EEA, 2019), considering normal soil pH and temperate climate as, to the author's knowledge, no study has been published that models these emissions for soilless crops. The amount of NO_3^- leached was then calculated as follows:

$$NO_3^-\ leached = Nadded_{fertilisation+irrigation} - Nuptake - N_2O - NH_3 - NO_x$$

As for phosphorus emissions, only phosphate (PO_4^{3-}) leaching was accounted for following the WFLDB guidelines (Nemecek et al., 2019) as, considering the system characteristics, soil erosion and phosphate runoff are negligible.

Pesticide emissions. Emissions from pesticide application were modelled following the recommendations of Antón et al. (2019). Pesticide air emissions due to the drift fraction exiting the greenhouse are estimated to be 5% of the average amount applied, as pesticides are applied with the greenhouse vents closed. For modelling the secondary distribution of these emissions, Nemecek et al. (2022) recommendations were accounted for, and the geographical ratio between surface water and soil of Uruguay, which is 0,007 (CIA, 2023), was used. Regarding soil emissions, Antón et al. (2019) recommendations for soilless cultivation were used, and they were considered null. Therefore, emissions to the crop surface represent 95% of the average amount applied. Regarding the secondary distribution of these emissions, two relevant characteristics of the pesticides used must be considered. First, most of them have a dissipation rate on plant matrix (RL_{50}) of days or even hours (Table 7.8), meaning the absorption process by the plant is almost immediate. And second, in general, they all have low vapour pressures (Table 7.9), so the plant-air secondary distribution is considered minimal. Therefore, counting the long cycle in which the seedlings are inside the greenhouse, the remaining pesticides are considered degraded and hence do not reach environmental compartments nor represent emissions in the inventory.

Water and energy consumption for irrigation. For calculating the water applied during the productive cycle, the information on the number and duration of irrigations according to the climatic season and the stage of the crop was used. For the cultivation in seedbeds, irrigations of 30 min once a week were accounted for in October and 60 min twice a week in November and December. For cultivation in pots, seven weekly irrigations of 30 min were considered in the summer, three weekly irrigations of 20 min in the winter and four weekly irrigations of 20 min in spring and autumn. The water consumed by the crop was calculated through a water balance as the difference between inputs (irrigation) and outputs (drainage). The ideal drainage was provided by the responsible for the nursery and is between 3-5% for the cultivation in the seedbeds stage and 5-20% for the cultivation in the pot stage. For the case study, the most conservative hypothesis was adopted; thus, the minimum of both drainage ranges (maximum water consumption of the seedling) was used.

The energy used to pump the water was calculated using the equation (1):

$$E = P \cdot V \cdot \varrho \cdot g \cdot 1.3 \qquad (1)$$

Where E is the energy needed for irrigation (J); P is the pressure necessary to carry out the irrigation (m of water column), which in the case study is the 60 m w.c. (30 m w.c. to elevate the water from the well, and 30 m w.c. needed in the irrigation head); V is the volume of irrigation water (L), ϱ the density of the water ($1\ kg \cdot L^{-1}$), and g is the acceleration of gravity ($9.807\ N \cdot kg^{-1}$). The energy required for irrigation is oversized by 30% to consider the pump performance and the losses in the water channelling to the irrigation head.

7.2.2.3. Impact categories and impact assessment methods

To quantify environmental impacts, EN 15804 +A2 impact assessment was used, in line with EPD (2023) recommendations, which proposes a default list of environmental performance indicators for non-construction products, whose CF are based on the "EN 15804 reference package" provided by the Joint Research Centre (JRC) (EC, 2023). Therefore, the impact categories assessed are climate change (CC), acidification (Ac), freshwater, marine and terrestrial eutrophication (FEu, MEu and TEu), photochemical ozone formation (impacts on human health) (POFhh), ozone depletion (OD), resource use of minerals and metals and fossils (RUm and RUf), and blue water scarcity (BWS). As well, freshwater ecotoxicity (ET) and human toxicity carcinogenic and non-carcinogenic (HTc and HTnc) were assessed using USEtox 2.12 (Rosenbaum et al., 2008). For all the applied compounds, CFs are available in USEtox 2.12 database except for abamectin, for which the CF corresponding to avermectin B1A was used.

Regarding BWS, specific monthly characterisation factors (CF) for the corresponding Uruguayan basin were used to calculate the direct water consumption in the nursery (Google Earth, 2023). For water consumption for producing fertilisers, pesticides, and substrates, as their origin is known, AWARE CFs for non-agricultural activities, retrieved from WULCA (2023) for the corresponding country, were used. The world average CF for non-agricultural activities was selected for the remaining indirect water consumption.

7.3. RESULTS AND DISCUSSION

7.3.1. Environmental impacts and alternatives for improvement

The environmental impact scores of the nursery stage for the impact categories assessed, calculated as the average of the 15 greenhouses analysed, are shown in Table 7.2, together with their standard deviations. The average values of each of the stages assessed and their standard deviations are shown in Table 7.10.

Table 7.2. Average scores and standard deviation for environmental impacts of citrus nursery stage

Climate change (kg CO_2 eq.·seedling^{-1})	4.0 ± 0.1
Ozone depletion (kg CFC11 eq.·seedling^{-1})	$2.0 \cdot 10^{-7} \pm 8.9 \cdot 10^{-9}$
Acidification (Mole of H^+ eq.·seedling^{-1})	$4.5 \cdot 10^{-2} \pm 9.8 \cdot 10^{-4}$
Freshwater eutrophication (kg P eq.·seedling^{-1})	$8.9 \cdot 10^{-4} \pm 2.6 \cdot 10^{-5}$
Marine eutrophication (kg N eq.·seedling^{-1})	$1.4 \cdot 10^{-2} \pm 1.2 \cdot 10^{-3}$
Terrestrial eutrophication (Mole of N eq.·seedling^{-1})	$1.2 \cdot 10^{-1} \pm 2.8 \cdot 10^{-3}$
Photochemical ozone formation, human health (kg NMVOC eq.·seedling^{-1})	$3.3 \cdot 10^{-2} \pm 6.8 \cdot 10^{-4}$
Resource use, mineral and metals (kg Sb eq.·seedling^{-1})	$2.7 \cdot 10^{-5} \pm 1.1 \cdot 10^{-6}$
Resource use, fossils (MJ·seedling^{-1})	$5.8 \cdot 10^{1} \pm 1.5$
Ecotoxicity (CTUe·seedling^{-1})	$1.3 \cdot 10^{4} \pm 4.1 \cdot 10^{2}$
Human toxicity, cancer (CTUh·seedling^{-1})	$9.0 \cdot 10^{-6} \pm 2.6 \cdot 10^{-7}$
Human toxicity, non-canc. (CTUh·seedling^{-1})	$1.9 \cdot 10^{-6} \pm 7.4 \cdot 10^{-8}$
Blue water scarcity (m^3eq.·seedling^{-1})	$1.5 \pm 4.7 \cdot 10^{-2}$

The variability of the impacts is low, with coefficients of variation (CV) between 2% and 8% depending on the impact category due to the low variability of the processes with the greatest impact. When analysing the relative contribution of the cradle-to-nursery gate stages, infrastructure and input transportation stand out as a hotspot in most impact categories assessed (Fig. 7.3), mainly due to the production of the galvanised steel structures and peat transportation by ship. Infrastructure production presents a CV of 2%-3% depending on the impact category, mainly associated with the number of plants leaving each greenhouse. The CV of peat transportation is 1% for all the impact categories. MEu shows the maximum variability (CV = 8%) due to the high variability of the NO_3^- leachate (CV = 34%).

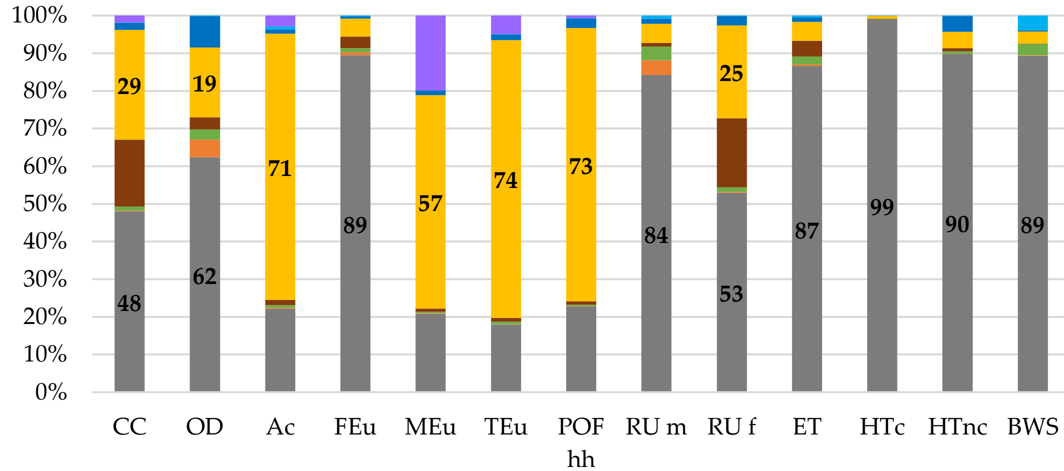


Fig. 7.3. Average percentual contribution of the life cycle stages to the environmental footprint of Uruguayan citrus nursery production. ■ Infrastructure, ■ Transport, ■ Pesticides production, ■ Machinery operations, ■ Fertilisers production, ■ Irrigation, ■ Substrates production, ■ On-field emissions. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Photochemical Ozone Formation impacts on human health (POFhh), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Blue Water Scarcity (BWS).

From the results obtained, evaluating potential alternatives to reduce environmental impacts involving the infrastructure and substrate becomes relevant. Considering that the greenhouse structure is already set, and the substrates' composition is based on previous suitability evaluations, the effect of extending the life span assigned to these inputs is analysed. As for the galvanised steel structure, a lifespan of 15 years has been considered based on literature recommendations (see Table 7.5). Since these structures tend to last more years in practice, a life span extension of 10 years has been analysed. Regarding the substrate, it must be borne in mind that the only substrate that could be reused is that of the seedbeds, as the one used in the pots is taken with the seedlings to the orchard. Hence, duplicating the life span of the seedbed substrate represents an interesting choice to be analysed.

Another alternative is to reduce the transportation distance of the peat, as it is currently brought from Lithuania. Therefore, studying possible suppliers closer to the nursery becomes an interesting option. The most relevant peat producers are in the northern hemisphere (MarketWatch, 2023), and the nearest is located in Ireland. Changing the supplier from Lithuania to Ireland would imply a 20% reduction in the travelled distance (Searates, 2023).

Of the studied alternatives, the reuse of the seedbed substrate has a negligible influence on the impact scores, generating reductions of 0 to 3% in the different impact categories, where the greatest reduction is observed in Ac, TEu and POFhh, mainly due to the decrease in the associated transport. The 10-year increase in the life span of structures reduces considerably almost all the assessed categories (Fig. 7.4a). Among them, the three related to toxicity stand out, with cuts of 28%, 39% and 31% in ET, HTc and HTnc, respectively (Fig. 7.4a). In addition, the reductions in BWS, FEu and RUm are around 28%. Reducing the transportation distance of the substrate by 20% mainly affects Ac, TEu and

POFhh, which decrease by 13%, 14% and 14%, respectively (Fig. 7.4b). MEu, OD, and CC impact categories are also reduced by 11%, 7% and 6%, respectively. In summary, these two alternatives represent a good option to reduce the impacts of the nursery stage. However, the effect of increasing 10-year the life span of structures is more relevant to the impact results.

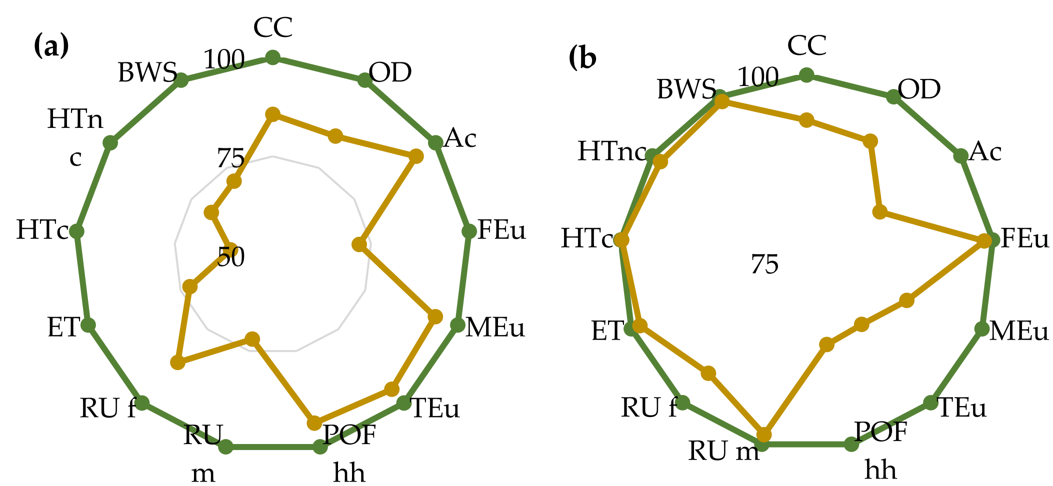


Fig. 7.4. (a) Radial plots representing percentage improvement for the 10-year increase in the life span of structures per impact category. (b) Radial plots representing percentage improvement for a reduction in 20% of the transport distance of the substrate per impact category. Green values are for the initial situation, and brown for the improvement alternative.

It is worth mentioning that even though the substrate mix was carefully tested and selected in the nursery analysed, it is mostly peat, and peatlands are vital ecosystems that are in danger. The Global Peatlands Assessment (UN, 2022) remarks that peatlands are being degraded worldwide, and one of the leading causes is their use in agriculture. Conservation, restoration, and sustainable management of peatlands are crucial since, besides their critical role in the water cycle by storing and filtering water and sheltering unique plants and animals, peatlands contain up to one-third of the world's soil carbon (UN, 2022). Thus, keeping this carbon locked away is critical to achieving global climate goals. Therefore, the design of new substrate mixes different from peat, for example, based on compost, is encouraged.

7.3.2. Relative contribution of the nursery process to the whole crop cycle

To assess the relative contribution of the nursery process to the whole citrus crop cycle, the stages of the tree must be considered. The cycle starts with the nursery stage, which usually lasts over two years, as seen in section 2.1. During the third year, the tree is transplanted in the orchard, where it does not produce citrus fruits for about three years but consumes inputs (non-productive stage). The tree gradually begins to bear fruit during the next three years (increasing yield stage). In the seventh year, the tree reaches the full production stage; that is, its yield is maximum. This stage lasts approximately 20 years, followed by the senescence phase, in which the yield begins to decrease, and the treetop is renewed for economic reasons (Fig. 7.5). Environmental impacts regarding Uruguayan citrus in full production are assessed specifically for lemons in Cabot et al. (2023a) and for mandarins in Cabot et al. (2023b). Data from experts was considered to estimate the impacts of the non-productive stage and increasing yield stage, and the consumption of inputs and the yield were accounted for.

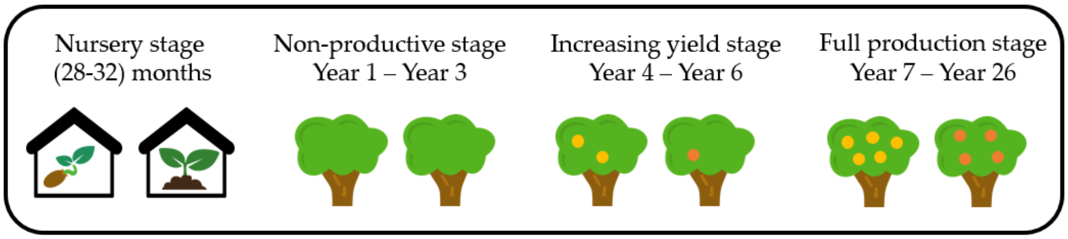


Fig. 7.5. Representation of the citrus crop cycle in Uruguay

The consumption of inputs during the three years of the non-productive stage is described below and was obtained from the responsible for the orchard. Specifically, it can be considered that during the first year, $2.3{\cdot}10^{-2}$ kg of N, $2.3{\cdot}10^{-2}$ kg of P_2O_5 and $2.3{\cdot}10^{-2}$ kg of K_2O are consumed per citrus tree. During the following two years, the consumption of each nutrient increases to $9.2{\cdot}10^{-2}$, $2.0{\cdot}10^{-2}$, $7.2{\cdot}10^{-2}$ kg·tree^{-1}, respectively. This value is maintained during the increasing yield stage, where the tree begins to bear fruit, with an average yield of 8 tonnes·ha^{-1} during the first year of this stage, 16 tonnes·ha^{-1} during the second and 32 tonnes·ha^{-1} during the third. As to pesticides, in the first year of the non-productive stage, a consumption of 36 kg·ha^{-1} is considered, increasing approximately one kg per year until reaching 40 kg·ha^{-1} in the 5th year (second year of the increasing yield stage). During the 6th year (the third year of the increasing yield stage), 50 kg·ha^{-1} of pesticide are consumed.

In order to understand the contribution of the non-productive and increasing yield stages to the environmental impacts, some calculations are performed. First, the macronutrients (N, P, K) applied per tree in the non-productive and increasing yield stages are divided by the total application per tree in the full production stage, using data of macronutrients applied for the latter from Cabot et al. (2023a) for lemons and from Cabot et al. (2023b) for mandarins. As a result, the fertiliser applied in the first stages weighs around 8% of the full production stage per lemon tree and 25% per mandarin tree. Using this procedure in pesticides, a similar percentage is obtained. However, as previously stated, the trees produce citrus fruits during the increasing yield stage and, considering that the average yield in the full production stage for lemons is $1.1 \cdot 10^{-1}$ $kg \cdot tree^{-1}$ (Cabot et al., 2023a) and for mandarins is $6.4 \cdot 10^{-2}$ $kg \cdot tree^{-1}$ (Cabot et al., 2023b), only 6% should be allocated per kilogram for lemons and 12% for mandarins. Taking into account that most of the environmental impacts in the different stages of the cycle are intrinsically linked to the amount of inputs added (i.e., input production, input transportation, machinery operations for input application and on-field emissions), the impacts of this stage can be estimated as a percentage of the impacts of the full production stage, applying the previously calculated percentage and taking into account the yields obtained in each tree stage, as follows:

$$\frac{impact_{FullProduction}}{yield_{FullProduction}} \cdot 0.06 = \frac{impact_{LowProduction}}{yield_{LowProduction}} \; for \; lemons$$

$$\frac{impact_{FullProduction}}{yield_{FullProduction}} \cdot 0.12 = \frac{impact_{LowProduction}}{yield_{LowProduction}} \; for \; mandarins$$

The scores obtained show that for lemons, the full production stage accounts for 99.0-99.7% of the impacts of the cycle, depending on the impact category, and for mandarins, it represents 95.5-98.8%. Compared to this stage, the impacts of the nursery stage and the low production stage (non-productive stage +

increasing yield stage) are almost negligible. For lemons, nursery production accounts for 0.0-0.7% of the impact, depending on the impact category and for mandarins for 0.2-3.6%. The low production stage accounts for 0.3% of the impacts for the case of lemon production and 0.9% for the case of mandarins. An impact category that represents an exception is HTc. In particular, the high toxicity involved in the production of galvanised steel for the greenhouse structure and the low toxicity scores of most of the pesticides applied in the nursery and the orchard explains that the nursery stage accounts for 14.4% of the impacts in the case of lemons and 50.4% in the case of mandarins.

The literature on perennial fruit trees also highlights the low contribution of the nursery stage to the total tree cycle. For French apples, the published figures range from 0.2 to 2.6% (Alaphilippe et al., 2016); however, this case study differs from the present one since the seedlings are produced in the open field. Brito De Figueirêdo et al. (2016) also report a small contribution of the nursery stage in a study on Brazilian cashew production. Cashews are grown in greenhouses using a substrate, as in the present study, but the authors do not model the substrate transport or the production of the greenhouse structure. In addition, the seedling's production process lasts 90-100 days, less than that of citrus seedlings, which lasts more than two years. Bessou et al. (2016) also agree that the impacts of the nursery stage are negligible for small citrus trees produced in Morocco except for terrestrial ecotoxicity, where the emissions from abamectin application stand out. In any case, the authors do not give details of the inventory for this stage or mention the use of substrate or greenhouses.

7.3.3. Comparison with processes in databases

Considering the gap detected in the LCA literature on nurseries of citrus fruits, the results of this study have been compared with those of seedling production proposed in two widely known databases, Agribalyse® v3.0.1 (Agribalyse, 2023) and Ecoinvent 3.8. (Moreno Ruiz et al., 2021; Wernet et al., 2016). Specifically, the processes selected are "Clementine, tree seedling (phase), Souss, at tree nursery – MA" from Agribalyse® v3.0.1 and "RoW: fruit tree seedling production, for planting" from Ecoinvent 3.8, which covers the production of tree seedlings in a nursery for plantation in fruit tree orchards such as apple orchards. The impact scores obtained in the present study are higher than those of Ecoinvent 3.8 and much higher than those of Agribalyse® v3.0.1 in almost all impact categories assessed (Table 7.3).

Table 7.3. Impact scores of producing one seedling in the nursery stage in this study and the commercial databases.

	This study	Ecoinvent 3.8	Impact ratio	Agribalyse	Impact ratio
Climate change (kg CO_2 eq.·seedling^{-1})	4.0	1.0	4	0.1	59
Ozone depletion (kg CFC11 eq.·seedling^{-1})	$2.0 \cdot 10^{-7}$	$9.5 \cdot 10^{-8}$	2	$8.4 \cdot 10^{-9}$	24
Acidification (Mole of H^+ eq.·seedling^{-1})	$4.5 \cdot 10^{-2}$	$7.7 \cdot 10^{-3}$	6	$5.3 \cdot 10^{-4}$	86
Freshwater eutrophication (kg P eq.·seedling^{-1})	$8.9 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$	2	$4.9 \cdot 10^{-5}$	18
Marine eutrophication (kg N eq.·seedling^{-1})	$1.4 \cdot 10^{-2}$	$1.4 \cdot 10^{-3}$	10	$9.0 \cdot 10^{-5}$	158
Terrestrial eutrophication (Mole of N eq.·seedling^{-1})	$1.2 \cdot 10^{-1}$	$1.9 \cdot 10^{-2}$	6	$1.0 \cdot 10^{-3}$	115
Photochemical ozone formation, human health (kg NMVOC eq.·seedling^{-1})	$3.3 \cdot 10^{-2}$	$4.2 \cdot 10^{-3}$	8	$2.2 \cdot 10^{-4}$	149
Resource use, mineral and metals (kg Sb eq.·seedling^{-1})	$2.7 \cdot 10^{-5}$	$3.6 \cdot 10^{-5}$	1	$3.7 \cdot 10^{-8}$	716
Resource use, fossils (MJ·seedling^{-1})	58.1	15.5	4	0.5	124
Ecotoxicity (CTUe·seedling^{-1})	$1.3 \cdot 10^{4}$	$1.2 \cdot 10^{4}$	1	$1.2 \cdot 10^{3}$	11
Human toxicity, cancer (CTUh·seedling^{-1})	$9.0 \cdot 10^{-6}$	$2.6 \cdot 10^{-7}$	35	$3.0 \cdot 10^{-9}$	3038
Human toxicity, non-canc. (CTUh·seedling^{-1})	$1.9 \cdot 10^{-6}$	$6.6 \cdot 10^{-7}$	3	$1.3 \cdot 10^{-8}$	143
Blue water scarcity (m^3eq.·seedling^{-1})	1.6	0.5	4	5.2	3

Impact ratio: impact score in this study/impact score in the database

The rationale behind these differences lies mainly in how the processes were modelled. In the Ecoinvent 3.8 process, nurseries are open-field, without irrigation, greenhouse, or substrate, which greatly differs from the typical citrus nursery. The functional unit is a one-year-old tree seedling at the nursery gate, and in the present case study, the seedlings leave the nursery after 28-32 months. The agricultural inputs (fertilisers and pesticides) differ in the type of products and dose applied. In the present study, the transportation of inputs (relevant hotspot detected) was considered, and in Ecoinvent 3.8 is not. The modelling of direct on-field emissions from fertilisers in the Ecoinvent 3.8 process is performed according to SALCA (Nemecek et al., 2010), and no information is provided on how pesticide emissions are modelled, while in the present study, the emissions are calculated using different approaches (see section 2.2.2.). Machinery operations also differ, since in Ecoinvent 3.8 process, as the nurseries are open-field, mowing, mulching, hoeing, tillage, and cultivation tasks between rows are considered, which are not performed in the present study.

The process of Agribalyse® v3.0.1 is also carried out in the open field. Thus, like in the Ecoinvent 3.8 process, neither a greenhouse structure nor a substrate is accounted for. As to the inputs applied, the production of only two fertilisers is modelled (ammonium nitrate phosphate and a cyclic N-compound) in Agribalyse® v3.0.1, while in the present study, ten different NPK fertilisers are modelled, in addition to calcium nitrate and magnesium sulphate. Regarding pesticide production, in Agribalyse® v3.0.1, the production of a single generic pesticide is modelled. In contrast, in the present study, the production of four fungicides, three insecticides and one acaricide is considered, of which only three were modelled as generic pesticides. In

Agribalyse® v3.0.1, inputs transportation is modelled using a tractor with a trailer, so it probably refers to its transport within the farm and not from the country of origin. Fertiliser emissions are modelled following standard guidelines (IPCC, EMEP, WFLDB) and details on how pesticide emissions are modelled are not provided. It could be stated then that using the seedling production processes of the studied databases would not be the best option for exploring the citrus nursery stage.

7.4. CONCLUSIONS

The first approach to quantify the environmental impacts of citrus nursery production was performed using LCA, studying a representative citrus nursery located in the south of Uruguay. Hotspots were detected, and alternatives to reduce them were explored. The contribution of this process to the whole citrus production cycle was also analysed.

The main hotspots detected for the nursery stage are infrastructure production and input transportation, mainly because of peat transport. The increase in the lifespan of the structures appears as a feasible alternative to reduce most of the environmental impacts, especially those related to toxicity. Similarly, selecting closer peat suppliers, thus reducing transportation distances by 20%, decreases Ac, TEu and POFhh impacts, for which this stage constitutes the main hotspot. Results highlight that the contribution of the nursery stage to the environmental impacts of the whole citrus productive cycle is negligible (0-3.6%) for almost all impact categories. High differences arise when comparing the results with those from commercial databases, mainly due to the process modelling. The latter are modelled in the open field;

thus, they do not consider a substrate or an infrastructure, obtaining lower impact scores and not being representative of most citrus nurseries.

Another aspect that arises from this study is the need to develop models or emission factors for nitrogen and phosphorus emissions in soilless crops. This is specifically relevant in this case study, considering the time the citrus crop remains in the greenhouse. Regarding pesticide emissions, the inclusion of processes such as cultivation in greenhouses in standardised models like pestLCI is also emphasised.

The present study seeks to contribute to developing citrus fruits LCAs, as it analyses a crop stage that was not studied in detail, incorporating primary data. The low scores obtained concerning those of the rest of the cycle reaffirm that most of the environmental impacts of citrus production are concentrated in the full production stage, at least for Uruguayan citrus production. Thus, the measures to promote sustainable production of citrus fruits, in line with SDG 12, should be aimed at that stage.

Funding

Maria Inés Cabot is the recipient of a PhD scholarship (POS_EXT_2018_1_154319) from the National Agency for Research and Innovation (ANII, Uruguay) and received a support scholarship for the completion of postgraduate studies (BFPD_2023_1#46477920) from the Postgraduate Academic Commission (CAP, University of the Republic).

CRediT authorship contribution statement

María Inés Cabot: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Investigation.

Joanna Lado: Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Matías Manzi: Writing – review & editing.

Neus Sanjuán: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing,

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors particularly acknowledge UPEFRUY-Uruguay fruits (http://uruguayfruits.com.uy/en) for their sincere collaboration and for sharing their data for this study. Special thanks to Gonzalo, Michel and Yoana for their patience and willingness to share their knowledge.

In addition, we want to thank Dr Antonio Lidon and Dra. Inmaculada Bautista from the Forest Science and Technology research group of the Universitat Politècnica de València for their help with the N balance.

As well we want to thank Dra. Nancy Peña from the Sustainability Accounting and Optimization research group of the Beta Tech Center (Universitat de Vic - Universitat Central de Catalunya) for her help with modelling pesticide emissions.

We also thank Gabriel Fontán from the Instituto Nacional de Semillas (INASE) for providing numbers regarding citrus plant production in Uruguayan nurseries.

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7.5. MATERIAL COMPLEMENTARIO DEL CAPÍTULO 7

La presente sección se divide en los siguientes apartados:

- Inventario ambiental detallado de la etapa de cultivo citrícola en vivero (insumos, emisiones y estructuras)
- Metadatos del modelado del proceso de cultivo citrícola en vivero
- Distancias de transporte de los insumos utilizados
- Tasa de disipación en la matriz vegetal y presiones de vapor de los pesticidas utilizados en el estudio
- Resultados promedio de los impactos ambientales y desviación estándar por etapa del cultivo citrícola en vivero

Table 7.4. Detailed inventory of the nursery stage (inputs and on-field emissions)

LCI data	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average	Standard deviation
Production	seedling · cycle^{-1}	6997	7077	7049	6988	6986	7007	6969	6857	6863	7007	6834	6534	6882	6787	6397	6882	191
Water withdrawal for irrigation	m^3 · seedling^{-1} · cycle^{-1}	$7.4\cdot10^{-2}$	$6.7\cdot10^{-2}$	$6.5\cdot10^{-2}$	$6.7\cdot10^{-2}$	$6.7\cdot10^{-2}$	$9.6\cdot10^{-2}$	$6.7\cdot10^{-2}$	$8.3\cdot10^{-2}$	$8.5\cdot10^{-2}$	$8.9\cdot10^{-2}$	$6.9\cdot10^{-2}$	$6.4\cdot10^{-2}$	$8.1\cdot10^{-2}$	$6.8\cdot10^{-2}$	$8.0\cdot10^{-2}$	$7.5\cdot10^{-2}$	$1.0\cdot10^{-2}$
Electricity for irrigation	kWh · seedling^{-1} · cycle^{-1}	$1.6\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.4\cdot10^{-2}$	$2.0\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.8\cdot10^{-2}$	$1.8\cdot10^{-2}$	$1.9\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1.4\cdot10^{-2}$	$1.7\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1.7\cdot10^{-2}$	$1.6\cdot10^{-2}$	$2.2\cdot10^{-3}$
Diesel for transporting substrates and finished seedlings	L · seedling^{-1} · cycle^{-1}	$1.3\cdot10^{-2}$	$9.3\cdot10^{-3}$	$8.9\cdot10^{-3}$	$9.3\cdot10^{-3}$	$9.3\cdot10^{-3}$	$1.8\cdot10^{-2}$	$9.3\cdot10^{-3}$	$1.2\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1.8\cdot10^{-2}$	$9.6\cdot10^{-3}$	$8.9\cdot10^{-3}$	$1.2\cdot10^{-2}$	$9.5\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.2\cdot10^{-2}$	$3.2\cdot10^{-3}$
Petrol for the aplication of phytosanitary products with backpack sprayers	L · seedling^{-1} · cycle^{-1}	$6.0\cdot10^{-3}$	$4.9\cdot10^{-3}$	$4.8\cdot10^{-3}$	$4.9\cdot10^{-3}$	$4.9\cdot10^{-3}$	$7.9\cdot10^{-3}$	$4.9\cdot10^{-3}$	$6.4\cdot10^{-3}$	$6.7\cdot10^{-3}$	$7.6\cdot10^{-3}$	$5.2\cdot10^{-3}$	$4.8\cdot10^{-3}$	$6.3\cdot10^{-3}$	$5.0\cdot10^{-3}$	$6.0\cdot10^{-3}$	$5.8\cdot10^{-3}$	$1.0\cdot10^{-3}$
Substrates																		
Peat, seedbeds stage	m^3 · seedling^{-1} · cycle^{-1}	$3.9\cdot10^{-4}$	$3.8\cdot10^{-4}$	$3.8\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$3.9\cdot10^{-4}$	$4.0\cdot10^{-4}$	$4.1\cdot10^{-4}$	$3.9\cdot10^{-4}$	$4.0\cdot10^{-4}$	$4.2\cdot10^{-4}$	$3.9\cdot10^{-4}$	$1.1\cdot10^{-5}$
Peat, pots stage	m^3 · seedling^{-1} · cycle^{-1}	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.7\cdot10^{-3}$	$4.7\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.7\cdot10^{-3}$	$4.7\cdot10^{-3}$	$4.7\cdot10^{-3}$	$4.5\cdot10^{-5}$
Perlite, pots stage	kg · seedling^{-1} · cycle^{-1}	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.7\cdot10^{-2}$	$4.7\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.6\cdot10^{-2}$	$4.7\cdot10^{-2}$	$4.7\cdot10^{-2}$	$4.7\cdot10^{-2}$	$4.5\cdot10^{-4}$
Fertilisers																		
N	kg · seedling^{-1} · cycle^{-1}	$4.8\cdot10^{-3}$	$5.5\cdot10^{-3}$	$6.5\cdot10^{-3}$	$5.6\cdot10^{-3}$	$5.7\cdot10^{-3}$	$4.5\cdot10^{-3}$	$5.6\cdot10^{-3}$	$4.7\cdot10^{-3}$	$5.0\cdot10^{-3}$	$4.8\cdot10^{-3}$	$5.8\cdot10^{-3}$	$3.9\cdot10^{-3}$	$6.2\cdot10^{-3}$	$4.6\cdot10^{-3}$	$4.7\cdot10^{-3}$	$5.2\cdot10^{-3}$	$7.1\cdot10^{-4}$
P_2O_5	kg · seedling^{-1} · cycle^{-1}	$2.9\cdot10^{-3}$	$2.9\cdot10^{-3}$	$3.7\cdot10^{-3}$	$2.9\cdot10^{-3}$	$3.0\cdot10^{-3}$	$2.7\cdot10^{-3}$	$3.0\cdot10^{-3}$	$2.4\cdot10^{-3}$	$2.8\cdot10^{-3}$	$2.7\cdot10^{-3}$	$3.3\cdot10^{-3}$	$2.2\cdot10^{-3}$	$3.6\cdot10^{-3}$	$2.3\cdot10^{-3}$	$2.3\cdot10^{-3}$	$2.8\cdot10^{-3}$	$4.5\cdot10^{-4}$
K_2O	kg · seedling^{-1} · cycle^{-1}	$3.6\cdot10^{-3}$	$3.7\cdot10^{-3}$	$5.0\cdot10^{-3}$	$3.8\cdot10^{-3}$	$3.9\cdot10^{-3}$	$3.4\cdot10^{-3}$	$3.8\cdot10^{-3}$	$3.0\cdot10^{-3}$	$3.6\cdot10^{-3}$	$3.5\cdot10^{-3}$	$4.3\cdot10^{-3}$	$2.8\cdot10^{-3}$	$4.7\cdot10^{-3}$	$2.9\cdot10^{-3}$	$3.0\cdot10^{-3}$	$3.7\cdot10^{-3}$	$6.4\cdot10^{-4}$

Table 7.4. (cont.) Detailed inventory of the nursery stage (inputs and on-field emissions)

LCI data	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average	Standard deviation
Fe 6%	kg · seedling^{-1} · cycle^{-1}	$2.3\cdot10^{-3}$	$3.7\cdot10^{-4}$	$2.4\cdot10^{-4}$	$4.2\cdot10^{-4}$	$3.9\cdot10^{-4}$	$1.3\cdot10^{-3}$	$4.7\cdot10^{-4}$	$7.6\cdot10^{-4}$	$1.6\cdot10^{-3}$	$1.7\cdot10^{-3}$	$4.8\cdot10^{-4}$	$7.3\cdot10^{-4}$	$4.8\cdot10^{-4}$	$4.9\cdot10^{-4}$	$5.2\cdot10^{-4}$	$8.1\cdot10^{-4}$	$6.1\cdot10^{-4}$
NPK 25-10-17	kg · seedling^{-1} · cycle^{-1}	$4.2\cdot10^{-3}$	$2.0\cdot10^{-3}$	$1.9\cdot10^{-3}$	$1.5\cdot10^{-3}$	$2.5\cdot10^{-3}$	$4.0\cdot10^{-3}$	$2.5\cdot10^{-3}$	$3.1\cdot10^{-3}$	$4.8\cdot10^{-3}$	$4.2\cdot10^{-3}$	$1.7\cdot10^{-3}$	$2.3\cdot10^{-3}$	$1.7\cdot10^{-3}$	$3.0\cdot10^{-3}$	$3.1\cdot10^{-3}$	$2.8\cdot10^{-3}$	$1.0\cdot10^{-3}$
Fertilizer - source of Ca	kg · seedling^{-1} · cycle^{-1}	$1.4\cdot10^{-4}$	0.0	0.0	0.0	0.0	$1.4\cdot10^{-4}$	0.0	0.0	$1.5\cdot10^{-4}$	$1.4\cdot10^{-4}$	0.0	0.0	0.0	0.0	0.0	$3.8\cdot10^{-5}$	$6.6\cdot10^{-5}$
NPK 30-0-0	kg · seedling^{-1} · cycle^{-1}	$3.2\cdot10^{-3}$	$5.8\cdot10^{-3}$	$4.2\cdot10^{-3}$	$6.0\cdot10^{-3}$	$5.4\cdot10^{-3}$	$2.9\cdot10^{-3}$	$5.5\cdot10^{-3}$	$6.2\cdot10^{-3}$	$3.7\cdot10^{-3}$	$3.5\cdot10^{-3}$	$3.8\cdot10^{-3}$	$4.2\cdot10^{-3}$	$3.9\cdot10^{-3}$	$5.8\cdot10^{-3}$	$6.0\cdot10^{-3}$	$4.7\cdot10^{-3}$	$1.2\cdot10^{-3}$
Fe 13%	kg · seedling^{-1} · cycle^{-1}	0.0	$5.3\cdot10^{-4}$	$6.2\cdot10^{-4}$	$2.1\cdot10^{-3}$	$1.1\cdot10^{-3}$	$7.1\cdot10^{-5}$	$1.1\cdot10^{-3}$	$5.5\cdot10^{-4}$	0.0	$7.1\cdot10^{-5}$	$5.5\cdot10^{-4}$	$1.0\cdot10^{-3}$	$5.4\cdot10^{-4}$	$5.5\cdot10^{-4}$	$5.9\cdot10^{-4}$	$6.3\cdot10^{-4}$	$5.6\cdot10^{-4}$
Fe 4% - Zn 4% - Mn 3%	kg · seedling^{-1} · cycle^{-1}	$3.4\cdot10^{-4}$	$3.1\cdot10^{-4}$	$2.9\cdot10^{-4}$	$1.5\cdot10^{-3}$	$7.8\cdot10^{-4}$	$2.7\cdot10^{-4}$	$7.3\cdot10^{-4}$	$3.6\cdot10^{-4}$	$3.7\cdot10^{-4}$	$2.9\cdot10^{-4}$	$3.2\cdot10^{-4}$	$6.9\cdot10^{-4}$	$3.1\cdot10^{-4}$	$3.7\cdot10^{-4}$	$4.1\cdot10^{-4}$	$4.9\cdot10^{-4}$	$3.3\cdot10^{-4}$
Calcium nitrate	kg · seedling^{-1} · cycle^{-1}	$1.9\cdot10^{-3}$	$8.2\cdot10^{-4}$	$6.8\cdot10^{-4}$	$1.0\cdot10^{-3}$	$9.7\cdot10^{-4}$	$2.0\cdot10^{-3}$	$9.8\cdot10^{-4}$	$7.0\cdot10^{-4}$	$1.9\cdot10^{-3}$	$2.0\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.1\cdot10^{-3}$	$1.1\cdot10^{-3}$	$7.1\cdot10^{-4}$	$7.5\cdot10^{-4}$	$1.2\cdot10^{-3}$	$5.2\cdot10^{-4}$
NPK 15-5-30	kg · seedling^{-1} · cycle^{-1}	$1.1\cdot10^{-3}$	$1.3\cdot10^{-3}$	$2.2\cdot10^{-3}$	$1.3\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.1\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.1\cdot10^{-3}$	$1.4\cdot10^{-3}$	$1.4\cdot10^{-3}$	$1.4\cdot10^{-3}$	$1.2\cdot10^{-3}$	$1.3\cdot10^{-3}$	$1.3\cdot10^{-3}$	$2.6\cdot10^{-4}$
NPK 18-18-18	kg · seedling^{-1} · cycle^{-1}	$6.1\cdot10^{-3}$	$2.3\cdot10^{-3}$	$2.3\cdot10^{-3}$	$2.6\cdot10^{-3}$	$2.9\cdot10^{-3}$	$5.3\cdot10^{-3}$	$2.9\cdot10^{-3}$	$3.4\cdot10^{-3}$	$5.2\cdot10^{-3}$	$5.5\cdot10^{-3}$	$1.7\cdot10^{-3}$	$2.8\cdot10^{-3}$	$1.7\cdot10^{-3}$	$3.1\cdot10^{-3}$	$3.3\cdot10^{-3}$	$3.4\cdot10^{-3}$	$1.4\cdot10^{-3}$
NPK 5.7-5.5-0	kg · seedling^{-1} · cycle^{-1}	$3.6\cdot10^{-4}$	0.0	$1.3\cdot10^{-4}$	0.0	0.0	$7.1\cdot10^{-5}$	0.0	0.0	$7.3\cdot10^{-5}$	$1.4\cdot10^{-4}$	$2.0\cdot10^{-4}$	$3.8\cdot10^{-4}$	$2.0\cdot10^{-4}$	$3.7\cdot10^{-4}$	$7.0\cdot10^{-5}$	$1.3\cdot10^{-4}$	$1.4\cdot10^{-4}$
NPK 24-8-20	kg · seedling^{-1} · cycle^{-1}	$2.9\cdot10^{-4}$	0.0	0.0	0.0	0.0	$2.9\cdot10^{-4}$	0.0	0.0	$2.9\cdot10^{-4}$	$2.9\cdot10^{-4}$	0.0	0.0	0.0	0.0	0.0	$7.7\cdot10^{-5}$	$1.3\cdot10^{-4}$
NPK 15-9-12	kg · seedling^{-1} · cycle^{-1}	0.0	$9.4\cdot10^{-3}$	$1.8\cdot10^{-2}$	$9.6\cdot10^{-3}$	$9.6\cdot10^{-3}$	0.0	$8.9\cdot10^{-3}$	0.0	0.0	0.0	$1.5\cdot10^{-2}$	0.0	$1.9\cdot10^{-2}$	0.0	0.0	$6.0\cdot10^{-3}$	$7.2\cdot10^{-3}$
NPK 0-40-20	kg · seedling^{-1} · cycle^{-1}	0.0	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	0.0	$1.7\cdot10^{-4}$	$1.8\cdot10^{-4}$	0.0	0.0	$1.8\cdot10^{-4}$	$1.8\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.8\cdot10^{-4}$	$9.4\cdot10^{-5}$	$1.2\cdot10^{-4}$	$7.9\cdot10^{-5}$
NPK 19-6-10	kg · seedling^{-1} · cycle^{-1}	$6.4\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.5\cdot10^{-4}$	$6.6\cdot10^{-4}$	$6.6\cdot10^{-4}$	$6.4\cdot10^{-4}$	$6.6\cdot10^{-4}$	$6.9\cdot10^{-4}$	$6.5\cdot10^{-4}$	$6.6\cdot10^{-4}$	$7.0\cdot10^{-4}$	$6.5\cdot10^{-4}$	$1.9\cdot10^{-5}$
NPK 14-16-18	kg · seedling^{-1} · cycle^{-1}	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.7\cdot10^{-3}$	$7.7\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.6\cdot10^{-3}$	$7.6\cdot10^{-3}$	$7.5\cdot10^{-3}$	$7.7\cdot10^{-3}$	$7.7\cdot10^{-3}$	$7.6\cdot10^{-3}$	$7.7\cdot10^{-5}$
Magnesium sulphate	kg · seedling^{-1} · cycle^{-1}	$1.5\cdot10^{-3}$	0.0	0.0	$6.4\cdot10^{-4}$	$2.9\cdot10^{-4}$	$1.2\cdot10^{-3}$	$2.9\cdot10^{-4}$	$5.1\cdot10^{-4}$	$1.5\cdot10^{-3}$	$1.5\cdot10^{-3}$	$6.6\cdot10^{-4}$	$4.6\cdot10^{-4}$	$6.5\cdot10^{-4}$	$2.9\cdot10^{-4}$	$3.1\cdot10^{-4}$	$6.5\cdot10^{-4}$	$5.2\cdot10^{-4}$

Table 7.4. (cont.) Detailed inventory of the nursery stage (inputs and on-field emissions)

LCI data	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average	Standard deviation
Fungicides																		
Benomyl	kg · seedling^{-1} · cycle^{-1}	$9.0\cdot10^{-6}$	$2.8\cdot10^{-5}$	$8.3\cdot10^{-5}$	$1.9\cdot10^{-5}$	$4.7\cdot10^{-5}$	$2.8\cdot10^{-5}$	$4.7\cdot10^{-5}$	$6.7\cdot10^{-5}$	$2.8\cdot10^{-5}$	$1.9\cdot10^{-5}$	$1.9\cdot10^{-5}$	$2.0\cdot10^{-5}$	$1.9\cdot10^{-5}$	$6.8\cdot10^{-5}$	$7.2\cdot10^{-5}$	$3.8\cdot10^{-5}$	$2.4\cdot10^{-5}$
Captan	kg · seedling^{-1} · cycle^{-1}	$4.8\cdot10^{-5}$	$2.9\cdot10^{-4}$	$3.2\cdot10^{-4}$	$2.5\cdot10^{-4}$	$1.5\cdot10^{-4}$	$4.0\cdot10^{-5}$	$1.6\cdot10^{-4}$	$1.9\cdot10^{-4}$	$3.8\cdot10^{-5}$	$4.7\cdot10^{-5}$	$2.6\cdot10^{-4}$	$2.9\cdot10^{-4}$	$2.6\cdot10^{-4}$	$2.0\cdot10^{-4}$	$2.1\cdot10^{-4}$	$1.8\cdot10^{-4}$	$1.0\cdot10^{-4}$
Fosetyl-aluminium	kg · seedling^{-1} · cycle^{-1}	$1.2\cdot10^{-4}$	$3.3\cdot10^{-4}$	$2.7\cdot10^{-4}$	$3.3\cdot10^{-4}$	$2.8\cdot10^{-4}$	$1.3\cdot10^{-4}$	$2.5\cdot10^{-4}$	$3.4\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.2\cdot10^{-4}$	$3.5\cdot10^{-4}$	$3.6\cdot10^{-4}$	$3.4\cdot10^{-4}$	$4.1\cdot10^{-4}$	$3.7\cdot10^{-4}$	$2.7\cdot10^{-4}$	$1.0\cdot10^{-4}$
Propamocarb	kg · seedling^{-1} · cycle^{-1}	$3.8\cdot10^{-4}$	$3.4\cdot10^{-4}$	$3.4\cdot10^{-4}$	$3.7\cdot10^{-4}$	$2.8\cdot10^{-4}$	$3.9\cdot10^{-4}$	$2.3\cdot10^{-4}$	$3.1\cdot10^{-4}$	$2.9\cdot10^{-4}$	$3.8\cdot10^{-4}$	$3.4\cdot10^{-4}$	$3.2\cdot10^{-4}$	$3.8\cdot10^{-4}$	$2.9\cdot10^{-4}$	$4.1\cdot10^{-4}$	$3.4\cdot10^{-4}$	$5.0\cdot10^{-5}$
Insecticides																		
Alpha-cypermethrin	kg · seedling^{-1} · cycle^{-1}	$3.6\cdot10^{-6}$	$1.7\cdot10^{-6}$	$4.0\cdot10^{-6}$	$1.1\cdot10^{-6}$	$1.1\cdot10^{-6}$	$4.8\cdot10^{-6}$	$1.1\cdot10^{-6}$	$2.3\cdot10^{-6}$	$7.9\cdot10^{-6}$	$4.7\cdot10^{-6}$	$1.1\cdot10^{-6}$	$1.2\cdot10^{-6}$	$1.1\cdot10^{-6}$	$2.3\cdot10^{-6}$	$2.4\cdot10^{-6}$	$2.7\cdot10^{-6}$	$2.0\cdot10^{-6}$
Chlorpyrifos	kg · seedling^{-1} · cycle^{-1}	$3.2\cdot10^{-5}$	$9.1\cdot10^{-5}$	$7.5\cdot10^{-5}$	$9.2\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.6\cdot10^{-5}$	$1.4\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.6\cdot10^{-5}$	$3.2\cdot10^{-5}$	$9.4\cdot10^{-5}$	$8.1\cdot10^{-5}$	$9.3\cdot10^{-5}$	$1.6\cdot10^{-4}$	$1.9\cdot10^{-4}$	$9.3\cdot10^{-5}$	$5.5\cdot10^{-5}$
Imidacloprid	kg · seedling^{-1} · cycle^{-1}	$1.8\cdot10^{-4}$	$7.9\cdot10^{-5}$	$1.2\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.2\cdot10^{-4}$	$2.5\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.5\cdot10^{-4}$	$2.2\cdot10^{-4}$	$2.5\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.3\cdot10^{-4}$	$1.2\cdot10^{-4}$	$1.9\cdot10^{-4}$	$1.6\cdot10^{-4}$	$1.6\cdot10^{-4}$	$5.1\cdot10^{-5}$
Acaricide																		
Abamectin	kg · seedling^{-1} · cycle^{-1}	$3.5\cdot10^{-6}$	$4.9\cdot10^{-6}$	$2.7\cdot10^{-6}$	$3.0\cdot10^{-6}$	$2.7\cdot10^{-6}$	$3.5\cdot10^{-6}$	$2.0\cdot10^{-6}$	$3.4\cdot10^{-6}$	$3.2\cdot10^{-6}$	$3.3\cdot10^{-6}$	$3.1\cdot10^{-6}$	$2.5\cdot10^{-6}$	$3.1\cdot10^{-6}$	$3.8\cdot10^{-6}$	$3.7\cdot10^{-6}$	$3.2\cdot10^{-6}$	$6.6\cdot10^{-7}$
On-field emissions																		
N_2O volatilised	kg · seedling^{-1} · cycle^{-1}	$2.3\cdot10^{-4}$	$2.6\cdot10^{-4}$	$3.0\cdot10^{-4}$	$2.6\cdot10^{-4}$	$2.7\cdot10^{-4}$	$2.2\cdot10^{-4}$	$2.6\cdot10^{-4}$	$2.3\cdot10^{-4}$	$2.4\cdot10^{-4}$	$2.3\cdot10^{-4}$	$2.7\cdot10^{-4}$	$1.9\cdot10^{-4}$	$2.9\cdot10^{-4}$	$2.2\cdot10^{-4}$	$2.3\cdot10^{-4}$	$2.5\cdot10^{-4}$	$3.1\cdot10^{-5}$
NH_3 volatilised	kg · seedling^{-1} · cycle^{-1}	$3.4\cdot10^{-4}$	$3.9\cdot10^{-4}$	$4.5\cdot10^{-4}$	$4.0\cdot10^{-4}$	$4.0\cdot10^{-4}$	$3.3\cdot10^{-4}$	$4.0\cdot10^{-4}$	$3.4\cdot10^{-4}$	$3.6\cdot10^{-4}$	$3.5\cdot10^{-4}$	$4.1\cdot10^{-4}$	$2.8\cdot10^{-4}$	$4.4\cdot10^{-4}$	$3.3\cdot10^{-4}$	$3.4\cdot10^{-4}$	$3.7\cdot10^{-4}$	$4.7\cdot10^{-5}$
NO_2 volatilised	kg · seedling^{-1} · cycle^{-1}	$2.1\cdot10^{-4}$	$2.3\cdot10^{-4}$	$2.7\cdot10^{-4}$	$2.4\cdot10^{-4}$	$2.4\cdot10^{-4}$	$2.0\cdot10^{-4}$	$2.4\cdot10^{-4}$	$2.0\cdot10^{-4}$	$2.1\cdot10^{-4}$	$2.1\cdot10^{-4}$	$2.4\cdot10^{-4}$	$1.7\cdot10^{-4}$	$2.6\cdot10^{-4}$	$1.9\cdot10^{-4}$	$2.0\cdot10^{-4}$	$2.2\cdot10^{-4}$	$2.8\cdot10^{-5}$
NO_3^- leached	kg · seedling^{-1} · cycle^{-1}	$6.4\cdot10^{-3}$	$1.5\cdot10^{-2}$	$1.9\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1.4\cdot10^{-2}$	$6.3\cdot10^{-3}$	$1.4\cdot10^{-2}$	$1.1\cdot10^{-2}$	$6.6\cdot10^{-3}$	$7.4\cdot10^{-3}$	$1.6\cdot10^{-2}$	$1.0\cdot10^{-2}$	$1.8\cdot10^{-2}$	$1.1\cdot10^{-2}$	$1.1\cdot10^{-2}$	$1.2\cdot10^{-2}$	$4.1\cdot10^{-3}$
PO_4^{3-} leached	kg · seedling^{-1} · cycle^{-1}	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	$3.0\cdot10^{-7}$	0.0

Table 7.5. Detailed inventory of the nursery stage (greenhouses structures)

Seedbeds greenhouses - allocated to the use of 3 seedbeds (enough to produce plants to fill 1 pot greenhouse)				
Component	Material	Lifespan (years)	Amount	Unit
Frame (horizontal and vertical beams + arches)	Steel	15[a,c,d]	1974.8	Kg
	Zinc coating	15[a,c,d]	12.8	m^2
Walls	Nylon 150μm	4[b]	1.8	kg
Roof	Nylon 150μm	3[b]	4.0	kg
Soil	Crushed stone	15[a]	1631.1	kg
Insect-proof screens	High Density Polyethylene	3[c]	0.8	kg
External irrigation system - underground and aerial	Polyvinylchloride	10[d]	11.4	kg
Shade nets	High Density Polyethylene	3[c]	1.4	kg
Wooden boxes	Raw softwood	3[b]	0.7	m^3
Wooden boxes inner coverage mesh	High Density Polyethylene	1[b]	1.0	kg
Plastic cover film	Low Density Polyethylene	3[c,d]	6.3	kg
Irrigation system - Pipes	Low Density Polyethylene	3[d]	0.5	kg
Irrigation system - High density micro sprinklers	High Density Polyethylene	3[c]	0.1	kg
Concrete blocks	Concrete	15[c,d]	442.5	Kg
Pot greenhouse - allocated to 1 pot				
Component	Material	Lifespan (years)	Amount	Unit
Frame (horizontal and vertical beams + arches)	Steel	15[a,c]	6.3	Kg
	Zinc coating	15[a,c]	$4.1 \cdot 10^{-2}$	m^2
Walls	Nylon 150μm	4[b]	$5.6 \cdot 10^{-3}$	kg
Roof	Nylon 150μm	3[b]	$1.3 \cdot 10^{-2}$	kg
Soil	Crushed stone	15[a]	5.2	kg
Insect-proof screens	High Density Polyethylene	3[c]	$2.6 \cdot 10^{-3}$	kg
External irrigation system - underground and aerial	Polyvinylchloride	10[d]	$3.7 \cdot 10^{-2}$	kg
Shade nets	High Density Polyethylene	3[c]	$4.6 \cdot 10^{-3}$	kg
Wooden structures	Raw softwood	3[b]	$1.2 \cdot 10^{-4}$	m^3
Wooden stakes	Planed softwood	1[b]	$1.2 \cdot 10^{-4}$	m^3
Pots	Recicled High Density Polyethylene	1[b]	$1.6 \cdot 10^{-1}$	kg
Irrigation system - Pipes	Low Density Polyethylene	3[d]	$1.1 \cdot 10^{-2}$	kg
Metal beams - support for wooden structures	Steel	15[a,c,d]	$3.0 \cdot 10^{-2}$	Kg
Concrete blocks	Concrete	15[c,d]	3.8	Kg

[a] UNE (2020), [b] information provided by the nursery managers, [c] Antón et al. (2014), [d] Torrellas et al. (2012)

Table 7.6. Life cycle inventory metadata for Uruguayan citrus nursery production

Input	LCI Name	Type of process	Source
Abamectin	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Alpha-cypermethrin	RER: pyrethroid-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Benomyl	RoW: benzimidazole-compound production	agg LCI result, cut-off method	Ecoinvent 3.8
Calcium nitrate	RER: calcium nitrate production	agg LCI result, cut-off method	Ecoinvent 3.8
Captan	RoW: captan production	agg LCI result, cut-off method	Ecoinvent 3.8
Chlorpyrifos	RoW: organophosphorus-compound, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Fe 4% - Zn 4% - Mn 3%	RoW: primary zinc production from concentrate	agg LCI result, cut-off method	Ecoinvent 3.8
Fe 4% - Zn 4% - Mn 3%	RER: manganese production	agg LCI result, cut-off method	Ecoinvent 3.8
Fosetyl-aluminium	RoW: fosetyl-Al production	agg LCI result, cut-off method	Ecoinvent 3.8
Imidacloprid	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Magnesium sulphate	GLO: magnesium sulfate production	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 0-40-20	US: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 0-40-20	US: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 14-16-18	GB: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 14-16-18	GB: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 14-16-18	GB: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 15-5-30	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 15-5-30	ES: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 15-5-30	ES: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8

Table 7.6. (cont.) Life cycle inventory metadata for Uruguayan citrus nursery production

Input	LCI Name	Type of process	Source
NPK 15-9-12	US: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 15-9-12	US: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 15-9-12	US: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 18-18-18	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 18-18-18	ES: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 18-18-18	ES: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 19-6-10	US: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 19-6-10	US: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 19-6-10	US: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 24-8-20	CH: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 24-8-20	CH: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 24-8-20	CH: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 25-10-17	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 25-10-17	ES: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 25-10-17	ES: market for inorganic potassium fertiliser, as K_2O	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 30-0-0	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 5.7-5.5-0	ES: market for inorganic nitrogen fertiliser, as N	agg LCI result, cut-off method	Ecoinvent 3.8
NPK 5.7-5.5-0	ES: market for inorganic phosphorus fertiliser, as P_2O_5	agg LCI result, cut-off method	Ecoinvent 3.8
Propamocarb	RoW: pesticide production, unspecified	agg LCI result, cut-off method	Ecoinvent 3.8
Peat	RoW: peat moss production, horticultural use	agg LCI result, cut-off method	Ecoinvent 3.8
Perlite	RoW: expanded perlite production	agg LCI result, cut-off method	Ecoinvent 3.8

Table 7.6. (cont.) Life cycle inventory metadata for Uruguayan citrus nursery production

Input	LCI Name	Type of process	Source
Concrete	RoW: concrete block production	agg LCI result, cut-off method	Ecoinvent 3.8
Crushed stone	RoW: limestone production, crushed, washed	agg LCI result, cut-off method	Ecoinvent 3.8
High Density Polyethylene	RoW: polyethylene production, high density, granulate	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: extrusion, plastic film	agg LCI result, cut-off method	Ecoinvent 3.8
Low Density Polyethylene	RoW: polyethylene production, low density, granulate	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: extrusion, plastic pipes	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: extrusion, plastic film	agg LCI result, cut-off method	Ecoinvent 3.8
Nylon 150μm	RoW: nylon 6 production	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: extrusion, plastic film	agg LCI result, cut-off method	Ecoinvent 3.8
Planed softwood	RoW: sawnwood production, softwood, dried (u=10%), planed	agg LCI result, cut-off method	Ecoinvent 3.8
Polyvinylchlo ride	RoW: polyvinylchloride production, suspension polymerisation	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: extrusion, plastic pipes	agg LCI result, cut-off method	Ecoinvent 3.8
Raw softwood	RoW: sawnwood production, softwood, raw, dried (u=10%)	agg LCI result, cut-off method	Ecoinvent 3.8
Recicled High Density Polyethylene	RoW: polyethylene production, high density, granulate, recycled	agg LCI result, cut-off method	Ecoinvent 3.8
	RoW: injection moulding	agg LCI result, cut-off method	Ecoinvent 3.8
Steel	RoW: steel production, electric, low-alloyed	agg LCI result, cut-off method	Ecoinvent 3.8
Zinc coating	RoW: zinc coating, pieces	agg LCI result, cut-off method	Ecoinvent 3.8
Diesel production	RoW: diesel production, petroleum refinery operation	agg LCI result, cut-off method	Ecoinvent 3.8
Diesel combustion	GLO: diesel, burned in agricultural machinery	agg LCI result, cut-off method	Ecoinvent 3.8
Petrol production	RoW: petrol production, unleaded, petroleum refinery operation	agg LCI result, cut-off method	Ecoinvent 3.8
Petrol combustion	GLO: petrol, unleaded, burned in machinery	agg LCI result, cut-off method	Ecoinvent 3.8

Table 7.6. (cont.) Life cycle inventory metadata for Uruguayan citrus nursery production

Input	LCI Name	Type of process	Source
Electricity production	UY: market for electricity, medium voltage	agg LCI result, cut-off method	Ecoinvent 3.8
Transportation by lorry	RoW: transport, freight, lorry 16-32 metric ton, EURO3	agg LCI result, cut-off method	Ecoinvent 3.8
Transportation by ship	GLO: transport, freight, sea, container ship	agg LCI result, cut-off method	Ecoinvent 3.8

Table 7.7. Transport distances for the inputs used in citrus nursery stage (Searates 2022)

Input	Use	Distance by ship (km)	Distance by truck (km)
Abamectin	Acaricide	23142.20	127.47
Alpha-cypermethrin	Insecticide	11229.93	110.87
Benomyl	Fungicide	23142.20	127.47
Ca	Fertiliser	0.00	300.00
Calcium nitrate	Fertiliser	9779.39	200.93
Captan	Fungicide	15617.77	558.21
Chlorpyrifos	Insecticide	23142.20	127.47
Fe 6%	Fertiliser	10863.97	84.07
	Fertiliser	11229.93	110.87
Fe 13%	Fertiliser	10863.97	84.07
Fe 4% - Zn 4% - Mn 3%	Fertiliser	10863.97	84.07
Fosetyl-aluminium	Fungicide	23142.20	127.47
Imidacloprid	Insecticide	23142.20	127.47
Magnesium sulphate	Fertiliser	23142.20	127.47
NPK 0-40-20	Fertiliser	12340.65	205.21
NPK 14-16-18	Fertiliser	12015.99	101.82
NPK 15-5-30	Fertiliser	10863.97	84.07
NPK 15-9-12	Fertiliser	12340.65	205.21
NPK 18-18-18	Fertiliser	10863.97	84.07
NPK 19-6-10	Fertiliser	12340.65	205.21
NPK 24-8-20	Fertiliser	11485.09	250.06
NPK 25-10-17	Fertiliser	10863.97	84.07
NPK 30-0-0	Fertiliser	10863.97	84.07
NPK 5.7-5.5-0	Fertiliser	10863.97	84.07
Peat, seedbeds and pots stage	Substrate	13621.02	74.30
Perlite, pots stage	Substrate	13621.02	74.30
Propamocarb	Fungicide	23142.20	127.47

Considering the size of the country, the average distance for Uruguayan products is established at 300km

Table 7.8. Dissipation rate on plant matrix for the pesticides used in the study (PPDB, 2023)

Input	Dissipation rate RL_{50} on plant matrix
Abamectin	0.2
Alpha-cypermethrin	-
Benomyl	6.1
Captan	7
Chlorpyrifos	3
Fosetyl-aluminium	-
Imidacloprid	2.5
Propamocarb	4.75

Table 7.9. Vapor pressures for the pesticides used in the study (PPDB, 2023)

Input	Vapor pressure (mPa)
Abamectin	0.0002
Alpha-cypermethrin	0.00038
Benomyl	0.005
Captan	0.0042
Chlorpyrifos	1.43
Fosetyl-aluminium	0.0001
Imidacloprid	0.0000004
Propamocarb	730

Table 7.10. Average impact results per stage and standard deviation of citrus nursery production in Uruguay

	Infrastructure	Pesticides production	Fertilizers production	Substrates production	Transport	Machinery operations	Irrigation	Field emissions
Climate change (kg CO_2 eq.·seedling^{-1})	$1.9 \pm 5.9\cdot10^{-2}$	$8.9\cdot10^{-3} \pm 1.2\cdot10^{-3}$	$4.4\cdot10^{-2} \pm 6.1\cdot10^{-3}$	$7.1\cdot10^{-1} \pm 7.1\cdot10^{-3}$	$1.2 \pm 1.1\cdot10^{-2}$	$7.3\cdot10^{-2} \pm 1.8\cdot10^{-2}$	$4.1\cdot10^{-3} \pm 6.1\cdot10^{-4}$	$7.4\cdot10^{-2} \pm 9.2\cdot10^{-3}$
Ozone depletion (kg CFC-11 eq.·seedling^{-1})	$1.3\cdot10^{-7} \pm 3.2\cdot10^{-9}$	$9.6\cdot10^{-9} \pm 1.3\cdot10^{-9}$	$5.4\cdot10^{-9} \pm 5.6\cdot10^{-10}$	$6.7\cdot10^{-9} \pm 6.4\cdot10^{-11}$	$3.8\cdot10^{-8} \pm 3.6\cdot10^{-10}$	$1.5\cdot10^{-8} \pm 3.4\cdot10^{-9}$	$3.8\cdot10^{-10} \pm 5.5\cdot10^{-11}$	0.0 ± 0.0
Acidification (Mole of H^+ eq.·seedling^{-1})	$1.0\cdot10^{-2} \pm 2.5\cdot10^{-4}$	$9.8\cdot10^{-5} \pm 1.7\cdot10^{-5}$	$3.3\cdot10^{-4} \pm 3.3\cdot10^{-5}$	$6.1\cdot10^{-4} \pm 6.0\cdot10^{-6}$	$3.2\cdot10^{-2} \pm 3.2\cdot10^{-4}$	$5.5\cdot10^{-4} \pm 1.4\cdot10^{-4}$	$3.8\cdot10^{-4} \pm 5.6\cdot10^{-5}$	$1.3\cdot10^{-3} \pm 1.6\cdot10^{-4}$
Freshwater eutrophication (kg P eq.·seedling^{-1})	$7.9\cdot10^{-4} \pm 2.1\cdot10^{-5}$	$6.9\cdot10^{-6} \pm 1.6\cdot10^{-6}$	$1.0\cdot10^{-5} \pm 1.2\cdot10^{-6}$	$2.6\cdot10^{-5} \pm 2.6\cdot10^{-7}$	$4.2\cdot10^{-5} \pm 4.1\cdot10^{-7}$	$7.6\cdot10^{-6} \pm 2.1\cdot10^{-6}$	$1.7\cdot10^{-6} \pm 2.5\cdot10^{-7}$	$9.9\cdot10^{-8} \pm 0.0$
Marine eutrophication (kg N eq.·seedling^{-1})	$3.0\cdot10^{-3} \pm 7.8\cdot10^{-5}$	$1.8\cdot10^{-5} \pm 2.4\cdot10^{-6}$	$5.3\cdot10^{-5} \pm 6.6\cdot10^{-6}$	$1.1\cdot10^{-4} \pm 1.2\cdot10^{-6}$	$8.1\cdot10^{-3} \pm 8.0\cdot10^{-5}$	$1.9\cdot10^{-4} \pm 5.0\cdot10^{-5}$	$5.5\cdot10^{-6} \pm 8.0\cdot10^{-7}$	$2.8\cdot10^{-3} \pm 9.5\cdot10^{-4}$
Terrestrial eutrophication (Mole of N eq.·seedling^{-1})	$2.2\cdot10^{-2} \pm 5.5\cdot10^{-4}$	$1.0\cdot10^{-4} \pm 1.3\cdot10^{-5}$	$8.0\cdot10^{-4} \pm 9.1\cdot10^{-5}$	$1.2\cdot10^{-3} \pm 1.1\cdot10^{-5}$	$8.9\cdot10^{-2} \pm 8.8\cdot10^{-4}$	$2.1\cdot10^{-3} \pm 5.4\cdot10^{-4}$	$6.0\cdot10^{-5} \pm 8.7\cdot10^{-6}$	$5.9\cdot10^{-3} \pm 7.5\cdot10^{-4}$
Photochemical ozone formation, human health (kg NMVOC eq.·seedling^{-1})	$7.6\cdot10^{-3} \pm 1.9\cdot10^{-4}$	$3.3\cdot10^{-5} \pm 4.2\cdot10^{-6}$	$1.1\cdot10^{-4} \pm 1.7\cdot10^{-5}$	$3.2\cdot10^{-4} \pm 3.0\cdot10^{-6}$	$2.4\cdot10^{-2} \pm 2.4\cdot10^{-4}$	$7.9\cdot10^{-4} \pm 1.9\cdot10^{-4}$	$3.9\cdot10^{-5} \pm 5.8\cdot10^{-6}$	$2.2\cdot10^{-4} \pm 2.8\cdot10^{-5}$
Resource use, mineral and metals (kg Sb eq.·seedling^{-1})	$2.2\cdot10^{-5} \pm 6.2\cdot10^{-7}$	$1.0\cdot10^{-6} \pm 1.4\cdot10^{-7}$	$1.0\cdot10^{-6} \pm 1.6\cdot10^{-7}$	$2.4\cdot10^{-7} \pm 2.4\cdot10^{-9}$	$1.3\cdot10^{-6} \pm 1.3\cdot10^{-8}$	$5.1\cdot10^{-7} \pm 1.4\cdot10^{-7}$	$2.4\cdot10^{-7} \pm 3.5\cdot10^{-8}$	0.0 ± 0.0
Resource use, fossils (MJ·seedling^{-1})	$3.1\cdot10^{1} \pm 7.7\cdot10^{-1}$	$1.4\cdot10^{-1} \pm 1.9\cdot10^{-2}$	$6.9\cdot10^{-1} \pm 7.5\cdot10^{-2}$	$1.1\cdot10^{1} \pm 1.1\cdot10^{-1}$	$1.4\cdot10^{1} \pm 1.4\cdot10^{-1}$	$1.4 \pm 3.6\cdot10^{-1}$	$1.1\cdot10^{-1} \pm 1.6\cdot10^{-2}$	0.0 ± 0.0
Ecotoxicity (CTUe·seedling^{-1})	$1.1\cdot10^{4} \pm 2.9\cdot10^{2}$	$5.7\cdot10^{1} \pm 8.2$	$2.8\cdot10^{2} \pm 4.1\cdot10^{1}$	$5.3\cdot10^{2} \pm 5.2$	$6.3\cdot10^{2} \pm 6.1$	$2.0\cdot10^{2} \pm 5.4\cdot10^{1}$	$6.9\cdot10^{1} \pm 1.0\cdot10^{1}$	$2.9\cdot10^{-1} \pm 1.3\cdot10^{-1}$
Human toxicity, cancer (CTUh·seedling^{-1})	$8.9\cdot10^{-6} \pm 2.6\cdot10^{-7}$	$7.9\cdot10^{-10} \pm 1.3\cdot10^{-10}$	$5.5\cdot10^{-9} \pm 1.4\cdot10^{-9}$	$4.4\cdot10^{-9} \pm 4.3\cdot10^{-11}$	$6.8\cdot10^{-8} \pm 6.7\cdot10^{-10}$	$5.8\cdot10^{-9} \pm 1.6\cdot10^{-9}$	$8.7\cdot10^{-10} \pm 1.3\cdot10^{-10}$	$2.3\cdot10^{-14} \pm 1.2\cdot10^{-14}$
Human toxicity, non-canc. (CTUh·seedling^{-1})	$1.7\cdot10^{-6} \pm 4.5\cdot10^{-8}$	$2.0\cdot10^{-9} \pm 2.8\cdot10^{-10}$	$1.0\cdot10^{-8} \pm 1.6\cdot10^{-9}$	$1.7\cdot10^{-8} \pm 1.6\cdot10^{-10}$	$8.2\cdot10^{-8} \pm 7.9\cdot10^{-10}$	$9.7\cdot10^{-8} \pm 2.6\cdot10^{-8}$	$2.5\cdot10^{-9} \pm 3.7\cdot10^{-10}$	$3.1\cdot10^{-11} \pm 9.5\cdot10^{-12}$
Blue water scarcity (m^3eq.·seedling^{-1})	$1.4 \pm 3.9\cdot10^{-2}$	$3.0\cdot10^{-3} \pm 1.0\cdot10^{-3}$	$4.8\cdot10^{-2} \pm 3.6\cdot10^{-3}$	$7.7\cdot10^{-4} \pm 7.5\cdot10^{-6}$	$5.1\cdot10^{-2} \pm 5.0\cdot10^{-4}$	$6.4\cdot10^{-3} \pm 1.8\cdot10^{-3}$	$1.1\cdot10^{-2} \pm 1.6\cdot10^{-3}$	0.0 ± 0.0

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Parte III. Discusión general y conclusiones finales

8. DISCUSIÓN GENERAL

La presente tesis ofrece una evaluación de los impactos ambientales asociados al cultivo de cítricos en el Uruguay mediante la metodología de análisis de ciclo de vida, abordando aspectos metodológicos clave para su aplicación. En el **capítulo 8** se discuten los principales resultados de la investigación, integrados y basados en las discusiones y conclusiones presentadas en los capítulos 3 a 7.

De esta forma, la discusión se estructura de la siguiente manera:

- Puntos críticos desde el punto de vista ambiental (*hotspots*) detectados en la producción citrícola del Uruguay y propuestas de mejora
- Contribuciones metodológicas a los ACV citrícolas y de cultivos perennes en general
- Investigación futura

8.1. PUNTOS CRÍTICOS DETECTADOS EN EL CULTIVO CITRÍCOLA DEL URUGUAY Y PROPUESTAS DE MEJORA

En la presente tesis se ha llevado a cabo la evaluación de los impactos ambientales asociados al cultivo en campo de las principales especies citrícolas producidas en el Uruguay. En concreto, se analizan casos de estudio en explotaciones citrícolas representativas del cultivo de limón, mandarina y naranja (capítulos 4, 5 y 6). Se detectaron algunos puntos críticos comunes que se discuten a continuación.

Las **emisiones en el campo consecuencia de la aplicación de fertilizantes** destacan como el principal punto crítico de la producción citrícola uruguaya en varias categorías de impacto. Por un lado, resalta su contribución a las categorías de **eutrofización** para las tres especies citrícolas, principalmente a la eutrofización marina debido a la lixiviación de nitrato y en menor medida a la eutrofización de agua dulce debido a la lixiviación y escorrentía de fosfato. Este punto también se destaca como crítico en la producción citrícola por otros autores, como Bonales-Revuelta et al. (2022), Alishah et al. (2019) y Bessou et al. (2016). Las emisiones en el campo también constituyen un punto crítico en la categoría de **acidificación**, tanto en el caso de estudio de limones como de mandarinas, principalmente debido a las emisiones de amoníaco y dióxido de nitrógeno, como también destacan los autores antes mencionados, además de Yang et al. (2020), Nicolo et al. (2017), Pergola et al. (2013) y Ribal et al. (2011). Las emisiones en el campo, en concreto las de óxido nitroso, también influyen en la categoría de **cambio climático**, teniendo más relevancia en el caso de estudio de limones que en el de mandarinas debido principalmente a que en el primero se aplica una mayor cantidad de fertilizante nitrogenado. En la revisión realizada, esta etapa se destaca como punto crítico por la mayoría de los autores reseñados excepto Bell y Horvath (2020), Martin-Gorriz et al. (2020), Nicolo et al. (2017), Ribal et al. (2017) y Pergola et al. (2013). Las propuestas de mejora detectadas se centran en la reducción del uso de compuestos nitrogenados, lo cual se puede lograr mediante la optimización del ciclo del nitrógeno. Como se comenta en el capítulo 4 y en el capítulo 6, existen varias alternativas para este fin. Por un lado, realizar una estimación de las necesidades de nutrientes del cultivo de forma más ajustada, utilizando para ello metodologías como el índice de vegetación diferencial normalizado (Pettorelli, 2013) o el manejo de nutrientes específicos del sitio (Buresh y Witt, 2007). Por otro lado, la utilización de fertilizantes de liberación lenta o recubiertos con materiales de baja permeabilidad (Mahmud et al., 2021, Cayuela et al., 2017, Skiba et al., 1997). Asimismo, la selección de portainjertos que absorban nitrógeno de manera más eficiente constituye otra opción interesante (Morales Alfaro et al., 2021).

La **producción de óxidos de cobre** para su uso como pesticida destaca como punto crítico en las categorías de **toxicidad y uso de recursos minerales** para los tres casos de estudio. Los óxidos de cobre son fungicidas ampliamente aplicados en la producción citrícola uruguaya. Como la producción de insumos no es responsabilidad directa de los productores citrícolas, en la presente tesis se proponen prácticas complementarias y culturales orientadas a reducir el inóculo de patógenos en el campo para evitar o reducir así el uso de este fungicida. Entre ellas se encuentran la poda y remoción de ramillas viejas, los acolchados orgánicos y las combinaciones con otras especies entre filas. Asimismo, la utilización de nuevas formulaciones basadas en diferentes principios activos, pero con una función similar (por ejemplo, quitosano, fosfitos, ácido hexanoico) podría ayudar a mitigar los ataques de patógenos mejorando la resistencia de las plantas y contribuyendo a un menor uso de compuestos a base de cobre (Lombardo et al., 2023, Caccalano et al., 2021, Garganese et al., 2019).

La **irrigación** destaca como un punto crítico en la categoría de **escasez de agua dulce** en los tres casos de estudio. Con el objetivo de reducir este impacto, se propone optimizar el régimen de riego (es decir, cantidad, momento y técnica de riego), lo cual ayudaría a reducir la evaporación. El riego por goteo es una práctica ampliamente recomendada para minimizar el uso de agua que se aplica actualmente en la mayoría de los campos uruguayos (incluso en los estudiados), por lo que las propuestas deberían enfocarse en otras alternativas, como por ejemplo el riego por goteo subterráneo, la programación avanzada del riego o el riego deficitario (García-Tejero et al., 2012). En cuanto a la minimización del consumo de agua por parte del cultivo, surgen interesantes alternativas como por ejemplo el uso de portainjertos con menores requerimientos hídricos, mallas de cobertura que reducen la demanda hídrica de los cultivos y la elección de variedades de cítricos que muestren una mayor eficiencia en el uso del agua (Lourkisti et al., 2021, Santana-Vieira et al., 2016, Wachsmann et al., 2014).

Por último, en el caso de estudio sobre la producción de naranjas destaca el **transporte de insumos** como punto crítico en la pérdida de biodiversidad, por lo cual tener en cuenta la distancia a la hora de elegir proveedores puede contribuir a reducir estos impactos. En el caso de la pérdida de servicios ecosistémicos del suelo destaca como punto crítico el **uso de suelo para el cultivo citrícola,** con la salvedad de que este contribuye positivamente a la recarga de las aguas subterráneas.

8.2. CONTRIBUCIONES METODOLÓGICAS A LOS ACV CITRÍCOLAS

Las contribuciones metodológicas desarrolladas en la presente tesis surgen a partir de las brechas detectadas en la revisión inicial (capítulo 3), donde se destacan diversas oportunidades de mejora en la aplicación del ACV en la evaluación ambiental de cultivos perennes, en general, y citrícolas en particular.

En primer lugar, se observó la relevancia de llevar a cabo estudios **representativos tanto desde una perspectiva espacial como temporal** cuando el objetivo del ACV es evaluar las prácticas agrarias en un determinado país o región. En cuanto a la primera, se recomienda o bien tomar una muestra representativa de campos que reflejen las prácticas agrícolas en la región o bien, en el caso de que se evalúe un solo campo, justificar claramente su representatividad. En cuanto a la representatividad temporal, hay que tener en cuenta que las prácticas realizadas en una explotación pueden cambiar por diversas razones, como pueden ser cambios climatológicos que influyen en la irrigación o en las plagas, cambios en los precios de los insumos agrarios, o por actualización de los conocimientos técnicos. Por ello, para capturar mejor la influencia de esta variabilidad en los impactos del cultivo, se recomienda considerar un mínimo de cuatro años en la evaluación (fig. 3.4). Se observa que en muchos de los ACV citrícolas publicados no se justifica cómo se garantiza la representatividad del campo evaluado ni se especifica cuántas temporadas de cultivo se evalúan y que la mayoría de los que sí lo hacen estudian solo una (Yang et al., 2020, Ribal et al., 2019, 2017, Nicoló et al., 2017, 2015, Yan et al., 2016, Knudsen et al., 2011). A lo largo de la presente tesis se pone especial hincapié en la justificación de la representatividad de los campos elegidos y se contemplan varias temporadas de cultivo (cuatro en el caso de limón y seis en el caso de mandarina y naranja).

Como se ha comentado, las prácticas agrarias y, en consecuencia, los impactos ambientales asociados a estas son altamente dependientes de variables climáticas, siendo esto de especial relevancia en los cítricos en particular, dado que algunas variedades presentan alternancia productiva, a pesar de que suelen utilizarse prácticas de aclarado (*thinning*) químico o manual para evitarla (Agustí et al., 2003). En este aspecto, una de las principales contribuciones metodológicas de la presente tesis es el estudio de la **variabilidad temporal de los impactos ambientales**. Para cuantificar esta variabilidad se ha utilizado el coeficiente de variabilidad (CV, %) para cada uno de los impactos evaluados y unidades funcionales utilizadas, que se calcula como la desviación estándar sobre la media aritmética. Además, para visualizar dicha variabilidad se ha representado gráficamente para cada impacto la ratio «valor del impacto en la temporada/valor de impacto medio».

Tabla 8.1. Coeficientes de variación de las categorías de impacto, en %, evaluadas para las tres especies citrícolas estudiadas, por hectárea y por tonelada

	CV limón (%) 4 temporadas de estudio		CV mandarina (%) 6 temporadas de estudio		CV naranja (%) 6 temporadas de estudio	
Impact category	UF = 1ha	UF = 1ton	UF = 1ha	UF = 1ton	UF = 1ha	UF = 1ton
CC	1	14	28	45	-	-
AO	0	14	44	70	-	-
AC	0	15	-	-	-	-
AA	-	-	47	66	-	-
AT	-	-	46	64	-	-
EAD	0	15	20	48	14	40
EM	6	14	66	92	76	95
ET	0	15	46	65	-	-
FOF, SH	0	15	22	48	-	-
UR, MM	0	15	34	59	-	-
UR, F	0	15	27	51	-	-
ETOX	0	15	35	59	31	53
TH, C	0	14	37	61	-	-
TH, NC	0	15	26	47	-	-
EAA	37	34	12	36	30	51
CA, SH	-	-	-	-	21	30
CA, ES	-	-	-	-	58	76
DA, ES	-	-	-	-	46	71
PPC	-	-	-	-	84	82
PE	-	-	-	-	0	43
PRRAS	-	-	-	-	0	43
PRI	-	-	-	-	16	50
PRFF	-	-	-	-	3	44
PRCOS	-	-	-	-	2	43
PB	-	-	-	-	45	71

CC: cambio climático, AO: agotamiento del ozono, AC: acidificación, AA: acidificación acuática, AT: acidificación terrestre, EAD: eutrofización de agua dulce, EM: eutrofización marina, ET: eutrofización terrestre, FOF, SH: impactos en la formación de ozono fotoquímico sobre la salud humana, UR, MM: uso de recursos - minerales y metales -, UR, F: uso de recursos - fósiles -, ETOX: ecotoxicidad, TH, C: toxicidad humana - cáncer, TH, NC: toxicidad humana - no cáncer, EAA: escasez de agua azul, CA, SH: daño a la salud humana debido al consumo de agua, CA, ES: daño a los ecosistemas debido al consumo de agua, DA, ES: daño a los ecosistemas debido a la degradación del agua, PPC: potencial de privación por contaminación, PE: potencial de erosión, PRRAS : potencial de reducción de la regeneración de aguas subterráneas, PRI: potencial de reducción de la infiltración, PRFF: potencial de reducción de la filtración fisicoquímica, PRCOS: potencial de reducción del carbono orgánico del suelo, PB: pérdida de biodiversidad.

Como se observa en la tabla 8.1, los CV son altos para la mayoría de las categorías de impacto evaluadas, tanto cuando se expresan los resultados por hectárea como por tonelada, siendo los últimos mayores que los primeros debido a la variabilidad propia del rendimiento antes mencionada. Es de destacar el caso de estudio de limones, en el cual las prácticas agrícolas son las mismas para todos los años evaluados, con excepción del riego. En consecuencia, se observa una baja variabilidad para la mayoría de los impactos al presentar los resultados por hectárea, con valores cercanos al 0 %, con excepción del impacto de escasez de agua, pues las variaciones interanuales de las condiciones climáticas influyen en el consumo de agua del cultivo. En cambio, al expresar los resultados por tonelada, la variabilidad aumenta debido a la variación observada en el rendimiento. Para mandarina y naranja, los CV por hectárea son mayores que para limón, ya que las prácticas agrícolas varían según la temporada analizada. Los CV por tonelada también son mayores porque, además de los cambios en las prácticas agrícolas, los rendimientos de estas dos especies presentan mayor variabilidad. En este sentido, los resultados obtenidos reafirman la importancia de evaluar varias temporadas de cultivo incluso cuando se evalúan árboles en plena producción (capítulos 4, 5 y 6) y aun cuando las prácticas agrícolas son constantes (capítulo 4).

Otro aspecto observado en el capítulo 3 y abordado en la presente tesis es la importancia de utilizar una **combinación de unidades funcionales**, por ejemplo, basadas en masa y en área. Todos los estudios revisados a excepción de Yang et al. (2020), Alishah et al. (2019), Ribal et al. (2017), Yan et al. (2016) y Pergola et al. (2013) utilizan una sola unidad funcional en sus estudios. En la presente tesis, para la evaluación de los impactos del cultivo en campo (capítulos 4, 5 y 6), todos los impactos ambientales se cuantifican tanto por tonelada de producto como por hectárea de campo ocupada, lo cual facilita la comparación con otros estudios, a la vez que permite observar distintos aspectos del proceso. Como se indica en el capítulo 3, las unidades basadas en el área pueden ocultar la influencia de las condiciones agroclimáticas en el rendimiento. En este sentido, el uso de una combinación de unidades funcionales también evita la sobrevaloración de la eficiencia en el uso de los recursos y la deslocalización de impactos ambientales.

En el capítulo 3 se hace especial hincapié en la relevancia del uso de **modelos específicos del sitio para la estimación de las emisiones en el campo** y se alienta el uso y desarrollo de métodos de nivel 2 y nivel 3 en lugar de los de nivel 1. Sin embargo, en ninguno de los estudios citrícolas revisados se aplican metodologías de nivel 3 para el modelado de las emisiones de campo (p. ej.: Bonales-Revuelta et al., 2022, Alishah et al., 2019). Teniendo en cuenta la relevancia de las emisiones en el campo, en especial las asociadas al uso de fertilizantes, en muchas de las categorías de impacto comúnmente evaluadas en los ACV, como se ha comentado en el apartado 8.1, se ha llevado a cabo el **estudio de la influencia del uso de metodologías específicas del sitio para el modelado de las emisiones nitrogenadas en los resultados de los impactos ambientales**, punto que se aborda principalmente en el capítulo 5. Para esto, se ha utilizado la metodología nivel 3 LEACHN (Hutson y Wagenet, 1992) para modelizar dichas emisiones y los resultados obtenidos, tanto para los valores de las emisiones como de los impactos ambientales, se han comparado con los obtenidos utilizando las metodologías nivel 1 y 2 propuestas en directrices ambientales como son las PCR para frutas (EPD, 2019), la huella ambiental de producto —PEF por sus siglas en inglés— (CE, 2018), la base de datos mundial para ACV de alimentos —WFLDB por sus siglas en inglés— (Nemecek et al., 2019), IPCC (2019) y EMEP y EEA (2019). Los resultados del caso de estudio de mandarinas mostraron que, para la mayoría de las emisiones, no hubo diferencias significativas entre su cuantificación mediante la metodología nivel 3 y las metodologías nivel 1 y 2 (tabla 8.2). De todas formas, para la mayoría de las emisiones, la metodología LEACHN presenta CV más altos, lo cual permite inferir que este método captura mejor la variabilidad de las prácticas agrícolas y el clima entre las distintas temporadas de cultivo.

Tabla 8.2. Resultados de las comparaciones pareadas no paramétricas *post hoc* realizadas mediante la prueba de Dunn para emisiones de N que presentan diferencias detectadas mediante la prueba de Kruskal-Wallis para la producción de mandarinas uruguayas.

	LEACHN vs. EPD	LEACHN vs. PEF	LEACHN vs. WFLDB	LEACHN vs. *updated method*
$N_2O \cdot ha^{-1}$	-	-	-	-
$N_2O \cdot ton^{-1}$	-	-	-	-
$NH_3 \cdot ha^{-1}$	-	0,01[a]	-	-
$NH_3 \cdot ton^{-1}$	-	0,04[a]	-	-
$NO_3^- \cdot ha^{-1}$	-	-	0,02[a]	-
$NO_3^- \cdot ton^{-1}$	-	-	0,02[a]	-
$NO_x \cdot ha^{-1}$	-	0[a]	-	-
$NO_x \cdot ton^{-1}$	-	0[a]	-	-

-: no se detectan diferencias significativas; a: diferencias significativas a nivel 0,05

La cuantificación del lixiviado de nitrato mediante la metodología propuesta por WFLDB para países no europeos, el modelo SQCB-NO_3 (Nemecek et al., 2019) y la cuantificación de las emisiones de amoníaco y óxidos nitrosos siguiendo la metodología propuesta en las PEF sí presentan diferencias significativas con la cuantificación realizada mediante LEACHN. Las primeras se explican principalmente porque, si bien el modelo SQCB-NO_3 contempla varios parámetros del suelo, así como la cantidad de fertilizante y agua agregados, no contempla el momento de aplicación (tabla 5.8), por lo que los valores de lixiviado son más altos. Dada la alta variabilidad de los factores climáticos y de manejo del cultivo en la citricultura uruguaya (capítulos 4, 5 y 6), se considera que este modelo no es el más adecuado para modelar la lixiviación de NO_3^- de los cultivos citrícolas. Las diferencias obtenidas en la cuantificación de las emisiones de NH_3 se deben principalmente a que LEACHN estima la hidrólisis diaria de la urea utilizando un factor de emisión más bajo que el rango propuesto en los lineamientos PEF. Por último, las diferencias observadas en los valores de NO_x radican en que los lineamientos PEF no proponen un factor para su modelización.

En cuanto a los impactos ambientales cuantificados para el caso de estudio de mandarinas, cuando se expresan los resultados por hectárea se observan diferencias significativas entre los resultados obtenidos modelizando las emisiones nitrogenadas utilizando LEACHN y siguiendo los lineamientos PEF en las categorías de impacto de acidificación acuática, acidificación terrestre y eutrofización terrestre (tabla 8.3), principalmente debido a las diferencias en los valores obtenidos para las emisiones de NH_3 y NO_X, que son las emisiones que más influyen en dichos impactos. Cuando estos resultados se expresan por tonelada de cítricos, no se observan diferencias significativas, probablemente debido a la alta variabilidad del rendimiento. En el caso de la eutrofización marina, se observan diferencias significativas entre LEACHN y WFLDB, tanto por hectárea como por tonelada (tabla 8.3), principalmente debido a las diferencias en los valores de la emisión más influyente, la lixiviación del NO_3^-.

Tabla 8.3. Resultados de las comparaciones pareadas no paramétricas *post hoc* realizadas mediante la prueba de Dunn para categorías de impacto que presentan diferencias detectadas mediante la prueba de Kruskal-Wallis para la producción de mandarinas uruguayas.

	LEACHN vs. EPD	LEACHN vs. PEF	LEACHN vs. WFLDB	LEACHN vs. *updated method*
$CC \cdot ha^{-1}$	-	-	-	-
$CC \cdot ton^{-1}$	-	-	-	-
$AA \cdot ha^{-1}$	-	0,01[a]	-	-
$AA \cdot ton^{-1}$	-	-	-	-
$EM \cdot ha^{-1}$	-	-	0,03[a]	-
$EM \cdot ton^{-1}$	-	-	0,02[a]	-
$AT \cdot ha^{-1}$	-	0,01[a]	-	-
$AT \cdot ton^{-1}$	-	-	-	-
$ET \cdot ha^{-1}$	-	0,01[a]	-	-
$ET \cdot ton^{-1}$	-	-	-	-

-: no se detectan diferencias significativas; a: diferencias significativas a nivel 0,05.
CC: cambio climático, AA: acidificación acuática, EM: eutrofización marina, AT: acidificación terrestre, ET: eutrofización terrestre.

De estos resultados se desprende la necesidad de profundizar en la aplicación del modelo LEACHN a más casos de estudio que contemplen las distintas características agroclimáticas del Uruguay y así obtener conclusiones generales sobre las ventajas de este modelo para la evaluación de los impactos de la producción citrícola uruguaya. Asimismo, sería interesante utilizar otros modelos nivel 3 para la estimación de las emisiones nitrogenadas de la producción citrícola, como el DNDC (University of New Hampshire, 2007), el Daisy (Hansen, 2002) o el Animo (Rijtema y Kroes, 1991), de manera de comparar los resultados obtenidos con los de la presente tesis. Desde el punto de vista práctico, destaca la utilidad de desarrollar factores de emisión para lixiviación de nitratos que tengan en cuenta aspectos agroclimáticos y con alta resolución temporal.

En cuanto a la **distribución primaria de las emisiones de la aplicación de pesticidas**, en el capítulo 3 se observa que, en la mayoría de los estudios revisados con excepción de Nicoló et al. (2017, 2015), se aplican porcentajes de distribución sin tener en cuenta características específicas del sitio. Es por esto por lo que en dicho capítulo se recomienda el uso de modelos como el pestLCI Consensus v1.0 (Fantke et al., 2017), el cual es utilizado en los capítulos 4, 5 y 6, ya que tiene en cuenta las etapas de crecimiento del árbol, la deriva, el método de aplicación del pesticida, la existencia de zonas *buffer* y el área del campo.

En el capítulo 3 se destaca la importancia de **mejorar los inventarios de agua en los ACV citrícolas**, incluyendo no solo la cantidad total aplicada en el riego, sino también su consumo, ya que ninguno de los estudios revisados cuantifica el consumo de agua por parte del cultivo (ej.: Martin-Gorriz et al., 2020, Ribal et al., 2011). La presente tesis ofrece una contribución en este sentido, ya que se estima el agua consumida por el cultivo utilizando distintos métodos. En los capítulos 4 y 6 se utiliza el método propuesto por la FAO para estimar la cantidad mínima de agua que necesita consumir el cultivo para mantener sus funciones teniendo en cuenta factores climáticos y del suelo (Allen et al., 1998). En el capítulo 5 se realiza un balance hídrico en el suelo utilizando el modelo LEACHM (Hutson y Wagenet, 1992) y se calcula el agua consumida como la evaporación más la absorción de agua por parte del cultivo. En los casos de estudio analizados, los valores promedio de consumo de agua para el cultivo en campo fueron de $2{,}5·10^3$ $m^3·ha^{-1}$ para limones, $8{,}9·10^3$

$m^3 \cdot ha^{-1}$ para mandarinas y $3{,}2 \cdot 10^3$ $m^3 \cdot ha^{-1}$ para naranjas. Estos valores son del mismo orden que los obtenidos por Munro et al. (2016) para cítricos sudafricanos, aunque dichos autores cuantifican el consumo de agua usando SAPWAT 3.0 (Van Heerden et al., 2009), un software desarrollado específicamente para las condiciones de Sudáfrica que se basa en balances de agua en el suelo y medidas experimentales. En el capítulo 7, el consumo de agua en la etapa de vivero se calculó mediante un balance de masa donde la entrada es la cantidad de agua irrigada mensualmente y las salidas son el agua drenada y la evapotranspirada, y tanto el agua irrigada como el drenaje fueron datos primarios proporcionados por el viverista.

Un punto clave para la mejorar los inventarios de agua en los ACV citrícolas es la armonización del método a utilizar para cuantificar el agua consumida por el cultivo. La inclusión de los cultivos leñosos en modelos aprobados internacionalmente, como el modelo AquaCrop sugerido por la FAO (ONUAA, 2016) o el desarrollo de softwares como el SAPWAT 3.0 adaptados a las condiciones de los distintos países productores de cítricos, constituyen interesantes puntos de partida.

En el capítulo 3 se detecta también la falta de estudios que aborden la **etapa de producción de cítricos en viveros a partir de datos primarios**, lo cual es un requisito planteado en las PCR de frutas cuando el proceso está bajo el control directo de la organización (EPD, 2019). Además, cuantificar los impactos de la producción de los plantones en el vivero es clave, puesto que permitiría decidir si la inclusión de esta etapa es relevante en la evaluación de los impactos ambientales del ciclo productivo citrícola. En la revisión se detecta que los únicos dos estudios que abordan esta etapa o bien lo hacen a partir de procesos disponibles en las bases de datos comerciales (Martin-

Gorriz et al., 2020) o bien no proporcionan suficientes datos para comprender cómo realizan su modelado (Bessou et al., 2016). Por tanto, el capítulo 7 de la presente tesis constituye un aporte metodológico en este sentido, ya que se **evalúa el impacto ambiental de la etapa de vivero citrícola a partir de datos primarios**, obtenidos a través de entrevistas con los responsables del vivero.

Mediante este estudio se ha podido observar que la importancia de esta etapa en cuanto a los impactos ambientales totales del ciclo productivo de los cítricos es baja, con contribuciones del 0 al 3,6 % dependiendo de la categoría de impacto y la especie. La fase de plena producción, que se extiende aproximadamente durante 20 años, es la más relevante desde el punto de vista de los impactos ambientales. Asimismo, se ha observado que los procesos de producción de plantones presentes en las principales bases de datos comerciales no son representativos del proceso más frecuente para viveros citrícolas, que implica el cultivo en invernaderos utilizando sustrato como medio de cultivo, ya que consideran el cultivo en campo abierto directamente en el suelo.

El desarrollo del caso de estudio de vivero permitió observar la falta de modelos de estimación o factores de emisión para las emisiones de nitrógeno y fósforo en cultivos sin suelo, especialmente para cultivos que se mantienen tanto tiempo en estas condiciones, así como la falta de modelos para las emisiones de la aplicación de pesticidas en lugares cerrados, destacando la relevancia que tendría incluir estas últimas en modelos estandarizados como el pestLCI.

En el capítulo 3 se detectaron dos aspectos principales en cuanto a la evaluación de impactos ambientales: la **necesidad de incluir la escasez de agua y los impactos sobre la biodiversidad** en los estudios de ACV citrícolas y la relevancia de la **utilización de métodos de caracterización de impacto regionalizados**. Respecto a ambos puntos, se busca generar una contribución con la presente tesis.

En cuanto a la **escasez de agua,** solo el estudio de Machín Ferrero et al. (2021) la cuantifica, para lo cual emplean el método AWARE. Este método se utiliza a lo largo de la presente tesis, desde el capítulo 4 al capítulo 7, utilizando factores de caracterización (CF) mensuales a nivel de la cuenca. La utilización de CF a ese nivel de detalle es de especial relevancia en los ACV agrícolas, como se destaca en el capítulo 5 al comparar los impactos obtenidos para limones y mandarinas. Asimismo, al comparar los valores de los CF propuestos en el método AWARE para Uruguay, se observa que estos van desde 0 $m^3eq.·m^{-3}$ en julio y agosto, meses donde la disponibilidad hídrica en las cuencas hidrográficas es mayor, hasta 0,75 $m^3eq.·m^{-3}$ en enero, mientras que el CF anual propuesto es de 0,58 $m^3eq.·m^{-3}$. A su vez, estos CF difieren de los valores propuestos para cada cuenca concreta donde se ubican las plantaciones de los casos de estudio. En la cuenca correspondiente al campo de limones, el CF mínimo es 0,81 $m^3eq.·m^{-3}$ para los meses de junio y julio, el máximo es 4,39 $m^3eq.·m^{-3}$ en enero y el valor anual 1,70 $m^3eq.·m^{-3}$. Para el campo de mandarinas y naranjas, el CF mínimo es el de mayo, 0,27 $m^3eq.·m^{-3}$, y el máximo 0,65 $m^3eq.·m^{-3}$, el de enero, siendo el anual de 0,52 $m^3eq.·m^{-3}$.

En la bibliografía consultada sobre ACV de cítricos, no se encontraron estudios que evalúen los **impactos sobre la biodiversidad**. En el capítulo 6 de la presente tesis se evalúa la pérdida de biodiversidad cuantificando tanto los impactos directos relacionados con el uso del suelo, utilizando los factores propuestos Chaudhary y Brooks (2018), como los impactos indirectos del proceso productivo, empleando para ello los CF de punto final de la metodología ReCiPe 2016 v1.1 (Huijbregts et al., 2017). Asimismo, se detectan y proponen aspectos metodológicos a mejorar para futuros estudios. Entre ellos, destaca el desarrollo de métodos para evaluar las pérdidas directas e indirectas de biodiversidad que tengan la misma resolución espacial y evalúen los mismos taxones, así como métodos de evaluación de los impactos indirectos sobre la biodiversidad que contemplen todas las categorías de impacto. Asimismo, el método para evaluar los impactos sobre la biodiversidad asociado al uso de suelo debería incluir la cuantificación de otros indicadores además de la riqueza de especies, como por ejemplo la abundancia de especies, la composición o la endemicidad. Por último, cabe destacar también la relevancia del desarrollo de métodos de evaluación de los impactos directos que contemplen la introducción de especies invasoras o la sobreexplotación de los recursos y que consideren las distintas prácticas agrícolas existentes (p. ej.: agricultura ecológica, biodinámica, etc.).

En el capítulo 6 también se evalúa una categoría de impacto tampoco considerada en los ACV citrícolas, la **pérdida de servicios ecosistémicos debido al uso del suelo**. Para su cuantificación se ha utilizado la metodología LANCA® v 2022.1 (Horn y Till, 2022), que proporciona CF para el país. Hay que señalar que, si bien esta cuantificación constituye una gran contribución metodológica a los ACV citrícolas, debería refinarse en futuros estudios. En esta línea, destaca la necesidad de desarrollar CF con mayor resolución espacial y que contemplen en detalle las prácticas agrícolas llevadas a cabo en el campo, así como de estudios orientados a cuantificar la generación de los servicios ecosistémicos y no solo su demanda.

En el capítulo 6 también se contempla un aspecto no evaluado en los ACV citrícolas revisados, que es la cuantificación de la **huella hídrica integral**. De esta manera, la evaluación de los impactos del consumo y degradación de agua de la producción citrícola, tanto con indicadores de punto medio como de punto final, puede considerarse un avance metodológico de la presente tesis. En el estudio llevado a cabo por Munro et al. (2016) para cítricos sudafricanos se cuantifica la huella hídrica, pero no se contemplan los impactos de la cuna hasta la puerta de la explotación agrícola mediante ACV, ya que solo se tiene en cuenta la etapa de cultivo en campo. Asimismo, se sigue la metodología propuesta por Hoekstra et al. (2012), en la cual se cuantifica el «agua virtual», es decir, el agua que se utiliza en la producción de los cítricos, tanto por consumo directo de agua dulce (huella hídrica azul) como por consumo de agua de lluvia (huella hídrica verde) o contaminación de agua (huella hídrica gris), por lo que en su análisis no se tiene en cuenta la escasez de la cuenca ni se cuantifican los impactos en la salud humana y los ecosistemas producto de la degradación y consumo de agua. Además, la degradación del agua se calcula contemplando solo el contaminante de nitrógeno más crítico y no se cuantifican los impactos de la eutrofización ni la toxicidad generadas.

En cuanto al **uso de métodos de caracterización de impacto regionalizados**, el estudio de Machín Ferrero et al. (2021), además de aplicar AWARE, que constituye una metodología regionalizada, aplica la metodología IMPACT World+ para la cuantificación de la acidificación de agua dulce. En la presente tesis se ha abordado la utilización de **métodos de caracterización de impacto regionalizados** tanto en el capítulo 5 como en el capítulo 6.

En el capítulo 5 se estudió la influencia del uso de CF regionalizados en la cuantificación de los impactos ambientales utilizando la metodología IMPACT World+ para estudiar las categorías de impacto de eutrofización marina y terrestre, y acidificación acuática y terrestre. Los resultados muestran que, para el caso de estudio de mandarinas, se observaron grandes reducciones en los valores de las categorías de impacto evaluadas, como se puede apreciar en la fig. 8.1, lo que resalta la importancia de aplicar métodos de regionalización del impacto. Un aspecto que destacar sobre esta metodología es que presenta CF para un grupo seleccionado de flujos, puntualmente los más relevantes para cada categoría de impacto.

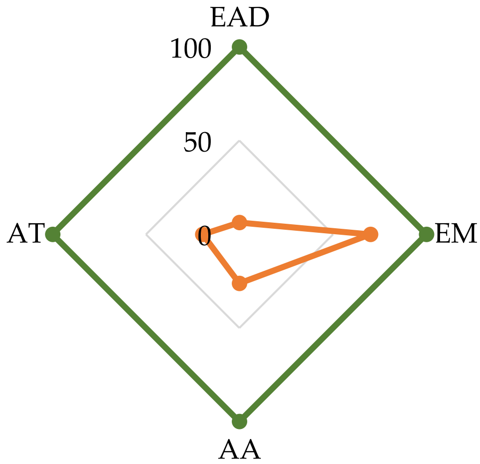

Fig. 8.1. Reducciones obtenidas en las categorías de impacto evaluadas. En verde se representan los valores de impacto sin regionalizar y en naranja los valores de impacto regionalizados. Eutrofización de agua dulce (EAD), eutrofización marina (EM), acidificación acuática (AA) y acidificación terrestre (AT).

En el capítulo 6 se utilizan diversas metodologías regionalizadas para el cálculo de los impactos ambientales. En primer lugar, para la cuantificación de los impactos del consumo de agua a punto final se utiliza la metodología LC-IMPACT 1.3 (Verones et al., 2020) utilizando CF para el país. Para la cuantificación de los impactos sobre los servicios ecosistémicos se utiliza la metodología LANCA® v 2022.1 (Horn y Till, 2022), empleando CF para cultivos permanentes de regadío también para el país. Para cuantificar la pérdida de biodiversidad se utilizaron los CF regionalizados correspondientes a tierras de cultivo con uso intensivo para la ecorregión sabana uruguaya propuestos por Chaudhary y Brooks (2018). Dada la importancia de regionalizar los impactos ambientales, cobra especial relevancia la adición de estos métodos regionalizados a softwares comerciales como GaBi.

8.3. INVESTIGACIÓN FUTURA

En línea con los resultados obtenidos en la presente tesis doctoral, y con el fin de mejorar la cuantificación de la sostenibilidad de la producción citrícola del Uruguay, en futuras investigaciones sería conveniente profundizar en los siguientes aspectos:

1. Cuantificar la huella ambiental citrícola del Uruguay

La aplicación de la metodología de ACV a los casos de estudio analizados y la cuantificación de los distintos indicadores ambientales sirve como antecedente clave para el desarrollo de una huella ambiental citrícola para el Uruguay. Con este objetivo se debería determinar una muestra de explotaciones citrícolas a analizar, la cual deberá ser representativa. Para ello, se debería tener en cuenta la distribución geográfica de los campos citrícolas, determinando el número de campos a estudiar en cada región mediante métodos estadísticos, contemplando también que estén presentes las tres especies citrícolas principales del país (naranja, mandarina y limón), así como la escala de producción (superficie de la explotación), y la consideración de sistemas de cultivo alternativos (p. ej.: agricultura ecológica).

2. Monitorear el progreso del sector hacia los objetivos de desarrollo sostenible

La metodología aplicada y los indicadores propuestos en la presente tesis tienen relación directa con varios de los ODS propuestos por las UN, contribuyendo así a su monitoreo. En esta línea, los distintos aspectos de la huella ambiental citrícola del Uruguay podrían ser incluidos en los informes nacionales voluntarios que publica el país desde el año 2017, permitiendo tener una visión más específica sobre el sector citrícola. Puntualmente, mediante el desarrollo de esta huella ambiental a escala nacional se podría reportar sobre el ODS 12, ya que aportaría a la construcción periódica de indicadores para el sector, con metodologías de medición avaladas. También al ODS 6, ya que se cuantificaría la huella hídrica integral, teniendo en cuenta no solo su consumo, sino también su degradación. Y, por último, se podrían realizar reportes sobre el ODS 15, aplicando indicadores innovadores para la cuantificación de la pérdida de biodiversidad y de servicios ecosistémicos debido al uso del suelo.

3. **Aplicación del ACV consecuencial para formular políticas de sostenibilidad agrícola**

La presente tesis propone parámetros específicos sobre los cuales se podrían desarrollar medidas políticas (p. ej.: impuestos o subsidios), o incluso estándares de desempeño ambiental. Por su parte, la cuantificación de la huella ambiental citrícola en el país permitiría contar con los valores base sobre los cuales materializar estas políticas. En esta línea sería interesante el desarrollo de **ACV consecuenciales**, que permitirían evaluar las consecuencias ambientales de los cambios en los patrones de producción y consumo determinados por estas políticas.

4. **Desarrollar criterios para el desarrollo de ecoetiquetas para el sector citrícola uruguayo**

La presente tesis allana el camino para el desarrollo de ecoetiquetas para el sector citrícola uruguayo. Para poder avanzar en esta dirección, se requerirá profundizar en la determinación de posibles indicadores a ser considerados, junto con su metodología de cálculo. Esto es de suma importancia teniendo en cuenta que los principales importadores de cítricos uruguayos (Unión

Europea y Estados Unidos) fomentan activamente su uso, además de que las ecoetiquetas son un instrumento clave para comunicar la información ambiental a los consumidores.

5. **Desarrollar factores de emisión de compuestos nitrogenados adaptados a las condiciones productivas uruguayas**

Teniendo en cuenta la relevancia de las emisiones nitrogenadas producto del uso de fertilizantes en el campo detectada en la presente tesis, surge la necesidad de profundizar en el desarrollo de factores de emisión adaptados a las características agroclimáticas de la producción citrícola del Uruguay. Para esto se deberían obtener inicialmente muestras representativas de los distintos tipos de suelo para las principales zonas productivas del Uruguay (norte y sur), así como de los distintos inputs y prácticas agrícolas llevadas a cabo en cada campo seleccionado, junto con la utilización de metodologías de Tier 3 para el modelizado de las emisiones.

6. **Desarrollar un indicador de sostenibilidad único para la producción citrícola del Uruguay**

Teniendo como base la aplicación de la metodología ACV para la cuantificación de los impactos ambientales llevada a cabo en la presente tesis, y con el objetivo de dar una visión holística de la sostenibilidad de la producción citrícola, sería interesante desarrollar un indicador de sostenibilidad único que integre las tres dimensiones de la misma: ambiental, económica y social. Para esto se debería profundizar en los indicadores que determinan la sostenibilidad económica, mediante la metodología de analisis de costes de ciclo de vida, y social, mediante ACV social, de la producción citrícola. Además, los resultados de los indicadores obtenidos para cada una de las dimensiones se podrían integrar mediante la aplicación de métodos de decisión multicriterio.

7. **Profundizar en aspectos metodológicos referentes a categorías de impacto.**

Además de los aspectos arriba referidos, que son más específicos para Uruguay, es importante seguir profundizando en el desarrollo de métodos de impacto regionalizados. En concreto, despierta gran interés el desarrollo de indicadores mejorados para cuantificar los impactos relacionadas con el uso del suelo y la biodiversidad, ya que son categorías altamente relacionadas con las prácticas agrícolas, y por tanto sitioespecificos.

9. CONCLUSIONES FINALES

En el **capítulo 9** se presentan las principales conclusiones obtenidas a lo largo del desarrollo de la presente tesis, con base en los resultados obtenidos en los capítulos 3 a 7.

- Se han propuesto **recomendaciones metodológicas** para una aplicación armonizada del ACV en frutas cítricas, contemplando las cuatro fases del análisis y con énfasis en la **representatividad temporal y geográfica**. Entre ellas destacan la necesidad de considerar al menos cuatro temporadas de cultivo para el análisis y la importancia de realizar un muestreo representativo de los campos a estudiar o, en el caso de considerar solo uno, justificar adecuadamente su representatividad. Además, se sugieren métodos actualizados para mejorar la representatividad regional de inventarios y la evaluación de impacto.

- Se han identificado las **áreas que merecen más investigación** en la aplicación de ACV a cultivos citrícolas, las cuales se han abordado en la presente tesis. En la fase de inventario se destaca la importancia del desarrollo de estudios que utilicen métodos específicos del sitio para el modelado de las emisiones de campo, que contemplen las primeras etapas del ciclo productivo y que cuantifiquen el consumo de agua por parte del cultivo. En cuanto a la evaluación de impacto, se destaca la necesidad de evaluar categorías relevantes para cultivos como el citrícola, entre ellas, la escasez de agua y la pérdida de biodiversidad. También se ha identificado la importancia del desarrollo de estudios que empleen metodologías de evaluación de impacto regionalizadas.

- Se ha observado la **utilidad de considerar múltiples unidades funcionales**, en especial de masa y de área, en los ACV citrícolas, ya que permiten desarrollar análisis ambientales más completos, dado que aspectos que se observan al utilizar una de ellas pueden quedar enmascarados al utilizar la otra y viceversa.

● En cuanto a la modelización de las emisiones nitrogenadas producto de la aplicación de fertilizantes en la etapa de campo, para la mayoría de las emisiones analizadas en el caso de estudio de producción de mandarinas en el norte de Uruguay, **no se observaron diferencias significativas entre su estimación con modelos específicos del sitio nivel 3 y con los modelos nivel 1 y nivel 2** propuestos en las directrices ambientales.

● Se han realizado recomendaciones específicas para análisis de impacto de la producción citrícola en Uruguay: 1. el modelo **SQCB-NO_3 no es adecuado para estimar la lixiviación de nitrato** y 2. las emisiones de **amoníaco y óxidos de nitrógeno** producto de la aplicación de fertilizantes **no deberían modelizarse** siguiendo los lineamientos ambientales sugeridos por las **PEF de la UE**.

● La **variabilidad temporal de los impactos ambientales observada** para el cultivo de cítricos es elevada en la mayoría de las categorías de impacto evaluadas, tanto cuando se expresan los resultados por hectárea como por tonelada. Se reafirma entonces la **importancia de evaluar varias temporadas de cultivo,** incluso cuando se evalúan árboles en plena producción, y aun cuando las prácticas agrícolas en el campo no varíen de una temporada a otra.

● La utilización de **metodologías regionalizadas para la cuantificación de los impactos ambientales** de las emisiones de campo del cultivo de mandarinas ha conllevado **reducciones de los impactos** en las categorías de eutrofización marina y terrestre y acidificación acuática y terrestre.

● Se ha observado que **la influencia de la etapa de vivero citrícola en los impactos ambientales del ciclo productivo es mínima** en comparación con la etapa de plena producción, por lo que las medidas para minimizar el impacto ambiental deberían ir orientadas a esta última.

● Las **emisiones de campo producto de la aplicación de fertilizantes**, la **irrigación** y la **producción de óxidos de cobre** son los principales puntos críticos de impacto ambiental detectados en la producción citrícola del Uruguay. Se observó también el **transporte de insumos al campo** como principal responsable de la pérdida de biodiversidad, fundamentalmente debido a su contribución a la ecotoxicidad terrestre. El **uso de suelo para el cultivo de cítricos** representa un punto crítico para la pérdida de los servicios ecosistémicos del suelo, pero presenta impactos positivos en la regeneración de las aguas subterráneas.

● La **optimización del ciclo del nitrógeno**, **del régimen de riego** (cantidad, momento y técnica de riego) y el desarrollo de **prácticas agrícolas orientadas a reducir la presencia de patógenos en el campo** con el objetivo de minimizar la utilización de óxidos de cobre constituyen **alternativas productivas para la minimización de los impactos ambientales** identificados.

Parte IV. Contribuciones científicas y bibliografía

10. CONTRIBUCIONES CIENTÍFICAS

La presente tesis se basa principalmente en los siguientes artículos publicados o en proceso de revisión en revistas indexadas revisadas por pares:

- Cabot MI, Lado J, Clemente G, Sanjuán N. 2022. Towards harmonised and regionalised life cycle assessment of fruits: A review on citrus fruit. Sustainable Production and Consumption, *33*. https://doi.org/10.1016/j.spc.2022.07.024
- Cabot MI, Lado J, Sanjuán N. 2023. Multi-season environmental life cycle assessment of lemons: A case study in south Uruguay. Journal of Environmental Management, *326*. https://doi.org/10.1016/j.jenvman.2022.116719
- Cabot MI, Lado J, Bautista I, Ribal J, Sanjuán N. 2023. On the relevance of site specificity and temporal variability in agricultural LCA: a case study on mandarin in North Uruguay. The International Journal of Life Cycle Assessment – Special Issue: The Role of Developing and Emerging Economies in Sustainable Food Systems. https://doi.org/10.1007/s11367-023-02186-6
- Cabot MI, Lado J, Sanjuán N. Addressing water footprint, ecosystem services and biodiversity in citrus LCAs: a case study in Uruguay. Enviado a la revista *Ecological Indicators.*
- Cabot MI, Lado J, Manzi M, Sanjuán N. Life cycle assessment of citrus nursery: are its environmental impacts relevant? Enviado a la revista *Environmental Impact Assessment Review.*

También forman parte de esta tesis doctoral las siguientes comunicaciones orales y pósters presentados y a presentar en congresos y jornadas:

- Cabot MI, Lado J, Sanjuán N. 2020. Environmental sustainability in the citrus chain: where do we stand? En: Congreso Iberoamericano de Ingeniería de los Alimentos (3.er, 2020, Uruguay). Libro de resúmenes. 137
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