

**UNIVERSIDAD DE LA REPÚBLICA
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**BRECHA DE RENDIMIENTO DE TRIGO: PÉRDIDA DE CALIDAD DE
SUELO COMO FACTOR DETERMINANTE**

por

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Dedico este trabajo a “la sub_30”
Me mantuvieron a flote cuando la correntada era más fuerte.

“We call on researchers, policymakers, and farmers to embrace this recalibrated vision of sustainable intensification. Time is short: The annual cycle of planting and harvest gives farmers fewer than 35 chances to transform their production systems by midcentury. Scientists also face a limited number of opportunities to develop and test new production and conservation strategies. As a group of young agricultural scientists (and one senior scientist), this is the challenge of our careers. By the time our generation retires, agriculture’s 2050 goals must be met.”

Hunter et al.,2017

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RESUMEN

El incremento de la producción de alimentos de los últimos 50 años provino de un proceso de intensificación caracterizado por alto uso de energía en mecanización y producción de agroquímicos, y cultivares con alto índice de cosecha y respuesta a nitrógeno (N). El éxito del proceso es aparente, generando impactos negativos sobre la calidad del suelo, emisión de gases con efecto invernadero, y contaminación del suelo y del agua. La producción de alimentos, fibra y energía requiere de cambios en los sistemas de cultivos, que reduzcan la brecha de rendimiento, incrementen la eficiencia de uso de los recursos escasos y aporten a su conservación. En esta tesis se estudia el impacto del proceso de intensificación ocurrido en la región, caracterizado por “años de agricultura continua (YCC) sin labranza después de una pastura perenne, sobre la función “productividad del suelo”. Esta se estima como rendimiento alcanzable de trigo (Yalc) y brecha de rendimiento (Yg). Se utiliza: i) una base de datos con registro de manejo y producción de trigo de cinco años con condiciones climáticas contratantes; ii) experimentos en campos de productores comparando la frontera de rendimiento aplicando criterios de fertilización actual contra la no limitada por nutrientes; iii) un experimento de largo plazo comparando sistemas de cultivos. YCC redujo el Yalc, particularmente bajo condiciones ambientales desfavorable para el cultivo. El efecto resultó de dos procesos: a) reducida capacidad de suministro de N desde el suelo; b) pérdida de otras propiedades del suelo, no directamente asociadas al suministro de nutrientes, como infiltración y estabilidad de agregados. El primero operó para $YCC \leq 5$, generando una Yg atribuible a nutrientes. El segundo limitó el Yalc generando un Yg no atribuible a nutrientes que alcanzó el 40% para $YCC=10$. Rotar cultivos_pastura sin labranza durante 20 años generó la menor Yg, asociada a mejores indicadores de calidad del suelo. Bajo agricultura continua, sólo incluyendo alta frecuencia de sorgo y maíz se logró un Yatt similar, pero incrementando el Yg atribuible a nutrientes. Se discute la sostenibilidad del proceso de intensificación de la agricultura operado en los últimos 20 años en la región.

Palabras clave: Rendimiento alcanzable, brecha de rendimiento, No laboreo, sistema de cultivo

WHEAT YIELD GAP: SOIL QUALITY DEPLETION AS DETERMINING FACTOR SUMMARY

During the last 50 years, food production was sustained by intensive use of energy in mechanization and agrochemicals, and cultivars with high response to nitrogen (N). This process generated negative impacts on soil and water quality, increasing greenhouse gas emissions. Food, fiber and energy increase for coming years requires new strategies, capable to reduce yield gap (Yg), increasing input and resource use efficiency, but contributing to natural resources conservation. We studied the impact of agricultural intensification process, defined as years of continuous cropping (YCC), on attainable wheat yield (Yatt) and Yg, (difference between Yatt and actual yield). We use three different approaches: i) quantifying YCC effect on soil productivity evolution in the short term (i.e. <10 years) using wheat Yatt derived from five-year producers' records; ii) studying soil properties underlining the response of wheat yield to YCC in 80 on-farm trials under limited and no limited nutrient supply; iii) comparing different cropping systems (CS) under three N levels (N0, N80 and N190 kg ha⁻¹) in a long term experiment. Our results show a negative effect of YCC on Yatt particularly under unfavorable environmental conditions for wheat production. Two processes are associated to YCC effects: a) reduced soil nutrient supply capacity; b) yield reduction due to other soil properties than nutrient supply capacity depletion, related to the soil physical properties. The first one operates for YCC≤5, generating a Yg attributable to nutrients. The second limits the Yalc generating Yg not attributable to nutrients supply, that reached 40% for YCC=10. Crop-pasture rotation under no-till determined the lowest Yg, associated to better soil quality indicators. Including high frequency of grain sorghum and maize under continuous no-till, we obtained similar Yatt that rotating with pasture, but increasing Yg attributable to nutrients supply. Based on our results, we discuss the sustainability of intensification process of agriculture operated in the last 20 years in this region.

Keywords: Attainable yield, Yield gap, No tillage, Cropping system

1. INTRODUCCIÓN

El siglo XX fue testigo de un cambio sustancial en la relación de la humanidad con la tierra. Hasta mediados del siglo, los aumentos en la producción de alimentos provinieron casi exclusivamente de la expansión del área de siembra, con relativamente baja producción por unidad de superficie (Ruttan, 1977), y sistemas de manejo que provocaron el deterioro y abandono de zonas inicialmente productivas (Foley et al., 2005). En la segunda mitad del siglo, la mayor parte del incremento de la producción provino de la intensificación agrícola. El proceso se caracterizó por el aumento en el uso de energía en mecanización y producción de agroquímicos, y la introducción de cultivares capaces de aprovechar altos suministros de nutrientes (Ruttan, 1977, Cassman y Harwood 1995, Cassman, 1999).

Alimentar a la población mundial estimada para el 2050 supone incrementar la producción de alimento entre un 25% y un 100% dependiendo de los autores y año de referencia (Ruttan, 2002, Nagarajan, citado por Kalra et al., 2007, Laborte et al., 2012, Hunter et al., 2017). Si no se modifican los patrones de consumo, existen dos opciones no excluyentes para alcanzar esa meta. La primera, ampliar la frontera agrícola, avanzando sobre ecosistemas con escaso uso agrícola actual y considerados ecológicamente valiosos o frágiles. Ejemplos en América del Sur son paisajes tropicales o semitropicales y llanuras de altura en el Cerrado y Amazonia de Brasil, Chaco de Paraguay y Argentina y áreas de Bolivia, Colombia, Venezuela, y Uruguay. La segunda sería continuar aumentando la producción por unidad de superficie y tiempo en las zonas ya incorporadas a la agricultura.

La primera opción está limitada por la escasez de tierras para uso agrícola, ya que afecta servicios ecológicos actuales de pasturas, montes y selvas naturales (Neumann et al., 2010). La segunda opción implica aumentar la productividad sin deteriorar los recursos naturales del agro-ecosistema, aumentando la eficiencia de uso de insumos (energía). Para lograrlo, la calidad del suelo no debería actuar como factor restrictivo del rendimiento ni de la eficiencia de uso de insumos, y debería ser mantenida o mejorada a lo largo del tiempo.

El cambio en el uso y manejo del suelo ocurrido en los últimos 20 años en el Este de las Pampas de América del Sur es un ejemplo de intensificación agrícola. El

mismo implicó sustituir un sistema de rotación compuesto de tres o cuatro años de cultivos anuales seguidos por tres o cuatro años con pasturas plurianuales compuestas por gramíneas y leguminosas perennes, por sistemas agrícolas sin labranza (Franzluebbers et al., 2014, Wingeyer et al., 2015). Considerando Uruguay, Argentina, Bolivia, Paraguay, y Estados del sur de Brasil (Rio Grande do Sul, Santa Catarina, y Parana), la superficie agrícola se incrementó en 6,2 millones de hectáreas, en un sistema dominado por soja, pero que incluye maíz y trigo en rotación como cultivos principales (63, 19 y 21 % de la superficie respectivamente) (FAOSTAT, 2016).

En Uruguay, la superficie ocupada por cultivos anuales incrementó exponencialmente desde menos de 350.000 ha en el año 2002 a más de 1.500.000 ha en el 2011. El 70% del crecimiento ocurrió en la zona agrícola tradicional (Departamentos de Colonia, Soriano, Río Negro y Paysandú), a expensas del tiempo de la rotación ocupado por pasturas, por lo que el sistema se transformó desde agricultura rotando con pasturas a agricultura continua sin laboreo. El 30% ocurrió como resultado de un proceso de expansión hacia nuevas zonas (DIEA, 2011).

El cambio se considera un proceso de intensificación agrícola en la medida de que se duplicó la producción acumulada de grano por unidad de superficie del sistema (Ernst y Siri-Prieto, 2011). No obstante, aún bajo un escenario de crecimiento del rendimiento por unidad de insumo aplicado, no implica que el proceso sea sostenible, ya que puede ocurrir a expensas de degradación y polución de los recursos naturales involucrados (Garnett y Godfray, 2012).

En el presente proyecto se plantea como hipótesis principal que la trayectoria de intensificación agrícola implementada en el pasado reciente en Uruguay y la región está generando un proceso sutil pero acumulativo de degradación del suelo, que reduce también de manera sutil y acumulativa, el rendimiento alcanzable por los cultivos. Esto ocurre tanto cuando sólo la disponibilidad hídrica es el factor limitante, como cuando lo son el agua y los nutrientes. El efecto resulta de una reducción en la capacidad de suministro de nutrientes y/o de agua para sostener el crecimiento de las plantas y, como consecuencia, se reduce la eficiencia con que se utilizan. Si ésta degradación es real, la intensificación sostenible debiera revertir, no acentuar, la degradación de suelo y el ambiente en general.

1.1. DESCRIPCIÓN GENERAL DEL PROBLEMA A NIVEL GLOBAL Y LOCAL

La seguridad de que la demanda para la agricultura continuará creciendo en las próximas décadas es el motor principal de la intensificación de la agricultura. Se estima que la superficie agrícola mundial al 2050 no crecerá más de 5%, por lo que el 90% del incremento de la demanda deberá ser cubierta por aumento de producción e intensificación del uso del suelo (Hochman et al., 2013).

En el pasado, el aumento de rendimiento se produjo por mejoras genéticas e incorporando insumos. Esta trayectoria implicó mayor uso de fertilizantes, pesticidas, maquinaria y riego. El proceso fue calificado por Burney et al. (2010) como un derroche de recursos naturales, que resultó en impactos negativos sobre la calidad del suelo, emisión de gases con efecto invernadero, y contaminación del suelo y del agua. Se estima que el 47% de los suelos afectados a la agricultura en América del Sur presentan un nivel moderado de degradación, lo que implica que la productividad agrícola está reducida, y que son necesarias medidas correctivas de manejo para restaurar tanto la productividad, como sus funciones biológicas (GLASOD, 2015). Por tanto, la intensificación de la agricultura supone compatibilizar la producción creciente de alimentos en cantidad y calidad, con la conservación y/o restauración de los recursos naturales necesarios para producirlos.

La Declaración de Río sobre el Medio Ambiente y el Desarrollo, describe el concepto de desarrollo sostenible en los siguientes términos: “Los seres humanos constituyen el centro de las preocupaciones relacionadas con el desarrollo sostenible. Tienen derecho a una vida saludable y productiva en armonía con la naturaleza” (Principio 1). “Para alcanzar el desarrollo sostenible, la protección del medio ambiente debe ser parte del proceso de desarrollo y no puede ser considerado por separado”. (Principio 4). El Protocolo de Kioto, como parte de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC), tiene por objetivo reducir las emisiones de seis gases de efecto invernadero que causan el calentamiento global, tres de los cuales están vinculados a las actividades agrícolas: dióxido de carbono (CO_2), gas metano (CH_4) y óxido nitroso (N_2O). Dentro de las medidas establecidas

en el Protocolo para actuar de forma efectiva contra el calentamiento global están: i) proteger y mejorar los sumideros y depósitos de gases de efecto invernadero y ii) promover modalidades agrícolas sostenibles con el cambio climático.

Siendo el suelo uno de los sumideros de carbono de importancia y su labranza identificada como uno de los manejos promotores de su degradación e impactos ambientales negativos asociados, como lo son la emisión de CO₂ por reducción del carbono orgánico del suelo, alto consumo de energía fósil, contaminación del agua de escorrentía por suelo y nutrientes arrastrados por erosión hídrica, la siembra sin laboreo se transformó en el nuevo paradigma de la agricultura sostenible post Protocolo de Kioto. Eliminando el laboreo como práctica de manejo en los sistemas agrícolas se evitaría la degradación del suelo, promoviendo el incremento de su contenido de carbono orgánico y reduciendo la erosión, por tanto, mejorando el rendimiento de los cultivos en el mediano plazo.

En el MERCOSUR la siembra sin laboreo se promovió y adoptó rápidamente, alcanzando en la actualidad más del 70% de la superficie comercial cultivada (Friedrich et al., 2012). En Uruguay alcanzó más del 90% de la superficie afectada a la agricultura, incluyendo aquella que está en rotación con pasturas utilizadas para pastoreo directo (DIEA, 2011).

Este cambio de paradigma sostuvo conceptualmente el crecimiento agrícola en la región. Los sistemas de agricultura continua sin laboreo avanzaron sobre regiones más frágiles, como el Chaco en Argentina y Paraguay y las zonas centro y noreste de Uruguay, y eliminaron/redujeron el tiempo afectado a pasturas en la rotación (Uruguay y región pampeana Argentina), con la expectativa de que ni la calidad del suelo ni el rendimiento de los cultivos serían afectados. No obstante, varios autores cuestionan la sostenibilidad de este proceso. La información local y regional muestra las ventajas de la rotación pasturas-cultivos cuando se evalúa su impacto sobre las propiedades físico químicas del suelo, el uso de agroquímicos, la estabilidad económica y productiva, y la emisión de gases causantes del efecto invernadero (Díaz Roselló 1992, Studdert et al., 1997, Terra y García-Préchac 2002, Díaz-Zorita et al., 2002, García-Préchac et al., 2004, Perdomo et al., 2009, Ernst y Siri-Prieto 2009, Salvo et al., 2010).

Comparado con el sistema tradicional de manejo del suelo con labranza intensiva, la siembra sin laboreo representa un cambio positivo, particularmente en ambientes con alto riesgo de erosión (García-Préchac *et al.*, 2004). No obstante, un análisis detallado de experimentos y relevamiento de sistemas productivos comerciales de la región demuestran que los impactos positivos sobre el carbono orgánico del suelo dependen de la condición inicial del suelo y productividad del sistema (Álvarez y Lavado 1998, Morón *et al.*, 2012, Conceição *et al.*, 2013, Mazzilli *et al.*, 2014, 2015). En suelos con alto contenido inicial de carbono el balance puede ser negativo (25% de los casos analizados por Álvarez 2005) y el rendimiento de los cultivos anuales sólo resulta consistentemente igual o mayor que el obtenido con labranza en condiciones de baja disponibilidad hídrica y ajustada fertilización nitrogenada (Álvarez y Steinbach 2009, Pittelkow *et al.*, 2015). Adicionalmente, luego de más de 20 años de siembra sin laboreo de manera continua, comenzaron a manifestarse problemas atribuidos a la compactación del suelo, cuantificados como cambios en la estructura de los agregados del suelo y su consiguiente efecto sobre las propiedades hídricas del suelo, específicamente la velocidad de infiltración del agua y conductividad hídrica del suelo (Aparicio y Costa 2007, Sasal *et al.*, 2006, Álvarez *et al.*, 2014, Sasal *et al.*, 2017).

Este escenario representa un cuestionamiento a la sostenibilidad del cambio implementado, sobre el cual existe escasa información que permita valorarlo en términos de productividad actual y, en especial, sobre sus impactos en la “productividad futura”, ambas definidas como requisito para la calificación de “intensificación sostenible”.

1.2. MARCO TEÓRICO

Intensificación sostenible es un concepto guía utilizado para diseñar un nuevo proceso de intensificación de la agricultura. Implica aumentar la producción de alimentos de la superficie actual bajo agricultura, implementando tecnologías que tengan un menor impacto ambiental y que no menoscaben nuestra capacidad de continuar produciendo alimentos en el futuro (Garnett *et al.*, 2013). Está asociado al concepto de eco-eficiencia, o producir más con menos impacto. A diferencia de la

intensificación ecológica, que incluye la complejidad que supone la consideración de una escala a nivel de paisaje, las decisiones son diseñadas a escala de unidad productiva (Tittonell 2014). No obstante, la implementación de ambos conceptos supone identificar y reducir las ineficiencias de uso de los recursos, de manera de reducir las consecuencias negativas de la agricultura sobre el ambiente tanto en el sitio, como fuera del sitio en el que se toman las decisiones.

A nivel global, la estrategia seguida es identificar las regiones productoras con mayor capacidad para obtener los aumentos de producción necesarios para proveer alimentos y energía a la población mundial estimada para el 2050. Los resultados se resumen en el proyecto internacional colaborativo denominado Global Yield Gap Atlas (GYGA), en el que se exploran las restricciones biofísicas del rendimiento de los principales cultivos a levantar para la seguridad alimentaria durante el siglo XXI. Para ello se estableció un protocolo de trabajo para estimar el rendimiento potencial (Y_p), el rendimiento limitado por agua (Y_w) y el rendimiento actual (Y_a), pudiendo así estimar las correspondientes brechas de rendimiento. Dado que alcanzar el Y_p o Y_w puede no ser económico y/o que es poco probable que se logre un manejo tan ajustado que permita alcanzarlo a nivel comercial, se definió la brecha explotable como la diferencia entre el rendimiento actual y el 80% del Y_p o Y_w , (van Ittersum et al., 2013).

La cuantificación de las brechas de rendimiento es un insumo de importancia para el desarrollo de programas de intensificación de la agricultura, pero no necesariamente logran identificar manejos de suelos que cumplan con uno de los requisitos establecidos para ser sostenible: “que conserven la calidad del suelo de manera de no menoscabar nuestra capacidad de continuar produciendo alimentos en el futuro”.

1.2.1. Conceptos y definiciones

1.2.1.1 Niveles de rendimiento

En el presente proyecto se consideran los niveles de producción distinguidos por Rabbinge (1993) en función de factores que definen el rendimiento, lo limitan o lo reducen.

El rendimiento potencial (Y_p) de un cultivo es el obtenido por un cultivar adaptado a un ambiente determinado creciendo en condiciones en las que ni el agua ni los nutrientes son limitantes y enfermedades, malezas y plagas son efectivamente controladas. En estas condiciones, el crecimiento del cultivo queda definido por factores que definen el crecimiento, radiación solar, temperatura y concentración de CO_2 atmosférico, y las variables de manejo con influencia en el largo del ciclo e intercepción de luz (madurez del cultivar, fecha de siembra, población y distribución de plantas). Es dependiente de la localidad por las variables de clima, pero no de las propiedades del suelo, siendo el rendimiento objetivo para condiciones de riego.

Limitan el crecimiento factores abióticos como agua y nutrientes. El rendimiento limitado por agua (Y_w) es el logrado en sistemas de producción bajo lluvia natural (secano), donde el agua almacenada en el suelo más la cantidad y distribución de las lluvias no es suficiente para alcanzar el Y_p . En estas condiciones resultan relevantes la capacidad de almacenar agua del suelo y las propiedades que condicionan el balance de agua para el cultivo, como profundidad de enraizamiento, contenido hídrico a distintas tensiones de matriz, pendiente, velocidad de infiltración y conductividad hidráulica.

Reducen el rendimiento factores bióticos como malezas, plagas y enfermedades. En este nivel se ubica el rendimiento actual (Y_a), que es el alcanzado por los productores en condiciones de campo. Lo representa el rendimiento medio en el tiempo y en el espacio de una región, bajo las prácticas de manejo más utilizadas.

El rendimiento alcanzable (Y_{alc}) es obtenido por los aquellos productores que aplican el paquete de medidas de manejo recomendado, considerando el riesgo económico e imperfecciones generadas por el mercado o la legislación (Fischer y Edmeades 2010).

Brecha de rendimiento (Y_g) es la diferencia entre Y_p (para cultivos regados) o Y_w (para condiciones de secano) y el Y_a siendo la brecha explotable la diferencia con el Y_{alc} (Fischer y Edmeades 2010) o el 80% del Y_p o Y_w (Cassman et al., 2003, Lobell et al., 2009).

1.2.1.2 Calidad del suelo

Si bien los conceptos “calidad de suelo” y “salud del suelo” son ambiguos, refieren a la capacidad del suelo de soportar la productividad biológica, mantener la calidad ambiental, mejorar la salud de plantas y animales. Incluyen la provisión de servicios ecosistémicos, la regulación y transporte del agua y los compuestos presentes o agregados al suelo (Doran y Parkin 1994, Karlen et al., 1998), y la capacidad de resistir o recuperarse de la degradación (Blum 2005).

Cuando el objetivo del manejo es lograr la sostenibilidad del agroecosistema, la calidad del suelo es uno de los componentes dentro del esquema jerárquico propuesto por Andrews et al., (2002) (Figura 1.1).

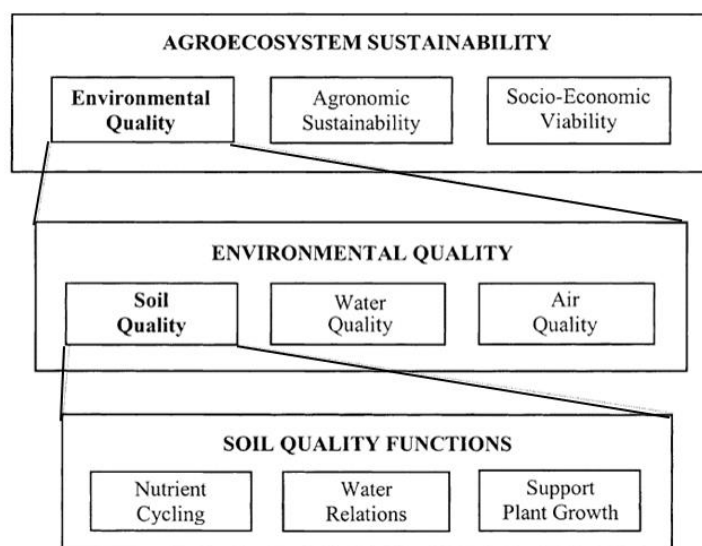


Figura 1.1. La calidad del suelo dentro de una jerarquía anidada para el estudio de la sostenibilidad de los agroecosistemas. Tomado de Andrews et al., 2002.

En general se acepta que las mismas propiedades que soportan la productividad contribuyen al buen funcionamiento de los servicios ambientales que cumple el suelo.

Por tanto, el rendimiento de los cultivos puede ser utilizado como integrador resultante de los cambios en la calidad del suelo impuestos por el manejo en el mediano o largo plazo (Arshad y Martin 2002, Wander et al., 2002).

Dentro de una región climática, el tipo de suelo es una fuente de variabilidad del Yw. La misma resulta de variaciones en la profundidad, propiedades hídricas y aporte de nutrientes. La descripción taxonómica de Series y Grupos de suelo y caracterización de sus propiedades originales son modificadas progresivamente por su manejo. El deterioro de la calidad del suelo generado por aplicar sistemas de producción y tecnologías inapropiadas, resultan en la pérdida de la capacidad para cumplir con la función asignada (Cassman 1999), generando según la definición de Droogers y Bouma (1997), distintos *fenofoms* a partir de un mismo *genoform* (suelo original). Diferentes *fenofoms* existen en la realidad productiva como consecuencia de diferentes sistemas de manejo de suelo y cultivos, incluyendo el tipo de rotación de cultivos. El concepto incluye, según Cassman (1999), la consideración de las sutiles y complejas formas de degradación que se producen aun en sistemas de producción de alta productividad, en los que la erosión dejó de ser el riesgo principal, y que acumuladas en el tiempo, comprometen la capacidad futura de producir biomasa (función productividad del suelo).

1.2.1.3 Pérdida de calidad de suelo como factor limitante del rendimiento

Cassman (1999) propuso un esquema teórico del efecto que la calidad del suelo tiene sobre la relación entre el rendimiento de un cultivo y la energía (insumos) necesaria en el proceso para alcanzarlo (Figura 1.2).

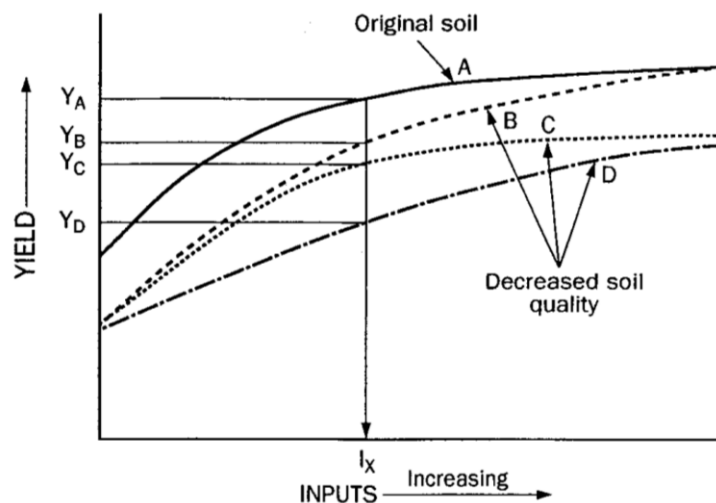


Figura 1.2. Modelo conceptual mostrando la relación entre el rendimiento de un cultivo y los insumos requeridos según la calidad del suelo. La pérdida de calidad desde el estado inicial (curva A) puede resultar en mayores necesidades de ingreso de energía, nutrientes, agua, semillas, control de enfermedades, malezas y plagas para lograr el mismo nivel de rendimiento (curva B). La pendiente y la asíntota de la curva de respuesta dependen del nivel de degradación y puede resultar en pérdida de eficiencia de uso de los insumos, rendimiento máximo o ambos (curvas B, C y D). (Tomado de Cassman 1999).

En la primera “fase del deterioro de la calidad del suelo”, la limitante principal puede ser corregida agregando insumos. En tanto, la curva C representa una “segunda fase” del deterioro de la calidad del suelo, ya que el rendimiento alcanzable es menor independientemente de la cantidad de insumo aplicada. Esto implica la existencia de una limitante estructural o “efecto fijo” sobre el mismo. El intercepto de las curvas representa la producción del sistema sin ingreso de insumos. Como consecuencia de la reducción progresiva de la capacidad de suministro de nutrientes y deterioro de propiedades físicas, un mismo suelo pasaría de la curva A a la D en un número variable de años lo que, analizado a través del tiempo, se traduce en rendimientos alcanzables decrecientes con el tiempo. Ejemplos de estos resultados son los obtenidos en el experimento de rotación cultivos-pasturas instalado en el Instituto Nacional de Investigación Agropecuaria (INIA), Estación Experimental La Estanzuela, Uruguay,

en los que la reducción de rendimiento de trigo se relaciona con la pérdida de carbono de suelo (suministro de nutrientes) y no pudo ser corregida por agregado de fertilizante nitrogenado (Díaz Roselló 1992). Wander et al., (2002) utilizaron este esquema para mostrar el efecto sobre el rendimiento medio de 30 años de maíz y el cambio en la eficiencia de uso de nutrientes luego de 130 años de diferentes rotaciones de cultivos en las Morrow Plots, el experimento de mayor antigüedad de USA. Ladha et al., (2003) y Manna et al., (2005) muestran reducciones de rendimiento en trigo y arroz en experimentos de largo plazo en respuesta a “sutiles cambios en la calidad del suelo, que se manifiestan en el tiempo en un efecto cascada”.

Tanto la intensificación sostenible (IS) como la intensificación ecológica de la agricultura (IEA) suponen que el proceso permite trabajar entre las situaciones representadas por las curvas A y B, lo que, al menos teóricamente, permitiría producir sin generar impactos negativos sobre la producción futura. Conceptualmente nuestra hipótesis supone identificar y cuantificar las causas de las diferencias en la productividad primaria de base (ordenada en el origen de cada curva), la pendiente de cada curva (eficiencia) y los valores críticos a partir del cual la pérdida de calidad de un suelo, además de modificar la eficiencia de uso de los recursos, limita el rendimiento alcanzable (Y_A , I_X e Y_C , I_X en la Figura 1.2, respectivamente). Para ello, es necesario identificar indicadores de la calidad del suelo que se relacionen con diferentes niveles de rendimiento y eficiencia de uso de los insumos.

1.3. PREGUNTAS A RESPONDER

El proceso de intensificación implementado en el MERCOSUR fue sostenido por dos paradigmas de la agricultura moderna: i) eliminar el laboreo tiene efecto positivo sobre la calidad del suelo; ii) la rotación de cultivos dentro de la secuencia mejora el rendimiento de los cultivos. Por tanto, sustituir el tiempo en pasturas de una rotación pasturas-cultivos por agricultura continua sin labranza no debería tener impactos negativos sobre la calidad del suelo ni sobre el rendimiento de los cultivos. El nuevo esquema permite aumentar la capacidad de producir grano y, bajo las condiciones dominantes del mercado, mejoraría la rentabilidad de la empresa.

Las preguntas a responder se pueden ordenar jerárquicamente en base a:

- i) ¿Es esto lo que está sucediendo en los sistemas comerciales de producción?
¿Cuál es el impacto de este proceso de intensificación sobre el rendimiento medio de los cultivos? Tomando el Yalc como indicador de la capacidad del suelo de mantener/mejorar la capacidad de producir ¿puede calificarse el cambio como un proceso de intensificación sostenible?
- ii) ¿cuál es el rol de la rotación de cultivos dentro de la secuencia agrícola?
- iii) ¿qué propiedades del suelo se modifican y se asocian a la respuesta en rendimiento?
- iv) ¿cuál es el impacto sobre la eficiencia de uso de los insumos?

1.4 OBJETIVOS Y ESTRATEGIA

En la tesis se desarrolla en cinco Capítulos:

Capítulo 1. Se realiza una introducción general al problema de la tesis, se describen los principales antecedentes y se plantean los objetivos de la investigación (este Capítulo).

Capítulo 2. Los objetivos planteados son: i) cuantificar el efecto de los años de agricultura continua (YCC) sin laboreo después de cumplida la última fase de pastura sobre el rendimiento actual, el rendimiento alcanzable y la brecha de producción del cultivo de trigo obtenido a nivel comercial; ii) identificar variables de manejo que expliquen la brecha Yatt-Ya. Los YCC fueron tomados como el indicador de intensificación del sistema de producción. El trabajo consistió en el análisis de 1072 registros de chacras de trigo suministrados por productores pertenecientes a la Federación Uruguaya de Centros Regionales de Experimentación Agropecuaria (FUCREA) de los años 2005 al 2009 incluidos, distribuidas geográficamente en las tres regiones agroclimáticas definidas por Corsi (1982) para trigo en Uruguay. Los registros incluyen variables de manejo, clima y rendimiento. La elección del cultivo con el cual evaluar la respuesta vegetal es relevante, ya que podrían existir respuestas diferenciales por cultivo. Es posible que la soja oculte el problema hasta niveles de

degradación superiores a los detectables con cebada o trigo, y que exista variabilidad dentro de cultivos. La elección de trigo se basa en que es el que ocupa mayor superficie dentro de los cultivos de invierno en Uruguay, y es el segundo en superficie sembrada después de la soja. Es un cultivo en el que existe profusa investigación nacional e internacional y se muestra sensible a cambios en las propiedades del suelo y el suministro de nitrógeno.

Hipótesis: la intensificación de la agricultura continua sin labranza implementada en los sistemas comerciales está produciendo una leve pero progresiva degradación de la calidad del suelo, que es posible cuantificarla en términos de rendimiento alcanzable de trigo. Su impacto es mayor en años climáticamente desfavorables para producir trigo e independiente de la manifestación de factores reductores del rendimiento.

Capítulo 3. Los objetivos fueron: (i) cuantificar los efectos de los YCC bajo no labranza sobre el rendimiento de trigo en condiciones de secano; (ii) cuantificar la proporción de la pérdida de rendimiento generada por los YCC que puede atribuirse a fallas en el suministro de nutrientes desde el suelo; (iii) identificar propiedades del suelo modificadas por los YCC que podrían explicar la reducción de rendimiento y, por tanto, generar una brecha incremental de rendimiento al alargar la fase agrícola pos pastura. La estrategia implicó experimentación en campos de productores de trigo, en una región acotada a un radio de 50 km de la Estación Experimental Dr. Mario A. Cassinoni, Facultad de Agronomía. Buscó reducir la variabilidad de clima, suelo y cultivo antecesor implícita en los resultados del Capítulo 2. El indicador de intensificación utilizado para elegir los sitios experimentales (80) también fue los YCC. En cada chacra se evaluó el efecto de dos niveles de nutrientes: (1) Actual: fertilizando siguiendo recomendaciones actuales para N, P y K; (2) Nutriente no limitante, en el cual se fertilizó con N, P, K y S de manera incremental, definiendo así un ambiente en el que el rendimiento no estuvo limitado por nutrientes.

Hipótesis: Intensificar la producción substituyendo la fase pastura de la rotación por cultivos anuales genera una progresiva degradación del suelo, medible en rendimiento

alcanzable de trigo, que puede ser atribuido en distintas proporciones a limitaciones en el suministro de nutrientes y a otras propiedades del suelo, no directamente relacionadas con el aporte de nutrientes, pero que definen su eficiencia de uso.

Capítulo 4. Los objetivos fueron: (i) cuantificar el efecto en el largo plazo del manejo del suelo y de la rotación sobre las propiedades del suelo y el rendimiento de trigo; (ii) cuantificar la proporción de la pérdida de rendimiento atribuible a la reducción de la capacidad de suministro de nitrógeno desde el suelo; (iii) identificar las propiedades modificadas por el manejo del suelo y la rotación que pueden actuar como factores limitantes, modificando la eficiencia de uso de los recursos. Para ello se utilizó un experimento de largo plazo instalado en 1993 en la Estación Experimental Dr. Mario A. Cassinoni de la Facultad de Agronomía en el que se evaluó hasta el año 2013, el efecto del sistema de labranza (convencional contra no laboreo) combinado con rotación o no con pasturas. Sobre cada uno de estos tratamientos se evaluaron tres niveles de fertilización nitrogenada, a un nivel de P, K y S definido como no limitante para la producción de trigo.

Hipótesis: las propiedades del suelo modificadas por el sistema de manejo aplicado en el largo plazo afectan las funciones del suelo, limitando progresivamente el rendimiento máximo de trigo. Esto genera una brecha de rendimiento explicada por pérdida de la capacidad de producir del suelo (función productividad), que no puede ser levantada por incremento en fertilización nitrogenada.

Capítulo 5. En este capítulo se discuten y sintetizan los principales resultados de la tesis, se relacionan con el conocimiento regional y global existente. Se plantean futuras líneas de investigación, así como los posibles usos de la información generada.

2. DEPRESSED ATTAINABLE WHEAT YIELDS UNDER CONTINUOUS ANNUAL NO-TILL AGRICULTURE SUGGEST DECLINING SOIL PRODUCTIVITY*

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2.1. RESUMEN

El incremento de la superficie cultivada anualmente en el este de las Pampas de América del Sur desde el 2002 substituyó el sistema de rotación de cultivos con pasturas por un sistema de cultivos anuales sin labranza. Estudiamos el impacto de esta forma de intensificación del uso del suelo sobre el rendimiento alcanzable de trigo (Y_{att}) y la brecha de rendimiento (Y_g), definida como la diferencia entre Y_{att} y el rendimiento actual (Y_a). La intensificación fue cuantificada como años de agricultura continua después de la última pastura (Y_{CC}). Ambos, Y_{att} e Y_g fueron estimados a partir de

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1072 registros de rendimiento de trigo suministrados por productores, correspondientes a los años 2009 a 2012. La base de datos incluyó rendimiento, zona, cultivo antecesor, fecha de siembra, cultivar, fertilización nitrogenada (N) e YCC. Para cada campo, se estimó un índice de clima (CI) que combina radiación, temperatura y precipitaciones durante el período crítico de definición del número de granos y durante el llenado de granos. Yatt fue estimado como la función de frontera de rendimiento usando CI, cultivar, región e YCC como variables explicativas e incluyendo el cultivo antecesor y N como términos de ineficiencias. Las ineficiencias representan el efecto del manejo sobre Yg. La brecha relativa de rendimiento (RYg) fue calculada como Yg/Yatt. El efecto de las variables de manejo integrantes de la función de ineficiencia sobre RYg fue cuantificado utilizando árboles de clasificación y regresión. El Yatt promedio fue $4.9 \pm 0.7 \text{ Mg ha}^{-1}$, variando en función del cultivar y de la interacción CI por YCC. Yatt fue mayor e independiente de YCC para condiciones de CI favorable para el cultivo (radiación y temperatura durante el período entorno a floración y durante el período de llenado de grano), pero se redujo linealmente con YCC bajo condiciones de CI desfavorables (lluvioso y cálido). Yg y RYg promedio fueron $1.5 \pm 0.8 \text{ Mg ha}^{-1}$ and 0.31 ± 0.17 . La cantidad de N explicó la mayoría de la variación del RYg, siendo YCC la segunda variable en importancia para condiciones de CI bajo. En tanto, con CI alto, la segunda variable en importancia fue el cultivo de invierno antecesor. Los resultados sugieren que, para CI bajo, la intensificación caracterizada por YCC causó una pérdida cuantificable tanto en Yatt como Ya. Estos efectos no pudieron ser compensados ni con la máxima cantidad de N utilizada por los productores. Interpretamos que el cambio desde un sistema integrado de cultivos y pasturas a un sistema de cultivos anuales continuos genera una limitación progresiva de la productividad del suelo que reduce el rendimiento de trigo e incrementa su variabilidad inter anual, aun en siembra sin laboreo.

Palabras clave: Rendimiento alcanzable, brecha de rendimiento, no laboreo, sistema de cultivos, trigo

2.2. SUMMARY

The increase in annually cropped area that has occurred in the eastern Pampas of South America (Uruguay) since 2002 was largely achieved by converting crop-pasture rotations to continuous annual no-till cropping systems. We studied the impact of this intensification on the attainable wheat yield (Y_{att}) and the yield gap (Y_g), with the latter defined as the difference between Y_{att} and actual yield (Y_a). Our measure of agricultural intensification is the length in years of continuous cropping (YCC). We computed both Y_{att} and Y_g from 1072 wheat yield records obtained from producers between 2009 and 2012. The database included grain yield, agro-climatic region, preceding crop, sowing date, cultivar, nitrogen (N) fertilization rate and YCC. For each field, we calculated a climatological index (CI) that combines temperature, radiation and precipitation during both the spike and grain growth phases. To estimate Y_{att} , we fitted a stochastic frontier production function that uses CI, cultivar, region and YCC as explanatory variables, and includes a term representing the inefficiency function. The latter quantifies management practice effects on Y_g . A relative yield gap (RYg) was calculated as the ratio Y_g/Y_{att} . We used regression trees to uncover relationships between RYg and variables integrated in the inefficiency function. The mean Y_{att} was $4.9 \pm 0.7 \text{ Mg ha}^{-1}$. Its variation was a function of the cultivar and the interaction of CI and YCC. The interaction term indicated that Y_{att} was highest and independent of YCC when the CI was favorable for wheat growth (high CI, sunny and temperate before flowering and during grain filling as opposed to low CI, rainy and warm), but declined rapidly with YCC when CI was unfavorable for wheat growth. The average Y_g and RYg were $1.5 \pm 0.8 \text{ Mg ha}^{-1}$ and 0.31 ± 0.17 . The fertilizer N rate explained most of the variation in RYg. When the CI was low, YCC was the second most important variable explaining RYg. When the CI was high, the variation in RYg was best explained by the preceding winter crop. Our results indicate that under low CI, intensifying crop production with continuous annual no-till cropping can cause a measurable reduction in Y_{att} and Y_a . The negative effect of YCC on Y_a was significantly higher under weather conditions unfavorable for wheat growth, increasing the RYg. These effects could not be compensated for with the maximum N fertilization rates used by producers under low CI or with a rotation of annual crops.

Our interpretation is that shifting cropping systems from a crop-pasture rotation to continuous annual no-till cropping generates a progressive limitation in soil productivity that reduces wheat yield and increases its inter annual variability.

Keywords: Attainable yield, Yield gap, No tillage, Cropping system, Wheat

2.3. INTRODUCTION

Driven by increasing grain prices, the area of grain crops in the South American Pampas has increased substantially since 2002. Following this regional trend in land use change, the annual cropped area in Uruguay increased from 400 thousand to 2 million ha in 10 years, with soybean and wheat sown on 50 and 25% of the area, respectively. This large increase in cropped area was achieved by shifting the production systems from crop-pasture rotations to continuous annual cropping under no-till systems (Franzluebbers et al., 2014; Wingeyer et al., 2015).

As a consequence of this shift, wheat is currently grown mainly after full season soybean or maize (42 and 13% of the area, respectively). In turn, soybean and maize are grown after a winter fallow (73%) or in a double cropping system following barley or wheat (27%). In contrast, in the previous traditional crop-pasture rotation, wheat would be sown after perennial pastures, a practice that now happens in only 7% of the wheat area (DIEA 2013). This expansion of no-till agriculture and shift in rotations constitutes a particular case of agricultural intensification.

Underlying this agricultural intensification are two paradigms of modern agriculture: i) No-till has positive effects on soil quality compared to tillage-based systems (Álvarez and Steinbach, 2009; Fuentes et al. 2009), and ii) rotating crops in the cropping sequence, even if they are annual crops, improves crop performance when compared to monocultures (Porter et al., 2003; Munkholm et al., 2013). Consequently, when producers changed their system to continuous no-till of annual crops, they expected to maintain both soil quality and grain yields, increasing the enterprise grain output with a larger share of grain crops in the rotation. Were these expectations realized? Does the yield attainable in commercial fields reflect any positive or negative effect of continuous no-till annual cropping?

One of the pillars of ecological intensification proposed by Cassman (1999) is the maintenance or improvement of soil quality, defined as the capacity of soils to sustain biological productivity (soil productivity function), while ensuring environmental, plant and animal health (Doran and Parkin, 1994; Blum, 2005). The soil quality concept includes subtle and complex forms of soil degradation that would compromise future food production capacity (Cassman, 1999).

A plausible framework to analyze these questions is derived from studies showing that soil quality is better under continuous no-till compared to conventional tillage systems (Álvarez and Steinbach, 2009; Conceição et al., 2013), and that soil quality is better under no-till crop-pasture rotations than under continuous cropping. Better soil quality is attributed to higher soil organic carbon content, better soil structure, and lower soil erosion rates (Díaz-Zorita et al., 2002 in Argentina; García-Préchac et al., 2004, and Ernst and Siri-Prieto, 2009 in Uruguay; Boeni et al., 2014 in Brazil). Then, it can be posited that while a conversion from conventional tillage to no-till can improve soil quality, removing perennial pastures from no-till rotations may gradually reduce soil quality, limiting soil productivity. The mechanism would be a gradual decline in soil water and nutrient supply capacity, which would limit crop resource capture and use efficiency (Cassman, 1999; Sadras et al., 2005; Tittonell and Giller, 2013). This proposition challenges the second paradigm previously mentioned, because it would imply that to retain high productivity, it is not only important to rotate annual crops but to rotate them with perennial pastures.

A straightforward way of evaluating the effect on soil productivity of the shift from crop-pasture rotations to continuous annual cropping systems is to study the impact of the shift on attainable yield (Y_{att}), yield gap (Y_g) and input use efficiency. Following Fischer and Edmeades, (2010), we defined Y_{att} as the yield achieved by a skillful producer using locally optimized agricultural best management practices and adapted cultivars, while taking into account production risks and economics. This represents the yield upper limit obtained under irrigated or rainfed conditions applying best management practices, and has also been defined as the maximum producers' yield (Lobell et al., 2009). The Y_{att} has been estimated using data from individual commercial farmers' fields (Hall et al., 2013), yield contest results (Duvick and

Cassman, 1999), on-farm and experimental station trials, regional yield statistics (Licker et al., 2010), and breeders' trials (Hall et al., 2013). It should be noted that irrigated and rainfed Yatt are not the same as potential and water-limited yield as defined by van Ittersum et al., (2013), which are estimated not from producers' yield records but by using crop simulation models (Lobell et al., 2009; Grassini et al., 2011; Laborte et al., 2012).

In this study we used a stochastic frontier function to estimate Yatt. This approach was developed in economics to compare the efficiency and productivity of enterprises (Battese, 1992), and has been applied to agricultural production (Neumann et al., 2010). Provided that a database from a large sample of fields and growing seasons in an agro-ecological region is available, and that the database includes skillful producers, the stochastic frontier function can estimate, in theory, the Yatt within the range of production conditions in the database.

We propose that Yatt can be used as a biological indicator of the relationship between changes in agricultural intensification and soil productivity. In particular, the rapid shift in cropping systems that occurred in Uruguay during the last decade provides an opportunity to evaluate the impact of agricultural intensification, quantified as the number of years under no-till continuous cropping systems, and crop sequence, on Yatt and Yg. To our knowledge, no previous study has used a stochastic frontier function and the concepts of Yatt and Yg to explore these relationships for a given region.

The objectives of this study were to quantify the effect of the number of years of continuous cropping (YCC) after a pasture phase in no-till rotations on wheat Yatt and Yg, and to quantify the effect of the preceding crop and nitrogen (N) application rate on wheat Yg. To accomplish these objectives, we quantified the effect of YCC on soil productivity evolution in the short term (i.e. <10 years) using wheat Yatt derived from producers' records using a stochastic frontier function; estimated Yatt considering yield defining factors for each field, including cultivar and climatic variables that depend on year, sowing date and cultivar phenology; and identified crop management variables that can control the effect of YCC on Yatt, Ya and Yg.

2.4. MATERIALS AND METHODS

2.4.1. Data base description

Wheat in Uruguay is a rainfed crop grown in a region located in the West of the country (31° to 35°S; 55° to 58°W) (Figure 2.1). Average wheat yields in the period 2009-2012 varied between 2.2 and 3.4 Mg ha⁻¹ (DIEA, 2011). Wheat is commonly sown from May 15th to June 30th, but sowing dates might be delayed in rainy years. We used a database containing 1072 records obtained from wheat-producing members of the Uruguayan Federation of Regional Consortia of Agricultural Experimentation (FUCREA using its Spanish acronym) during four growing seasons (2009-2012). These years represent three different ENSO conditions. According to the International Research Institute for Climate and Society they were classified as “El Niño” (2009, characterized by higher chances of rainfall above average, especially during October, November and December), “Niña” (2010 and 2011, sunny and drier than the average) and “Neutral” (2012). Each record corresponds to one field in one growing season. The average field size was 61 ± 22 ha. The fields were distributed in three of the four agro-climatic regions identified for wheat production in Uruguay by Corsi (1982). These regions are differentiated by average temperatures and expected soil water excess during the wheat heading stage (Figure 2.1). The soils in most agricultural fields are Typic Argiudolls.

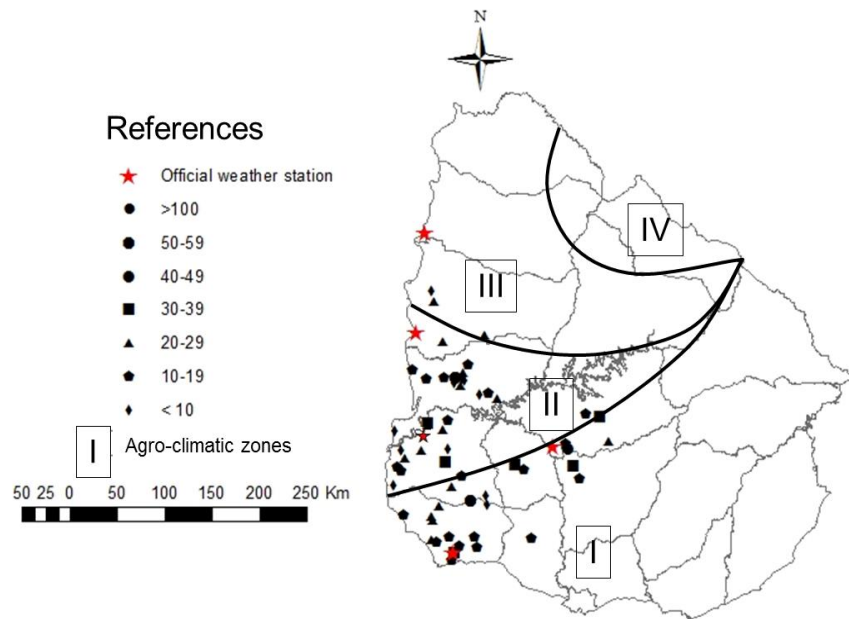


Figure 2.1. Map of Uruguay showing the location of the fields surveyed during the 2009–2012 seasons and the location of official weather stations. Fields are shown grouped in symbols near the localities with rainfall records. The thick lines delimit four agro-climatic-regions differentiated by the average temperatures and expected soil water excess during the wheat heading stage (Corsi, 1982). The number range next to each symbol in the legend indicates the number of field records. The meteorological stations network of the National Directorate of Meteorology can be found at <http://meteorologia.gub.uy/ServCli/mapasEstaciones>.

The database has the following information: grain yield (0% grain moisture), location of the field, preceding crop, sowing date, cultivar, N fertilization rate and years of continuous cropping (YCC) defined as number of years since the last perennial pasture (Table 2.1). The pastures in the rotation are usually composed of grass and legume mixtures and last three to four years. Sixteen cases with more than 10 YCC were considered as YCC = 10. All records correspond to no-till cropping systems.

2.4.2. Estimated variables

Climatic variables related to crop growth and wheat growth in particular were paired with each record, including solar radiation load ($\text{MJ m}^{-2} \text{ d}^{-1}$), temperature ($^{\circ}\text{C}$), precipitation (mm) and the derived variable photothermal quotient (Q). The former is the ratio of average total radiation to mean temperature above 4.5°C during the 30 days around heading stage, and reflects the favorability of growing conditions for grain set. Fischer (1985) and Thome and Wood (1987) found a linear relationship between the number of wheat grains per m^{-2} (sink size) and Q. Thus, radiation and temperature during this period, along with mean temperature during grain filling (T_{FILL}), have a strong influence on Yatt (Abbate et al., 1995). To estimate the weather conditions around heading stage and during grain filling, we estimated heading date for each field and growing season, which depends on sowing date and each cultivar's flowering photothermal response. For this purpose we used a locally calibrated and validated phenology model for wheat (INIA, 2015). Using the estimated heading date we calculated Q, T_{FILL} , mean total radiation during grain filling (RAD_{FILL}), rainfall around heading and grain filling stages (RAIN_{CP} and $\text{RAIN}_{\text{FILL}}$), and number of days from sowing to heading (DH) (Table 2.1).

Table 2.1. Recorded and estimated variables used to estimate the attainable wheat yield and the exploitable yield gap in Uruguay from 2009-2012.

Variable	Abbrevia tion	Units	Source
<u>Recorded variables</u>			
Actual Yield	Ya	kg ha ⁻¹	FUCREA data base
Sowing date	SD	Julian day	FUCREA data base
Years of continuous cropping	YCC	years	FUCREA data base
Nitrogen fertilization	N	kg ha ⁻¹	FUCREA data base
Cultivar		nominal	FUCREA data base
Preceding crop ¹		nominal	FUCREA data base
Region ²		nominal	FUCREA data base
<u>Estimated variables</u>			
Heading date	Heading	Calendar day	Estimated from cultivar-specific thermal time and weather records ³
Days to heading	DH	days	Sowing date to heading date
Photothermal Quotient ⁴	Q	MJ m ⁻² d ⁻¹ °C ⁻¹	Estimated for the period heading ±15 days
Cumulative rainfall during critical period	RAIN _{CP}	mm	Estimated for the period heading ±15 days
Mean temperature during grain filling	T _{FILL}	C°	Mean temperature from heading + 30 days
Mean RAD during grain filling	RAD _{FILL}	MJ m ⁻² día ⁻¹	Mean RAD from heading + 30 days
Cumulative rainfall during the grain filling period	RAIN _{FILL} (mm)		Cumulative rainfall from heading + 30 days

¹ Perennial pasture composed by a mixture of legume and grasses; double cropping wheat/soybeans or barley/soybeans; full season sorghum, maize and soybean, winter fallow, and winter cover crop.

² Defined as Corsi, (1982).

³ http://www.inia.org.uy/estaciones/la_estanzuela/actividades/documentos/trigo.htm

⁴ From Fischer (1985).

Radiation and temperature were taken from five official weather stations: Faculty of Agronomy, Paysandú; INIA, La Estanzuela, Salto and Mercedes; and

Uruguayan National Directorate of Meteorology, Durazno (Figure 2.1). For each field within a 50 km radius around each station, we used the data from the nearest station. For sites located outside this radius (n=178), radiation and temperature were obtained from NASA's Prediction of Worldwide Energy Resources (NASA/POWER; power.larc.nasa.gov). We checked the level of agreement between NASA's weather data and that of the official weather stations by comparing data from both sources for co-located coordinates, and found that for daily radiation and average temperature, the root mean squared error between NASA and the weather stations was $0.1 \text{ MJ m}^{-2} \text{ d}^{-1}$ and $0.15 \text{ }^{\circ}\text{C}$, respectively, which we considered acceptable for the analysis. Rainfall records were obtained from a network of producer cooperative records and when unavailable, from the records of the Uruguayan National Directorate of Meteorology (INUMET, 2015). Weather conditions generated by year, region, planting date and phenology of each wheat cultivar were summarized through Q , T_{FILL} , RAD_{FILL} , RAIN_{CP} and $\text{RAIN}_{\text{FILL}}$.

Because the climatic variables were co-linear, we used principal component analysis (PCA) to generate a new variable called Climatic Index (CI). The CI includes Q , RAIN_{PC} , RAD_{FILL} , T_{FILL} and $\text{RAIN}_{\text{FILL}}$. Uncorrelated variables were selected based on a correlation matrix, and a new analysis was used to generate CI. The CI was calculated as the sum of the standardised Principal Components with a vector > 1 and a partial correlation coefficient $> 5\%$. The CI quantifies and integrates climatic factors for each observation during the 30 days around the heading stage. The CI had a zero mean and varied between -4.9 and +3.5; it was included in the stochastic frontier production function as a variable that defines Y_{att} , replacing the climatic variables that compose it.

Cultivar, preceding crop, and agro-climatic region are nominal variables. To include them in the stochastic frontier production function, we converted them to quantitative variables. We accomplished this by generating a yield index, estimated as the mean of the top decile of Y_a for each cultivar's (YI_c) preceding summer crop (YI_s), preceding winter crop (YI_w), and agro-climatic region (YI_r) (Table 2.2). This method was used by other authors to estimate the Y_{att} in different regions (Licker et al., 2010; Laborte et al., 2012; Hall et al., 2013) and implies that the effect of each

nominal variable is represented in the model by the upper yield percentile, providing an estimate of the yield that can be reached by producers in a specific zone, planting a specific cultivar or after a specific preceding crop under current technology. In the four growing seasons considered, 38 different cultivars were sown, whose YI_C varied between 3.2 and 5.6 Mg ha⁻¹.

Table 2.2 Mean wheat yields, standard deviation and yield index (mean yield of the top decile) for agro-climatic region, preceding summer crop and preceding winter crop.

Variable	n	Mean Yield	S.D.	Yield Index (P90)
		----- kg ha ⁻¹ -----		
All records	1074	3419	1082	4897
<u>Agro-climatic Region (YI_R)</u>				
I	646	3438	1074	4900
II	203	3473	1230	5142
III	225	3313	947	4578
<u>Preceding summer crop (YI_S)</u>				
Double anual cropping system	308	3121	959	4513
Sorghum full season	22	3258	1024	4897
Maize full season	48	3273	1157	5100
Soybean full season	628	3588	1102	5023
Perennial pasture	26	3442	1137	5206
<u>Preceding winter crop (YI_W)</u>				
Wheat	187	3177	900	4440
Barley	118	3036	913	4442
Cover crop	94	3191	1114	4552
Fallow	571	3524	1121	5032
Perennial pasture	84	3945	1029	5284

2.4.3. Estimation of the attainable yield and yield gap

We estimated Yatt using a stochastic frontier production function (Neumann et al., 2010; Verburg et al., 2000) built from producers' records (Lobell et al., 2009, Hall et al., 2013; Grassini et al., 2015). We estimated the Yg in each field-year combination as the difference between Yatt and Ya. We used this approach over crop simulation

models because we do not have the detailed soil data from each location necessary for simulating each observation independently, and because even if we did have the data, simulation models do not have yet the ability to simulate the yield effects of the small and gradual changes in soil properties that might occur in the short term (10 years or less) (Bouma and Droogers, 1999). Using the database of producers' records to estimate Yatt allowed us to integrate the inherent variability existing in real-world farming as determined by variations in sowing dates, cultivars, intra-field variability, and other site- and time- specific properties of each observation.

The deterministic component of the stochastic frontier function represents Yatt and the inefficiency function represents Yg (Eq. 1). To estimate Yatt we included in the stochastic frontier production function the climate composite index CI, cultivar (YI_C and DH), the agro-climatic region (YI_R) and years of continuous cropping (YCC). We included YI_R to account for factors other than climate that might be affected by the location of the field. We assumed that the YCC modifies soil chemical, physical and biological properties, affecting soil water and nutrient supply capacity, as well as the biotic environment for the wheat crop, and that the integrated response to these factors can be measured thorough Yatt.

The stochastic frontier function was specified as:

$$\ln(Y_{ai}) = \beta_0 + \beta_1 \ln(CI_i) + \beta_2 \ln(YI_{Ci}) + \beta_3 \ln(DH_i) + \beta_4 \ln(YI_{Ri}) + \beta_5 \ln(YCC_i) + V_i - Yg_i$$

where Y_{ai} = Actual yield (kg ha⁻¹) of the ith field (i = 1, 2, . . . , 1072), CI is the climatic index (+ 5 was added to all values to obtain positive values), YI_C is the yield index for each cultivar (kg ha⁻¹), DH is days from sowing to heading (days), YI_R is the yield index for region (kg ha⁻¹), YCC is the years of continuous cropping (years), V is the random error (mean = 0), and Yg is the inefficiency function or yield gap (Yatt - Y_a, positive values only).

We included in the inefficiency function the effects of both preceding crop (previous winter and summer) and N fertilization. The inefficiency function was specified as:

$$Yg_i = \delta_0 + \delta_1(YI_{Si}) + \delta_2(YI_{Wi}) + \delta_3(N_i)$$

where Yg_i is the yield gap of the i^{th} field ($i = 1, 2, \dots, 1072$), YI_w is the yield index for each preceding winter crop ($kg\ ha^{-1}$), YI_s is the yield index for each preceding summer crop ($kg\ ha^{-1}$), and N is the total N applied as fertilizer ($kg\ ha^{-1}$),

The stochastic frontier production function and the inefficiency function were estimated using FRONTIER 4.1 software (Coelli, 1996). The software uses the maximum-likelihood method for simultaneous estimation of the parameters of both functions. We tested all interactions and retained those that were statistically significant at the 5% level. Combining both functions we estimated $Yatt$ as:

$$Yatt_i = Ya_i / \exp(-Yg_i).$$

The most common output-oriented measure of technical efficiency is the ratio of observed output to the corresponding stochastic frontier output (Battese and Coelli, 1995). However, we preferred to calculate a relative yield gap (RYg) as:

$$RYg_i = Yg_i / Yatt_i$$

The RYg varies from 0 to 1 representing the relative distance from Ya to $Yatt$ in each field, allowing a comparison of Yg among fields with different $Yatt$.

2.4.4. Quantifying the effects of years of continuous cropping and wheat management on wheat attainable yield and relative yield gap

We fitted a response surface in which $Yatt$ was a function of CI and YCC. The model allowed for the intercept, linear, quadratic and interactive terms. The coefficients were retained if their inclusion improved the overall model fit based on Fisher's F-test at 95% confidence level. The regression models were used to generate dimensional and contour maps. We also did regression analysis with $Yatt$, Ya , Yg and RYg as response variables and YCC, CI or YI_c as independent variables. A critical value for the relationship between $Yatt$ and CI was estimated by downhill simplex method and the function adjusted by the Levenberg-Marquardt method (Balzarini et

al., 2008). This enabled categorization of the climatic conditions for wheat production as either high-yield environment (HYE, i.e. cases above the CI threshold) or low-yield environment (LYE, i.e. cases below or equal to the CI threshold).

To identify the main factors controlling RYg variability and to categorize the observations into relatively homogeneous groups, we used Classification and Regression Trees Analysis (CART). Since we found a significant CI*YCC interaction, we did CART analyses separately for HYE and LYE. Because YCC was included in Yatt estimation (frontier function) and RYg is calculated as Yg/Yatt ratio, we tested collinearity between them. A variance inflation factor (VIF) test between RYg, Yatt and Yg was very low (VIF=1.7); therefore, YCC was also incorporated as a variable determining RYg in the CART analysis.

We chose the least squares method for regression trees. The optimal split was the one that maximized the LogWorth statistic, defined as $-\log_{10}(\text{p-value})$. We also established 150 objects as the minimum node population that would enable further splits. To test the strength of the variables selected by CART we used bootstrap resampling with 500 replicates.

2.5. RESULTS

2.5.1. Attainable yield and yield gap

The frontier function for wheat yield (likelihood ratio = 124, $P \leq 0.01$) indicated that Yatt was controlled by CI, YIC and the YCC*CI interaction ($P \leq 0.05$). The variation in output due to variables integrated in the inefficiency function, represented in the model by the parameter gamma, was significantly different from zero (Table 2.3). The analysis indicates that the variables included in the inefficiency function explained Yg. Preceding winter crop and total N applied, but not preceding summer crop, were statistically significant terms affecting Yg (Table 2.3).

The average Yatt was $4.9 \pm 0.7 \text{ Mg ha}^{-1}$ (Table 4), the maximum observed yield was 6.6 Mg ha^{-1} , and the average Yg was $1.5 \pm 0.8 \text{ Mg ha}^{-1}$, representing about 31% of the average Yatt.

Table 2.3. Coefficients and standard error (s.e.) for the parameters of the wheat stochastic frontier production function for the period 2009-2012 in Uruguay.

	Parameter	Coefficient ¹	Standard error	t-value
<u>Frontier production function (Yatt)</u>				
Constant	β_0	-2.82	3.35	-0.8
Climatic Index (CI)	β_1	0.06	0.3	2.0*
Cultivar Index (YI _C) (kg ha ⁻¹)	β_2	0.73	0.05	15.1*
Days to heading (DH) (days)	β_3	0.02	0.06	0.3
Region (YI _R) (kg ha ⁻¹)	β_4	0.58	0.39	1.5
Year of continuous cropping (YCC) (years)	β_5	-0.98	2.71	0.36
YCC x CI	β_6	0.04	0.02	2.0*
<u>Inefficiency function (Yg)</u>				
Constant	δ_0	15.6	3.0	5.2
Preceding summer crop index (YI _S) (kg ha ⁻¹)	δ_1	0.36	0.4	0.9
Preceding winter crop index (YI _W) (kg ha ⁻¹)	δ_2	-2.12	0.46	-4.7*
Nitrogen applied (N) (kg ha ⁻¹)	δ_3	-0.46	0.19	-2.4*
<u>Variance parameters</u>				
Variance	σ^2	0.16	0.02	8.3
Gamma	γ	0.94	0.02	55.9

Likelihood ratio statistic (LR) =124* ;

Critical t-value= 1.7 P≤0.05

Observations: 1.072

*=P≤0.05

¹A positive coefficient in the frontier production function indicates that the variable has a positive influence on Yatt. A positive coefficient in the inefficiency function indicates that the variable has a negative influence on Yg.

Table 2.4. Attainable wheat yield, yield gap and relative yield gap in Uruguay (2009-2012).

Variable	Mean	S.D	P(90)	Maximum
Attainable yield (kg ha ⁻¹)	4,945	711	5,631	6,565
Yield gap (kg ha ⁻¹)	1,526	811	2,733	3,591
Relative yield gap	0.31	0.17	0.56	0.70

2.5.2. Response of attainable yield and yield gap to climate

The Yatt had a linear-plateau response to CI ($P \leq 0.05$) (Fig. 2.2). The Yatt increased 0.3 Mg ha⁻¹ per unit change in CI when $CI < 0.2$ ($P < 0.01$), remaining constant for $CI \geq 0.2$. This threshold CI enabled us to categorize the climatic conditions for wheat production into two groups: a low-yield environment (LYE) sensitive to CI for $CI < 0.2$, and a high-yield environment (HYE) for $CI \geq 0.2$. These two groups had almost no overlap in the range of weather variables analyzed (Table 2.5).

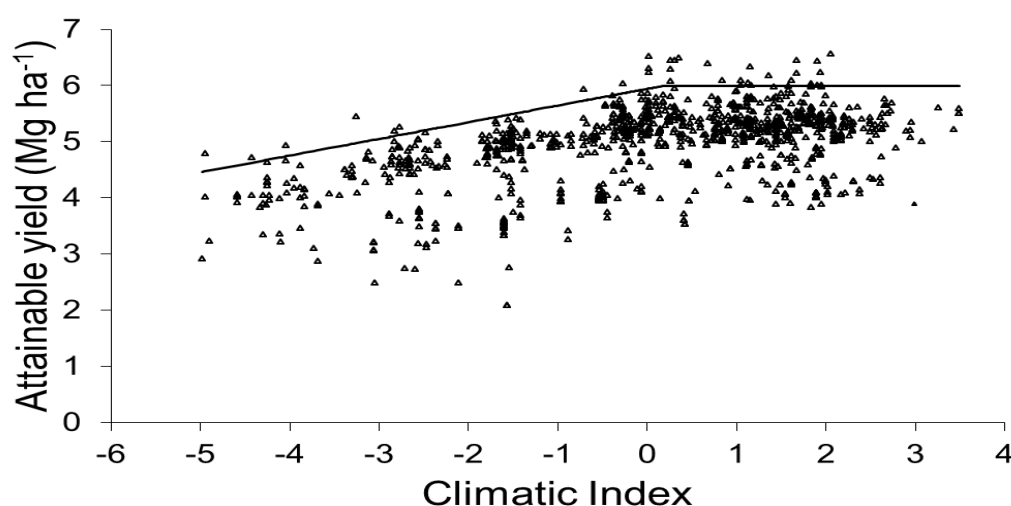


Figure 2.2. Attainable wheat yield as a function of the climatic index (CI) in Uruguay for the years 2009 and 2012. Triangles: Yatt for 1,072 wheat fields; solid line: P(90) adjusted linear-plateau model $Yatt = \text{For } CI < 0.2, Yatt = 5,882 + 297 \times CI; \text{ for } CI \geq 0.2, Yatt = 5,882$.

Table 2.5. Photothermal quotient (Q) and accumulated rainfall during critical period determining sink size (RAIN_{CP}), mean solar radiation and mean temperature during grain filling (RAD_{FILL} and T_{FILL}, respectively) under high-yield environment (HYE) or low-yield environment (LYE). The corresponding means for the 10th (P10) and 90th (P90) percentile within HYE or LYE are also shown.

Environment	Variable	Mean	S.D.	P10	P90
High yield (HYE) n=588	Q (MJ m ⁻² d ⁻¹ °C ⁻¹)	1.7	0.24	1.5	2.1
	RAIN _{CP} (mm)	95	74.4	18	210
	RAD _{FILL} (MJ m ⁻² d ⁻¹)	20.7	1.5	18.9	22.4
	T _{FILL} (C°)	16.8	1.9	15.1	18.9
	Actual wheat yield (kg ha ⁻¹)	3,774	1,007	2,420	5,100
	Attainable yield (kg ha ⁻¹)	5,205	529	4,304	5,760
	Yield Gap (kg ha ⁻¹)	1,431	755	529	2,474
	Relative yield gap (kg ha ⁻¹)	0.28	0.15	0.09	0.47
Low yield (LYE) n=484	Q (MJ m ⁻² d ⁻¹ C ⁻¹)	1.3	0.21	1.0	1.5
	RAIN _{CP}	188	70.3	86.6	262.7
	RAD _{FILL} (MJ m ⁻² d ⁻¹)	17.6	2.5	13.4	20.8
	T _{FILL} (C°)	17.6	2.2	15.5	20.6
	Actual wheat yield (kg ha ⁻¹)	2,987	1,015	1,800	4,550
	Attainable yield (kg ha ⁻¹)	4,630	690	3,597	5,362
	Yield Gap (kg ha ⁻¹)	1,642	866	495	2,937
	Relative yield gap (kg ha ⁻¹)	0.36	0.18	0.12	0.61

S.D. =standard deviation; n= observations.

About 54% of the observations corresponded to HYE, which had higher average Q and RAD_{FILL}, combined with lower RAIN_{CP} and T_{FILL}. Although the average wheat yield was higher for the HYE than for the LYE, there was a wide variation within groups and overlap between groups (2.4 to 5.1 Mg ha⁻¹ for HYE and 1.8 to 4.6 Mg ha⁻¹ for LYE).

2.5.3. Effect of cultivar on attainable yield and yield gap

The cultivar effect on Yatt was significant ($P \leq 0.01$) and of similar magnitude in both yield environments. However, the cultivar effect on Ya was higher in HYE than in LYE ($P \leq 0.01$) (Table 2.6). More than 90% of the increase expected from using a high-yielding cultivar was captured in the Ya of HYE (0.74/0.81 in Table 2.6), but only 44% was captured in LYE (0.31/0.70 in Table 6). As a result, the Yg was affected by the cultivar in LYE, ranging from 1.2 to 2.4 Mg ha⁻¹ depending on YI_C.

Table 2.6. Relationship between the cultivar yield index (YI_C) and attainable wheat yield, actual wheat yield, yield gap and relative yield gap under high yield (HYE) environment and low yield environment (LYE).

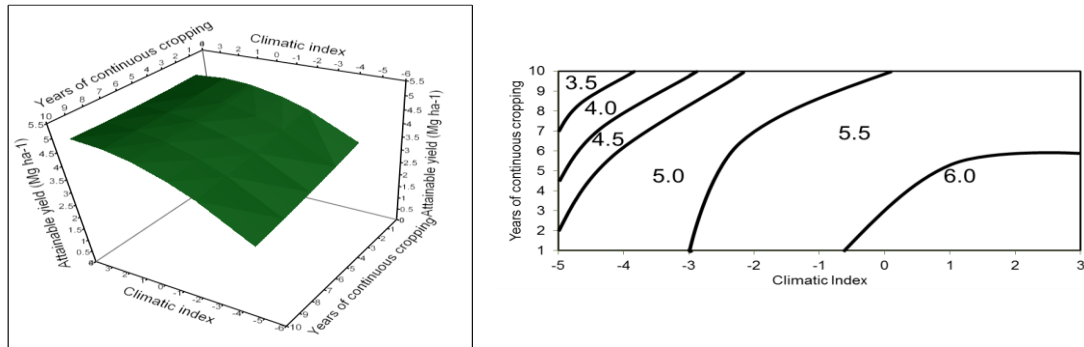
Regression coefficient	kg ha ⁻¹ YI _C ⁻¹			
	Attainable yield	Actual yield	Yield gap	Relative yield gap (%)
β HYE	0.81 **	0.74 **	ns	-0.03**
β LYE	0.70 **	0.31 **	0.4 **	0.04**
β HYE – β LYE	ns	0.43 **	0.4 **	0.07**

**= $P \leq 0.01$; * = $P \leq 0.05$; ns = not significant

2.5.4. Relationship between the length of continuous annual cropping and attainable yield and yield gap

Years of continuous cropping after the last perennial pasture interacted quadratically with CI to determine Yatt (Fig. 2.3A). The percent of the variance explained by each term of the model was 43% for CI, 23% for YCC and 11% for the CI*YCC interaction. The distance among iso-yield lines in Figure 2.3B indicates the response of Yatt to CI and YCC, and the change in the dimensions of the ellipsoidal contours gives a visual clue of the interaction between variables. The shortest distance among iso-yield lines under LYE indicates that YCC increases the sensitivity of grain yield to CI. Specifically, the negative impact of YCC on Yatt is accentuated in unfavorable weather conditions in the ≈ 30 days bracketing the heading stage (i.e. when

CI is computed), but is almost unnoticeable under favorable weather conditions during that stage.



$$Y_{att} = 5270 - 73.2 \times YCC + 85.5 \times CI + 2.8 \times YCC^2 - 33.2 \times CI^2 + 12.2 \times CI \times YCC$$

Figure 2.3. Fitted response surface (A) and contour plots (B) of attainable wheat yield (Yatt) related to climatic index (CI) and years of continuous cropping (YCC).

The highest average Yatt was obtained when $CI > -0.5$ and $YCC \leq 5$ (average Yatt = 6.0 Mg ha⁻¹) (Figure 2.3B). The second highest Yatt ($5.5 \leq Yatt < 6.0$) occurred when $-3 \leq CI < 1.5$. Subsequent splits indicate that Yatt could only be maintained if CI was high. The worst case scenarios were for $YCC > 5$ and $CI < -3$, when the interaction between YCC and CI had the strongest negative impact on Yatt. The average Yatt in such conditions was only 60% of that under optimal CI.

A linear regression analysis also showed that the negative effect of YCC on Yatt was stronger under LYE than under HYE ($P \leq 0.01$, Table 2.7). We estimated a reduction in Yatt of 79 kg ha⁻¹ per year ($P \leq 0.01$) for LYE and only 18 kg ha⁻¹ per year of continuous cropping ($P \leq 0.05$) in HYE. When YCC increased, the Yg was reduced at the same annual rate in both environments (-22 and -23 kg ha⁻¹ year⁻¹). Under HYE, the reduction in Yg was due to a small negative effect of YCC on Yatt, with no effect on Ya, while under LYE the negative effect of YCC on Yatt was larger than on Ya (-79 and -56 kg ha⁻¹ year⁻¹). Consequently, the RYg decreased by 0.43% year⁻¹ under HYE and increased 0.11% year⁻¹ under LYE.

Table 2.7. Regression coefficients between years of continuous cropping and attainable wheat yield, actual wheat yield, yield gap and relative yield gap under high yield (HYE) environment and low yield environment (LYE).

Regression coefficient	Attainable yield	Actual yield	Yield gap	Relative yield gap
	kg ha ⁻¹ y ⁻¹			%
β_{HYE}	-18*	ns	-23 +	-0.43**
β_{LYE}	-79**	-56**	-22**	0.11**
$\beta_{HYE} - \beta_{LYE}$	61**	56**	ns	0.54

**= $P \leq 0.01$; *= $P \leq 0.05$; += $P \leq 0.1$; ns= no significant

2.5.5. Response of the relative yield gap to N fertilization, preceding crop and years of continuous cropping

Nitrogen fertilization and preceding winter crop, but not preceding summer crop, affected Yg ($P \leq 0.05$, Table 2.3). The CART analysis indicated that RYg increased as the N fertilization rate decreased under both weather conditions (Fig. 2.4). The second most important variable explaining RYg was YCC for LYE and preceding winter crop for HYE. The model explained 59% and 52% of RYg variability under HYE and LYE, respectively. For LYE, the optimum regression tree had two splits. Fields under LYE and total N applied < 66 kg ha⁻¹ had the highest average RYg. The average N fertilization rate in these fields was 54 kg ha⁻¹. When the total N applied was ≥ 66 kg ha⁻¹ under LYE, fields with $YCC \leq 4$ had lower RYg than fields with $YCC > 4$, with roughly the same average N fertilization rate (100 and 104 kg ha⁻¹ respectively). This finding indicates that lengthening YCC increased the relative yield gap within the range of N fertilization rates used by the producers (average 100 kg N ha⁻¹, range 66 to 133 kg N ha⁻¹). Therefore, the negative effect of lengthening YCC could not be compensated for with the maximum rates of N fertilization used by producers in LYE. In agreement with this analysis, the bootstrap probability for the combination N applied-YCC was 68% under LYE. The threshold values obtained by

bootstrap re-sampling for total N applied varied between 58 and 72 kg ha⁻¹, a range that compares well with the 66 kg ha⁻¹ obtained with CART for all data.

For HYE, the optimum regression tree had three splits. The first split was produced by the total N applied rate (80 kg ha⁻¹). Each of these two groups was further split on the basis of previous winter crop. At N fertilization rate < 80 kg ha⁻¹, wheat sown into wheat or barley stubble had a higher RYg than wheat seeded after pastures, winter fallow or a winter cover crop (0.40 vs 0.31, respectively). A similar effect of the previous winter crop was observed at N fertilization rate ≥ 80 kg ha⁻¹, where wheat sown after pasture, winter fallow or a winter cover crop had the lowest average RYg (Fig. 2.4). The bootstrap re-sampling analysis also indicated that total N applied was the more important variable to set the tree (87% of the runs).

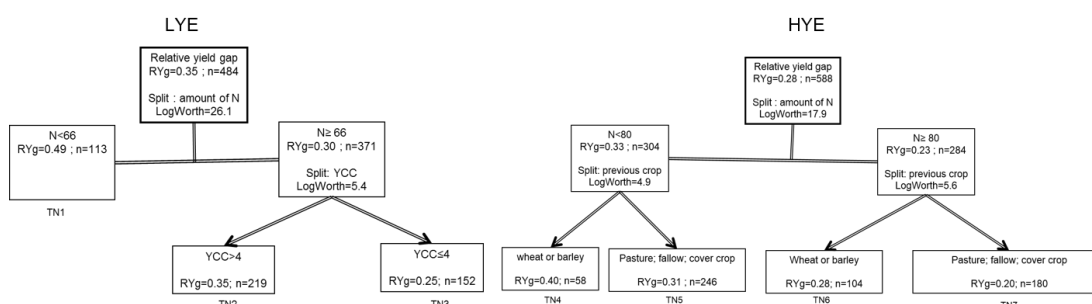


Figure 2.4. Classification and regression tree model to describe relative wheat yield gap in Uruguay (2009-2012). Within each box the following information is given: classification criterion, the relative yield gap (RYg) and the number of observations (n) within the group, variable that splits the group of observations in two new nodes, and its statistical significance as LogWorth where $\text{LogWorth} = -\log_{10} * (\text{p-value})$. If $\text{LogWorth} \geq 1.3$ then $\text{p-value} \leq 0.05$. TN = terminal node.

2.6. DISCUSSION

The stochastic frontier analysis allowed us to define the wheat attainable yield, the yield gap, and their main controls for this selected group of wheat producers in Uruguay. The Yatt estimated in our analysis (5.6 and 6.6 Mg ha⁻¹ for P(90) and maximum, respectively) compares well with previous estimates obtained

independently by breeders' trials and with simulation models. Berger et al. (2015) reported an average yield of $6.0 \pm 2.0 \text{ Mg ha}^{-1}$ for the top five yielding cultivars in the trials of the National Testing Network of Wheat Cultivars from 2003 to 2013. Both Mazzilli et al. (2013), using the model Cropsyst, and Balkovic et al. (2014), using the model EPIC, estimated a water-limited yield for wheat in Uruguay between 7.0 and 8.0 Mg ha^{-1} . These comparisons show that our estimation of Yatt is close to the 'exploitable yield' defined as 80% of water-limited yield (Lobell et al., 2009).

The most significant result of our analysis was that intensifying crop production by lengthening YCC, i.e. the annual cropping phase, caused a measurable reduction in Yatt and Ya in LYE. As a result, lengthening YCC increased inter annual yield variability and consequently production risks. In Uruguay, it is predicted that global climate change will increase the mean temperature and rainfall during the critical period defining wheat's sink size (Baethgen and Magrini 1995; Baethgen et al., 2003). These conditions would cause a higher frequency of LYE years, which would allow the expression of lower Yatt and Ya as the trend is for YCC to lengthen.

We interpret that the reduction of Yatt with increasing YCC in LYE is a response to a progressive loss in soil quality caused by continuous cropping, even under no-till. There are several lines of evidence in our analysis that point in this direction. First, the yield reduction under LYE is not caused simply by pathogens because YCC includes cereal and non-cereal crops in the rotation. In fact, preceding crop did not affect yield significantly in LYE (but did so in HYE as discussed below, Fig 2.4). Second, although lengthening YCC reduced Yg in both LYE and HYE environments (Table 2.5), it did so by reducing Yatt and Ya in LYE, and by only reducing Yatt modestly in HYE (Table 2.7). This response to a lengthening in YCC seems to quantify a progressive degradation of one or more soil properties that limits Yatt and Ya, particularly under LYE. The analysis cannot reveal which soil property or properties underlie the yield reduction, as soil properties are not included in the database. However, it clearly points to a cumulative loss that could not be overcome by the N fertilization rates used by producers in this study; therefore, soil properties other than N availability must be limiting the expression of the wheat yield potential. Third, if such a degradation of soil properties or soil quality does occur, it is more

likely to be expressed as a negative effect on plant growth under unfavorable weather conditions. The reason for this is that LYE is mostly associated with high rainfall during the critical period defining wheat's sink size ($RAIN_{CP}$). Under such conditions, reduced soil hydraulic conductivity (Aparicio and Costa, 2007) and infiltration rate (Álvarez et al., 2014) under no-till annual cropping can be associated with a poor soil environment for the roots. Therefore, a gradual loss of soil quality could be a plausible explanation for the decrease in Yatt from 5.0 Mg ha^{-1} in HYE to 4.0 Mg ha^{-1} in LYE when $YCC = 1$ year, but from 5.0 (HYE) to 3.0 (LYE) Mg ha^{-1} when $YCC = 10$ years.

The analysis also suggests that N fertilizer management needs to be adjusted when operating in LYE or HYE environments. The soil N supply is reduced with increasing YCC compared to N supply following a pasture (Studdert et al., 1997; Heenan et al., 2004; Videla et al., 2005). Considering our estimated Yatt under LYE (4.6 Mg ha^{-1} , Table 2.5), the average N rate, and the RYg of terminal nodes TN1, TN2 and TN3 (Fig. 3), the average Ya were 2.4 , 3.0 and 3.5 Mg ha^{-1} , respectively. Comparing TN2 and TN3 to TN1, the wheat response to additional N applied was 14 and $22 \text{ kg grain kg}^{-1} \text{ N}$ for the nodes with $YCC > 4$ years (TN2) or ≤ 4 years (TN3), respectively, reducing the RYg from 0.35 to 0.25 . Thus, long term continuous annual cropping seems to reduce N use efficiency, which contrasts with one of the pillars of ecological intensification proposed by Cassman (1999): increased resource use efficiency.

The depression in yield typically expected under monocultures vs diversified crop sequences was also detected in the analysis. The wheat yield depression when wheat followed wheat or barley might be due to diseases, which express readily under continuous no-till (Carignano et al., 2008). Conversely, crop rotations or break crops can overcome limitations, reducing yield losses and production costs (Bailey et al., 2001; Kutcher, et al., 2013; Kirkegaard and Ryan, 2014). The break crop effect was detected in HYE, where the highest RYg under both low and high N fertilization rates was associated with wheat following wheat or barley (TN4 and TN6, Fig. 2.4). This effect indicates that in the environment of Uruguay and under no-till, wheat following wheat does not capitalize on the potential of HYE. Furthermore, in the long term and in LYE, the depression caused by lengthening YCC cannot be neutralized by rotating

wheat with other annual crops, a fact that may also reflect gradual changes in soil properties as discussed earlier (Novelli et al., 2013; Álvarez et al., 2014).

Depending on commodity prices and production costs, the expected yield loss caused by a lengthening of YCC may re-invigorate the inclusion of pastures in the rotation and a shortening of YCC, a typical Ricardian response (Mendelsohn et al., 1994). Our analysis did not focus on alternatives to neutralize or reduce the negative effect of continuous cropping other than the inclusion of pastures in the rotation. Yet, the results of this study provide a strong foundation for investigating the ultimate mechanisms by which YCC affect soil properties that limit wheat yield. At least two questions seem relevant for future research: 1) if the crop-pasture rotation neutralized the negative effect of continuous cropping, how many years of the pasture phase are necessary to obtain its beneficial effect? 2) Can the negative effect of a long cropping phase ($YCC \geq 7$) under LYE be mitigated by management practices such as increasing the total N fertilization rate, modifying the N application strategy, diversifying annual crops in the rotation, and subsoiling? The answers to these questions would allow a better assessment of the length of the annual cropping phase that maintains the soil productivity function. Meanwhile, it can be safely assumed that Yatt will decrease after four years of continuous cropping following a perennial pasture when weather conditions for wheat growth are suboptimal for the region.

2.7. CONCLUSIONS

Using a database of producers' wheat management and yield records, we showed that agricultural intensification via a lengthening of the annual cropping phase under no-till decreased wheat attainable yield when weather conditions were unfavorable for wheat growth. We interpreted that this decrease reflects a progressive loss of soil quality, i.e. a loss of the soil capacity to sustain higher biological productivity, which results in lower wheat yields and higher production risks. These results strongly indicate that while intensification by lengthening the annual cropping phase may increase overall grain output, the retention of perennial pastures in the rotation may be required in order to preserve the soil productivity function and reduce production risks.

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3. SHIFTING CROP-PASTURE ROTATIONS TO NO-TILL ANNUAL CROPPING REDUCES SOIL QUALITY AND WHEAT YIELD.[†]

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3.1. RESUMEN

Cuando la rotación cultivos-pastura es sustituida por un sistema de cultivos anuales continuos, el rendimiento de trigo se reduce en respuesta a los años de agricultura continua (YCC), incrementando la brecha de rendimiento (Yg), aun bajo no laboreo. Analizamos las propiedades del suelo asociadas a esta respuesta durante tres estaciones de crecimiento, en 80 ensayos instalados en campo de productores. Determinamos la frontera de rendimiento y la Yg bajo condiciones de rendimiento limitado por nutrientes (Y_F^-) y no limitadas por el suministro de nutrientes (Y_F^+ , agregando cantidades adicionales de nitrógeno, fósforo, potasio y azufre). En cada campo se relevó la calidad del suelo, cuantificando su concentración de carbono orgánico (SOC), fósforo (Bray I), textura, tasa de infiltración de agua (INF) y potencial de

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mineralización de nitrógeno (PMN), y se calculó un índice de clima (CI) que combina temperatura, radiación y precipitaciones en el período entorno a espigazón y durante el llenado de granos. Y_F^- e Y_F^+ se estimaron como la función de frontera de producción con CI, YCC y propiedades del suelo como variables predictoras. Y_F^- e Y_F^+ siguiendo a una pastura perenne fueron 6.9 y 8.4 Mg ha⁻¹, siendo 1.5 Mg ha⁻¹ la Yg atribuible al suministro de nutrientes. Y_F^- se redujo en 0.12 Mg ha⁻¹ y⁻¹ desde YYCC=1 a 10 ($P \leq 0.05$); Y_F^+ se mantuvo constante hasta YCC= 5, reduciéndose 0.17 Mg ha⁻¹ y⁻¹ para YCC>5 ($P \leq 0.05$). Durante los primeros años pos pastura se cuantificó una reducción en la capacidad de suministro de nutrientes desde el suelo, parcialmente cuantificada como PMN, que fue mitigada con fertilización suplementaria. En tanto, el descenso de Y_F^- para YCC>5 no pudo compensarse con incremento en el suministro de nutrientes. Luego de 10 años Yg entre Y_F^+ de YCC = 1 e Y_F^- de YCC = 10, incrementó a 2.6 Mg ha⁻¹. Hasta un 40% de este Yg se explicó por deterioro en la calidad del suelo de manera independiente del suministro de nutrientes. La reducción en Y_F^+ para YCC>5 fue asociada a reducida INF. Como resultado, sistemas de cultivos anuales continuos, aun sin labranza, generó un progresivo incremento de Yg de trigo asociado a deterioro en la calidad del suelo que pudo ser corregido por fertilización suplementaria solo durante los primeros 5 años pos pastura. Fases agrícolas más prolongadas generaron un deterioro cuantificable en las propiedades físicas del suelo que limitó el rendimiento, afectando la eficiencia de uso de recursos e insumos.

Palabras clave: Frontera de rendimiento, brecha de rendimiento, no laboreo, sistema de cultivos, trigo

3.2. SUMMARY

When crop-pasture rotations are converted to continuous no-till annual cropping systems, the grain yield of wheat crops in the rotation stagnates or declines in response to the number of years of continuous cropping (YCC). We studied the soil properties underlining the response of wheat yield to YCC in 80 on-farm trials during three growing seasons. We determined the frontier yield and the yield gap under limited (Y_F^- , or best technical means) and unlimited nutrient supply (Y_F^+ , supplemental

additions of nitrogen, phosphorus, potassium and sulfur). For each field, we assessed soil quality based on soil organic carbon (SOC), phosphorus (Bray I), soil texture, field water infiltration rate (INF), and potentially mineralizable nitrogen (PMN). We also calculated a climatological index (CI) that combines temperature, radiation and precipitation during both the spike and early grain growth phases. We estimated Y_F^- and Y_F^+ using stochastic frontier production functions with CI, YCC and soil properties as predictor variables. The Y_F^- and Y_F^+ after a perennial pasture were 6.9 and 8.4 Mg ha⁻¹, with the 1.5 Mg ha⁻¹ yield gap attributable to nutrient supply limitations. However, while Y_F^- declined by 0.12 Mg ha⁻¹ y⁻¹ from YCC = 1 to 10 ($P \leq 0.05$), Y_F^+ stayed at roughly the same level till YCC = 5, declining thereafter by 0.17 Mg ha⁻¹ y⁻¹ ($P \leq 0.05$). Reduced soil nutrient supply capacity, partially quantified as PMN and amendable with supplemental fertilization, limited Y_F^- during the first five years after pasture. The subsequent Y_F^- decline could not be compensated by increased nutrient supply. After 10 years, the yield gap between Y_F^+ for YCC = 1 and Y_F^- for YCC = 10, increased to 2.6 Mg ha⁻¹. Up to 40% of this gap was explained by a deterioration of the soil quality that was independent of the nutrient supply; the Y_F^+ decline after five years of continuous cropping was best explained by INF. Thus, continuous annual cropping under no-till generated a progressive increase in the wheat yield gap associated to deterioration in soil quality that could be corrected with supplemental fertilization only in the first years after a pasture, but not thereafter, when soil physical properties seemed to degrade past a threshold that limited wheat yield and reduced nutrient use efficiency.

Keywords: Frontier yield, Yield gap, No tillage, Cropping system, Wheat

3.3. INTRODUCTION

The shift from crop-pasture rotations to continuous no-till annual cropping that occurred in the eastern Pampas of South America since the early 2000s are a prime example of agricultural intensification. In this region, agricultural systems shifted from a rotation composed of a three- or four-year annual cash crop phase alternating with a three- or four-year grass-legume pasture phase, all under no-till (ROT_{NT}), to

continuous annual cropping under no-till (CC_{NT}) (Franzluebbers et al., 2014; Wingeyer et al., 2015). Under ROT_{NT} , and in Uruguay in particular, wheat would typically be sown after a perennial pasture, a practice currently restricted to 7% of the wheat area. Most wheat is now grown after soybean (42%) or maize (13%) (DIEA, 2013). We consider CC_{NT} “agricultural intensification” due to the output increase when compared with ROT_{NT} . However, greater outputs, and even increasing yield per unit of input (Garnett and Godfray, 2012), do not mean that a given path to agricultural intensification is sustainable if pollution is not abated or soil resources degrade severely.

Compared to tilled systems, no-till has been proposed as a strategy to mitigate soil organic carbon (SOC) depletion (Díaz-Zorita et al., 2002), and improve biological, chemical and physical soil properties that affect productivity such as nutrient supply, soil water infiltration and water holding capacity (Munkholm et al., 2013; Boeni et al., 2014). Consequently, the shift to CC_{NT} occurred under the assumption by growers, technical advisers and scientists that the continuous and diversified no-till production of annual grain crops would prevent soil degradation and sustain crops yields provided that crop residues ensure ground cover (Ernst and Siri-Prieto, 2009; Kirkegaard and Ryan, 2014). However, Ernst et al., (2016) found a detrimental effect of years of continuous agriculture (YCC) under no-till on wheat yield in seasons with unfavorable weather for wheat (rainy and warm before flowering and during grain filling). These authors concluded that this reduced resilience reflected a progressive loss of soil quality, i.e. a loss of soil capacity to sustain higher biological productivity, which results in lower wheat yields and higher production risks. While the analysis did not reveal which soil properties underlie the yield reduction, the results indicate that continuous annual cropping under no-till undermines one of the pillars of ecological intensification: the maintenance or improvement of soil quality (Cassman, 1999), defined as the capacity of soils to sustain biological productivity (soil productivity function) while ensuring environmental, plant and animal health (Doran and Parkin, 1994; Blum, 2005).

To characterize the factors limiting crop growth we consider first a ceiling yield defined by the crop phenology and unlimited water and nutrient supply, second a

water-limited yield as determined by the precipitation pattern and soil water storage capacity (Y_w) and a nutrient limitation determined by the nutrient supply. A third limitation imposed by biotic stresses and pollutants can be accounted for (Rabbinge, 1993) but does not apply to this investigation. Y_w is a relevant benchmark because it defines the nutrient demand. However, Y_w is unknown when deciding the proper nutrient supply, and therefore, as stated by Fischer and Edmaedes (2010), “nutrient input is adjusted taking prudent account of economics and risk”. The yield potential does not vary for two environments with the same climate but different soil properties. However, the interaction between climate and soil properties can limit crop growth. When compared to continuous cropping (CC), annual crops rotating with pastures (ROT) have higher grain yield (Franzluebber et al., 2014). Such improved performance reflects a superior environment, where inputs are used more efficiently under ROT than under CC (de Wit, 1992).

Specifically, the higher grain yield under ROT has been partially attributed to improved soil nitrogen (N) supply under ROT and increased incidence of pests, diseases and weeds under CC (Struik and Bonciarelli, 1997; Kirkegaard and Ryan, 2014). In fact, soils under ROT have higher SOC, total N content and potentially mineralizable nitrogen (PMN), better structure and higher water infiltration than under CC (Díaz-Zorita et al., 2002; Fabrizzi et al., 2003; García-Préchac et al., 2004; Ernst and Siri-Prieto, 2009; Boeni et al., 2014). Furthermore, even under CC_{NT}, total porosity of the top horizon is lower than under a pasture, with macropores oriented in parallel to the soil surface and limiting soil water infiltration (Sasal et al., 2006, Álvarez et al., 2014). This phenomenon is due to an increased platy structure in the top horizon that reduces soil water infiltration (Sasal et al., 2017).

Removing the perennial pasture phase from the rotation creates increasingly limiting conditions for crop growth that do not seem to operate additively and are difficult to neutralize. Increasing the nutrient supply and controlling for biotic stresses cannot always compensate for the grain yield loss under such conditions. Russell et al. (1987) named that portion of the yield that cannot be compensated for with synthetic chemicals the “rotation effect”. Despite decades of agricultural research, the causes of this rotation effect are not well understood (we mean rotation with a perennial pasture

in this context). The rotation effect can be linked in broader terms with the concept of soil quality, which lumps the indicators of soil processes and properties that affect soil functions (Doran and Jones, 1996). Soil quality, a complex functional concept (Stocking, 2003), cannot be measured directly but may be assessed from management-induced changes in soil attributes. Conveniently, crop yield can be used as an integrator of the resultant of these indicators (Arshad and Martin, 2002; Wander et al., 2002). We argue that CC_{NT} may negate the rotation effect by gradually reducing soil quality. Following Ernst et al. (2016), we also argue that the magnitude of the soil quality deterioration could increase with the annual cropping phase length.

In this study, we used the wheat phase of different rotations to test hypotheses pertaining to the impact of agricultural intensification via a lengthening of the annual cropping phase on soil properties and crop performance. Our hypotheses were: (1) Intensifying agricultural production by lengthening annual cropping phase after pastures, even under no-till, causes a gradual, cumulative, and measurable reduction of wheat's Y_w that can be apportioned to nutrient supply and non-nutrient supply limitations; (2) This yield loss can be related to a gradual and cumulative soil quality degradation. The objectives of this study were to: (i) quantify the effect of years of no-till continuous agriculture on rainfed wheat yield; (ii) quantify to which extent the yield loss observed under continuous agriculture can be buffered by increased application of fertilizers; iii) investigate which soil properties could explain the yield loss under no-till continuous agriculture.

3.4. MATERIALS AND METHODS

We pursued these objectives through a network of on-farm trials in farmers' rainfed wheat fields during three growing seasons. In the trials, we compared two nutrient supply strategies: non-limiting supply of N, phosphorus (P), potassium (K) and sulfur (S) versus a limited nutrient supply. The latter is also considered a "best technical means" nutrient management recommendation, which follows current guidelines from local research stations (Hoffman et al., 2010). All plots were managed to ensure no impact on crop yield of weeds, diseases and pests. We selected fields spanning from one to 10 years of continuous cropping after the pasture phase and

before the current wheat crop. We defined the yield of plots with non-limiting supply of N, P, K and S as yield not limited by nutrients (Y^+) and the yield of plots fertilized following best technical means as yield limited by nutrients (Y^-).

3.4.1. Study area and experimental setup

The study area is located in the northwestern part of Uruguay. All selected wheat fields were inside a 50 km radius from the Faculty of Agronomy research station in Paysandú (32.37 W; 58.04 S). Soils are classified as Typic Argiudolls and Hapludolls, and are considered prime agricultural land. In Uruguay, wheat is grown rainfed and under no-till, commonly sown from May 15 to June 30 and harvested in November and December. The climate is meso-thermal sub-humid with a mean daily temperature from May to November of 16.5 °C. Mean annual precipitation is about 1200 mm, fairly evenly distributed throughout the year, but with large intra- and inter-annual variations. Water deficits occur frequently between November and March and water surpluses between May and October.

Data were collected from 80 on-farm trials over three growing seasons: 44, 26 and 10 during 2011, 2012 and 2013, respectively. At each field, we installed two pairs of 10x10-m plots after wheat emergence; each pair included both nutrient supply treatments. Each field had one of the five top yielding cultivars in the trials of the National Testing Network of Wheat Cultivars for each year. The earliest and latest sowing dates in each season were less than 15 days apart. Wheat was seeded following winter fallow/soybean (YCC from 2 to 10) or pastures (YCC = 1). The pastures were a mixture of grass and legumes that were grown for three to four years. Wheat was maintained free of weeds and diseases with timely applications of herbicides and fungicides. Wheat phenology was recorded using the Zadoks scale (Zadoks et al., 1974). Crop yield was determined by hand-harvesting 10 m² per plot. Details about the fertilization treatments are provided in Table 3.1.

Table 3.1. Fertilization criteria for plots managed according to best technical means (limited by nutrients), following recommendations from local agronomy research stations (Hoffman et al., 2010), and for plots fertilized with un-limiting amounts of N, P, K and S (Not limited by nutrients). All soil analyses for fertilization purposes apply to the 0-20 cm top soil layer. N-NO₃ is in mg kg⁻¹ soil, P is in mg kg⁻¹ soil (Bray I), and the aboveground plant N concentration (Nc) is in %. The fertilization rates are in kg ha⁻¹ of N (Nf), kg P₂O₅ ha⁻¹ for P (Pf), kg K₂O ha⁻¹ for K (Kf), and kg ha⁻¹ for S (Sf).

Timing of fertilizer application	Limited by nutrients	Not limited by nutrients
At sowing	$N_f = \begin{cases} 5 \times (18 - N - NO_3^-) & \text{for } N - NO_3^- < 18 \\ 0 & \text{for } N - NO_3^- \geq 18 \end{cases}$ $P_f = \begin{cases} 5 \times (15 - P) & \text{for } P < 15 \\ 0 & \text{for } P \geq 15 \end{cases}$ $K_f = 0$ $S_f = 0$	$N_f^+ = N_f + 30$ $P_f^+ = P_f + 90$ $K_f^+ = 80$ $S_f^+ = 16$
Z22*	$N_f = \begin{cases} 10 \times (12 - N - NO_3^-) & \text{for } N - NO_3^- < 12 \\ 0 & \text{for } N - NO_3^- \geq 12 \end{cases}$ $S_f = 0$	$N_f^+ = N_f + 46$ $S_f^+ = N_f / 7$
Z30*	$N_f = \begin{cases} 20 \times (4.2 - N_c) & \text{for } N_c < 4.2 \\ 0 & \text{for } N_c \geq 4.2 \end{cases}$ $S_f = 0$	$N_f^+ = N_f + 46$ $S_f^+ = N_f / 7$
Z49*	$N_f = 0$ $S_f = 0$	$N_f^+ = N_f + 40$ $S_f^+ = 6$

* Crop development stage (Zadocks scale (1974))

3.4.2. Soil quality assessment and meteorological data

Following the minimum data set concept (Arshad and Martin, 2002), we surveyed soil properties prioritizing those that react to soil management under no-till (Wander and Bollero, 1999; Arshad and Martin, 2002; Álvarez and Steinbach, 2009; Morón et al., 2012; Álvarez et al., 2014), and that affect biological productivity (Aparicio and Costa, 2007; Fuentes et al., 2009). Soil samples were taken within 10 days prior to sowing. The samples were composites of 10 cores taken from each site to a depth of 20 cm. We sampled the most sensitive soil layer to soil management under no-till (Blanco-Canqui and Lal, 2008; Álvarez and Steinbach, 2009; Ernst and Siri-Prieto, 2009; Salvo et al., 2010; Sasal et al., 2017). Dried soil samples were analyzed for SOC (Nelson and Sommers, 1996), extractable phosphorus (P) (Bray I), exchangeable potassium (K) (extraction with 1 M acetate), nitrate concentration ($N-NO_3^-$) and soil texture (Bouyoucos method). Each soil was characterized by its clay/sand content ratio.

Additionally, $N-NO_3^-$ in the 0-20-cm layer was measured when wheat was at the Z 2.2 stage (second tiller visible, or tip of the fifth leaf visible). Field water infiltration rate (INF, cm d^{-1}) was determined using the method developed by the Soil Quality Institute (1999), which consists on recording the time to infiltrate 2.54 cm of water. A 15-cm in diameter ring was pressed 8 cm vertically into the topsoil. The ring was lined up with plastic wrap and a 2.54 cm sheet of distilled water applied. The plastic wrap was then removed to begin wetting and to homogenize soil moisture. After infiltration was completed, the procedure was repeated, recording the time required for all water to infiltrate into the soil. Three replicates were taken at each site. Potentially mineralizable N (PMN, $\text{mg of } N-NH_4 \text{ kg}^{-1}$) was estimated following Waring and Bremner, (1964), as an indicator of soil N supply capacity.

Solar radiation load ($\text{MJ m}^{-2} \text{ d}^{-1}$) and temperature ($^{\circ}\text{C}$) were recorded at the Faculty of Agronomy research station. Precipitation (mm) was recorded at each field. Variation on weather conditions generated by year, planting date and heading date were summarized through a photothermal quotient (Q), calculated as the ratio of average total radiation to mean temperature above 4.5°C , accumulated precipitation during the 30 days around heading stage ($Rain_{PC}$), and accumulated precipitation and

mean temperature during grain filling period ($Rain_{FILL}$ and T_{FILL} , respectively). Q and $Rain_{PC}$ summarize weather conditions during the critical period defining the sink potential size (Fischer, 1985; Thome and Wood 1987), and $Rain_{FILL}$ and T_{FILL} do so during grain filling (Abbate et al., 1995).

Because climatic variables were co-linear, we used principal component analysis (PCA) to generate a new variable called Climatic Index (CI). The CI was calculated as the sum of the standardised Principal Components with a vector > 1 and a partial correlation coefficient $> 5\%$. Following Ernst et al., (2016) we use the CI to quantify weather conditions for each field during 30 days around heading and grain filling stages.

3.4.3. Data analysis

Cumulative frequency distributions of wheat yield variation obtained under Y^+ and Y^- was tested using Shapiro-Wilks test within each year. Random Forest (RF) was used to identify the variables most related to wheat yield and to obtain the partial dependence of wheat yield on PMN, INF, SOC, texture (CI/Sd ratio), climatic index (CI) and YCC. Partial dependence functions (Friedman, 2001) represent the effect of selected explanatory variables on the dependent variable, incorporating the effects of other variables, and can be used to interpret “black box” models (Cutler et al., 2007; Elith et al., 2008). They can, however, hide important interactions as the average response to the independent variable is plotted. The number of trees generated by bootstrapping from the original data set was limited at 500, the default setting in the RF package (Liaw and Wiener, 2002), with three or two variables tried at each split for wheat yield or soil properties as the response variable, respectively.

3.4.4. Response of frontier yield to years of continuous cropping

The frontier yield under limited (Y_F^-) and non-limiting (Y_F^+) nutrient supply were estimated using stochastic frontier production functions (SFPP) built from records obtained from the field trials. The SFPP provided the upper boundary of wheat yield under varying conditions of the deterministic components of the function for both nutrient managements. We included as deterministic components of SFPP the weather

conditions integrated in the CI, CI/Sd ratio, INF, PMN and YCC. The frontier yield represents the yield upper limit obtained under rainfed conditions applying best management practices. It should be noted that Y_F^- and Y_F^+ are not the same as “water and nutrient limited yield level” and “water limited yield level” as defined by van Ittersum et al., (2013), which are estimated not from on-farm field trials but by using crop simulation models (Lobell et al., 2009; Grassini et al., 2011; Laborte et al., 2012).

The SFPF was specified as:

$$\ln(Y_i) = \beta_0 + \beta_1 \ln(CI_i) + \beta_3 \ln(CI/Sd_i) + \beta_4 \ln(Inf_i) + \beta_4 \ln(PMN_i) + \beta_5 \ln(YCC_i) + V_i - u_i$$

where, $Y_i = Y^+$ or Y^- (kg ha^{-1}) of the i^{th} field ($i = 1, 2, \dots, 80$), V is the random error (mean = 0), and u_i is the inefficiency function (estimated frontier yield – observed yield, positive values only).

The SFPF was estimated using FRONTIER 4.1 software (Coelli, 1996). This software uses the maximum-likelihood method where $\ln(Y_i)$ is simultaneously estimated with inefficiency effects. Then, the efficiency (Eff) of each yield record is calculated as the ratio of observed to frontier yield (Coelli et al., 2005) for both Y_F^- and Y_F^+ :

$$Y_{F(i)}^+ = Y_i^+ / \text{Eff}$$

$$Y_{F(i)}^- = Y_i^- / \text{Eff}$$

The Y_F^+ and Y_F^- responses to YCC were fitted using both linear continuous or linear segmented models. A linear continuous model best fitted to Y_F^- , while a segmented model with two linear segments fitted to Y_F^+ . The segments were jointed by a threshold estimated by the downhill simplex method and the function adjusted by the Levenberg-Marquardt method (Balzarini et al., 2008).

3.4.5. Yield gap response to number of years of continuous cropping

We estimated the yield reduction due to soil nutrient supply

($Yg_{(i)}^{nutrients} = Y_{F(i)}^+ - Y_{F(i)}^-$), yield reduction due to other soil properties than nutrient supply capacity depletion ($Yg_{(i)}^{others} = Y_{F(i=1)}^+ - Y_{F(i)}^+$), and yield gap total ($Yg_{(i)}^T = Yg_{(i)}^{nutrients} + Yg_{(i)}^{others}$), as displayed in Fig. 3.1.

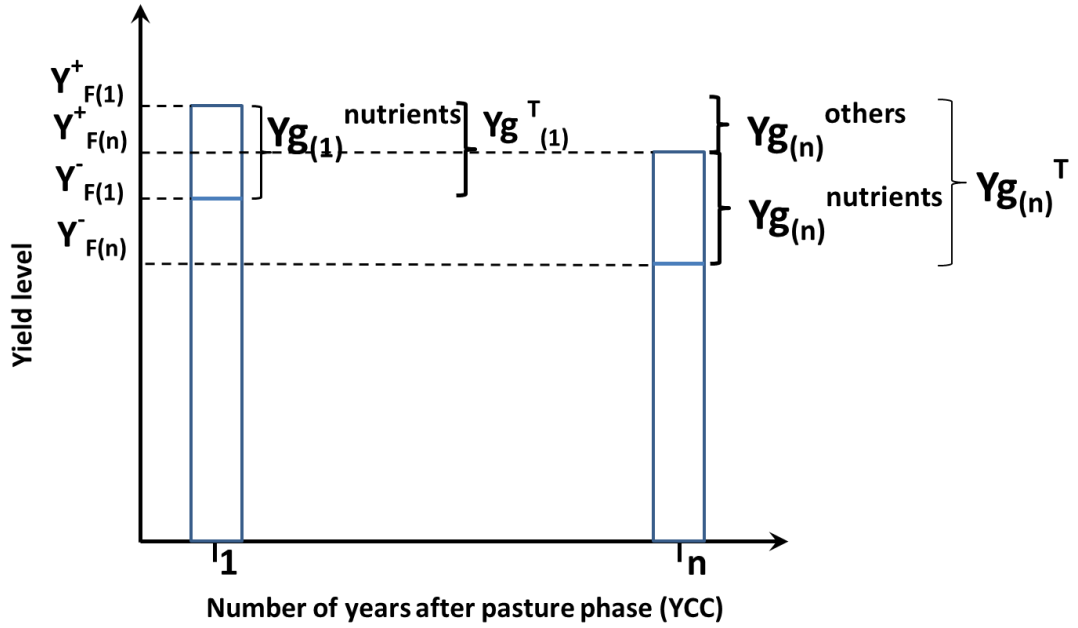


Figure 3.1. Production levels determined by declining soil quality in response to years of continuous cropping after pasture. Y_F^+ = frontier yield not limited by nutrients; Y_F^- = frontier yield limited by nutrients; $Yg^{nutrients}$ = yield gap due to soil nutrient supply capacity; Yg^{others} = yield gap due to soil properties other than nutrient supply capacity depletion; Yg^T = total yield gap; and n is the number of years after the pasture phase ends.

3.4.6. Soil properties response to years of continuous cropping

Fields were classified into three groups based on YCC: A group representing a traditional ROT system composed by three years of an annual cropping phase and three or four years of pasture ($YCC \leq 3$), and two groups that extended the annual cropping phase further ($4 \leq YCC \leq 6$ and $7 \leq YCC \leq 10$). These groups were defined based on

results obtained from the RF partial dependence of wheat yield on YCC, PMN and INF. An ANOVA was performed considering each field random within each group. Least square means comparisons were made using Fisher's protected least significant differences (LSD). A significance level of $P \leq 0.05$ was established *a priori*.

3.5. RESULTS

3.5.1. Growing season description

All fields were sown around June 10 (day 161 ± 13), within the time window recommended for this region, and with similar cultivars each year, resulting in small differences between fields in heading date (day 276 ± 8) (Table 3.2). Consequently, climatic conditions within each year were very similar among fields. However, there were differences among years. During 2011 and 2013, $Rain_{PC}$ and Q were higher and lower than the long term average, respectively. Year 2012 was drier ($Rain_{PC}$ 30% below long-term average) but with the highest Q . $Rain_{PC}$ and Q were negatively related ($P \leq 0.05$).

Table 3.2. Mean and standard deviation for planting day, heading day, rainfall ($Rain_{PC}$, mm) and Q quotient ($MJ\ day^{-1}\ m^{-2}\ C^{-1}$) during the critical period defining grain yield (heading day ± 15 days). The 20-y mean for $Rain_{PC}$ and Q considering the time period 276 ± 15 days are also shown for comparison.

	2011	2012	2013	20 years 1993- 2013
Planting date (DOY)	162 ± 7	160 ± 5	161 ± 3	
Heading date (DOY)	275 ± 9	276 ± 7	276 ± 9	
$Rain_{PC}$ (mm)	181 ± 127	79 ± 28	156 ± 41	142
Q	1.4 ± 0.2	1.5 ± 0.1	1.4 ± 0.1	1.4

DOY= day ordinal year

The mean Y^+ and Y^- were 6.8 vs 5.4 Mg ha⁻¹. The average yield difference between these treatments was 1.4 Mg ha⁻¹ (21% drop from Y^+). Wheat yield was normally distributed under both, years and nutrient treatments (Table 3.3).

Table 3.3. Shapiro-Wilks test (W) of wheat yield (Mg ha⁻¹) in the northwest of Uruguay (2011-2013) on 80 on-farm trials for the fertilization treatments limited by nutrients (fertilized according to best technical means following recommendations from local agronomy research stations) and not limited by nutrients (fertilized with un-limiting amounts of N, P, K and S). Mean wheat yield, standard error (S.E.), and P values (unilateral D) are presented by year.

Treatment	Year	Yield	S.E.	W*	P
		Mg ha ⁻¹			
Limited by nutrients	2011	5.6	1.4	0.97	0.7
	2012	5.0	0.9	0.94	0.3
	2013	5.2	0.5	0.87	0.1
Average		5.4	1.2	0.98	0.8
Not limited by nutrients	2011	7.0	1.4	0.95	0.1
	2012	6.6	0.7	0.94	0.3
	2013	6.4	0.5	0.92	0.5
Average		6.8	1.2	0.96	0.1

The total N fertilizer added when following current recommendations (limited nutrient supply) varied according to YCC (Figure 3.2). Within each year, the range of N fertilization rates reflected differences in NNO_3^- at sowing date and Z22, as indicated in Table 3.1. The average N fertilization rate increased by about 5 kg y⁻¹ under continuous cropping, with a similar trend for the minimum and maximum rates observed each year.

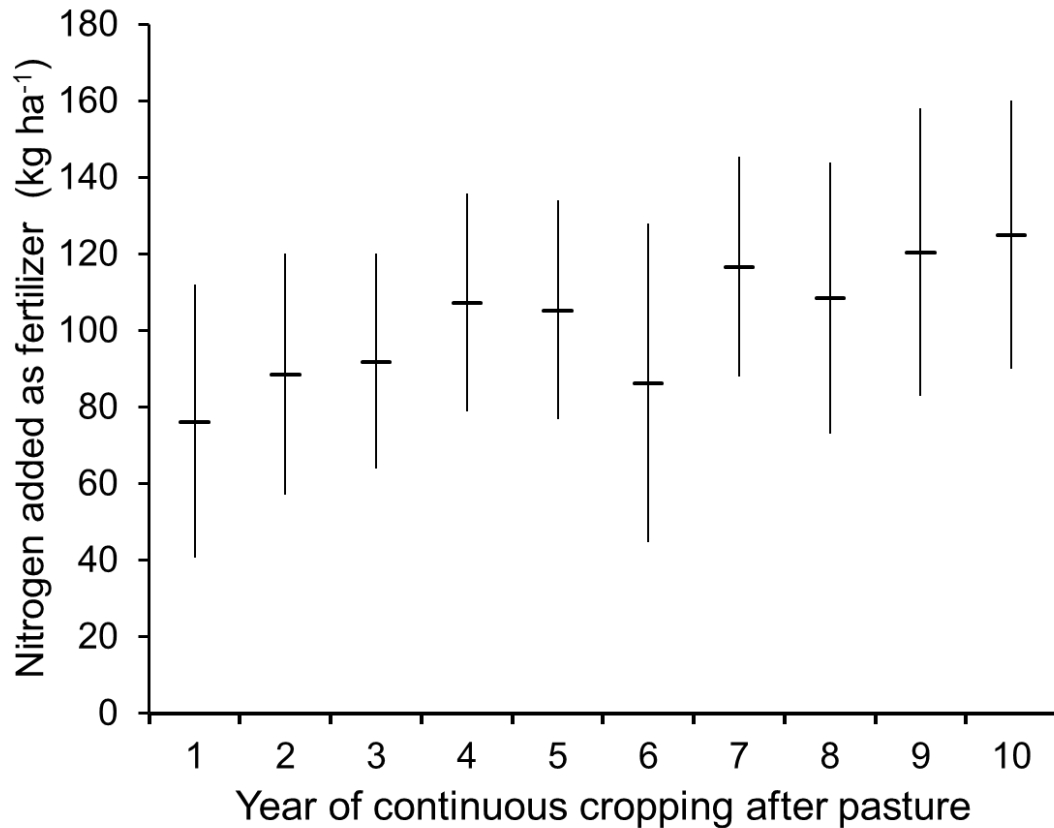


Figure 3.2. Total nitrogen added as fertilizer following current recommendations for wheat production in Uruguay (Hoffman et al., 2010) as a function of the numbers of years of continuous cropping. Horizontal lines are the average and vertical lines the observed range, which depended on field and year variations in soil analysis and other considerations.

3.5.2. Effect on yield of fertilization treatment, YCC and soil quality

The RF model showed that about 40% of the total variance of wheat yield (pseudo- R^2) was explained by Nutrients, INF, PMN, and YCC, with approximately 25, 13, 9 and 5% of the variance attributable to each variable, respectively (Fig. 3.3). Wheat yield was related to INF, with a critical threshold at approximately 15 cm d⁻¹. Wheat yield tended to decay with YCC, with steeper decay rates after YCC = 3. Partial dependence of yield on PMN showed a non-linear relationship suggesting interactions with other soil properties.

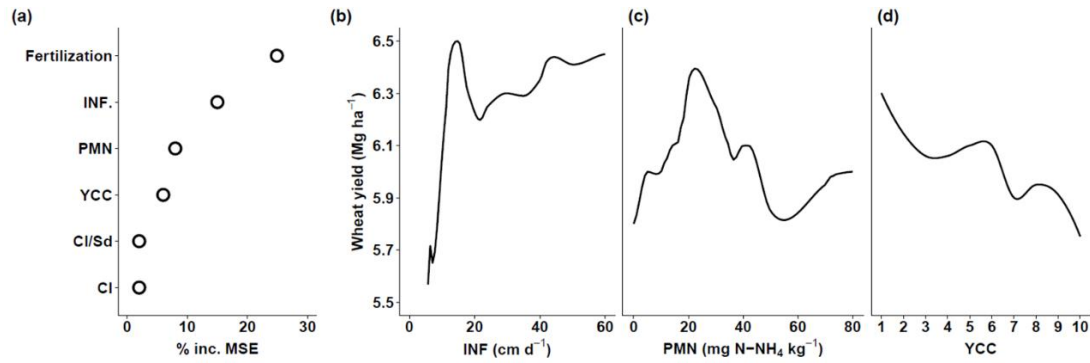


Figure 3.3. Random Forest analysis of wheat yield. Panel (a) shows the Increment of Mean Square Error (IncMSE, %) or variable importance plot; the other panels show partial dependence plots of wheat yield for: water infiltration rate (INF, cm day⁻¹) in panel (b), potential mineralization nitrogen, (PMN, mg N-NH₄ kg⁻¹) in panel (c), and years of continuous cropping (YCC, years) in panel (d). CI and CI/Sd stand for climatic index and the ratio of clay to sand, respectively.

3.5.3. Frontier wheat yield

The maximum likelihood estimate of the SFPP showed that Y_F^- was significantly reduced by YCC, CI/Sd ratio and INF ($P \leq 0.05$), while Y_F^+ was significantly reduced by YCC ($P \leq 0.10$) and INF ($P \leq 0.05$), and significantly increased by CI ($P \leq 0.05$) (Table 3.4). In the SFPP, estimated coefficients represent the percentage change in output per percent increase in input. The parameter gamma was significantly different from zero ($P \leq 0.05$) for both nutrient supply treatments, which indicates that the technical efficiency affected wheat yield.

Table 3.4. Coefficients for the parameters of the stochastic frontier production function for the frontier yield not limited by nutrients (Y_F^+) and frontier yield limited by nutrients (Y_F^-).

Variable	Y_F^+	Y_F^-
Intercept	9.27**	9.48**
<i>Cropping system</i>		
YCC	-0.04*	-0.03+
<i>Climatic conditions</i>		
CI	0.12	0.30*
<i>Soil properties</i>		
Cl/Sd	-0.36*	-0.16
PMN	0.01	0.02
INF	0.05**	0.04**
δ^2	0.11**	0.07**
γ	0.84**	0.90**
γ	0.84**	0.90**

**= $P \leq 0.01$; *= $P \leq 0.05$ significant; + $P \leq 0.1$

YCC = years of continuous cropping, (years); CI = climatic Index; Cl/Sd = clay/Sand ratio; INF = water infiltration rate (mm day⁻¹); PMN= (potentially mineralizable N, mg N-NH₄ kg⁻¹).

3.5.4. Years of continuous cropping and wheat yield

The YCC reduced both Y_F^+ and Y_F^- , but timing and magnitude of the reduction differed between treatments. While Y_F^- was reduced at the same rate of 0.12 Mg ha⁻¹ y⁻¹ from YCC 1 to 10, Y_F^+ was maintained at the same level until YCC = 5 and reduced by 0.17 Mg ha⁻¹ y⁻¹ from YCC 6 to 10 ($P \leq 0.05$) (Fig. 3.4).

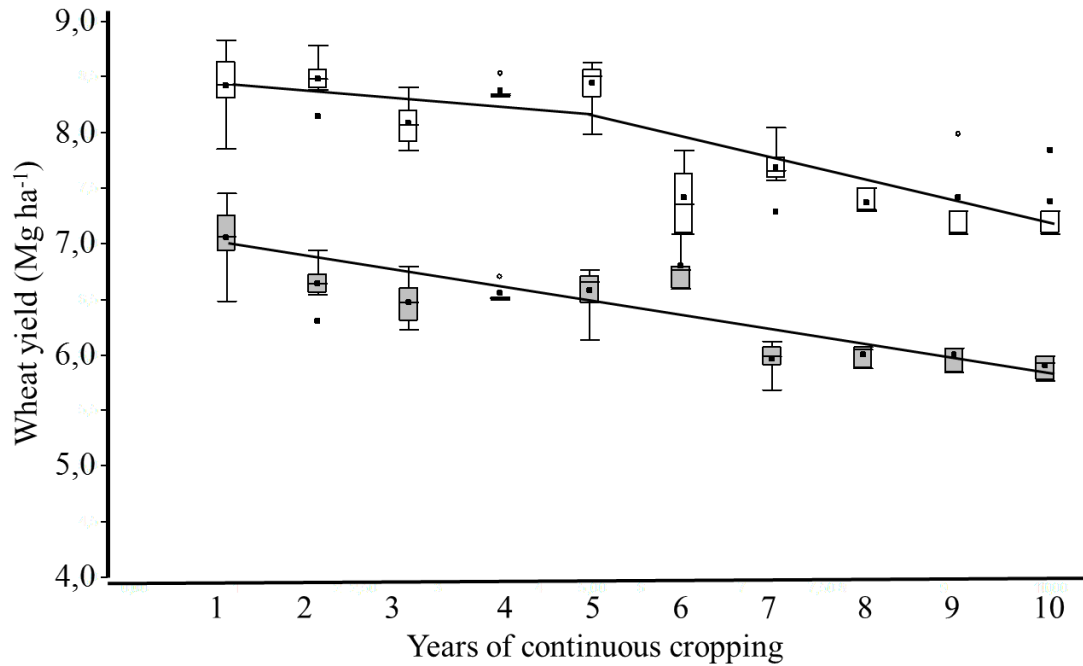


Figure 3.4. Boxplots of frontier wheat yield not-limited by nutrients (Y_F^+) or limited by nutrients (Y_F^-), as a function of years of continuous cropping after a perennial pasture (YCC). Lower and upper boundaries for each box are the 25th and 75th percentiles. The line inside each box indicates the median. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles. Continuous lines are the adjusted functions:
 $Y_F^- = 7.04 - 0.12YCC$ ($R^2 = 0.69$);
 $Y_F^+ = 8.42 - 0.03YCC$ for $YCC \leq 5$; $Y_F^+ = 8.27 - 0.17YCC$ for $YCC > 5$ ($R^2 = 0.57$).

The Y_F^- and Y_F^+ after a perennial pasture were 6.9 and 8.4 Mg ha⁻¹, respectively, with 1.5 Mg ha⁻¹ yield gap attributable to nutrient supply. After five years of continuous cropping, $Y_{g(5)}^{nutrient}$ increased to 1.8 Mg ha⁻¹, while at the same time $Y_{g(5)}^{others}$ was only 0.12 Mg ha⁻¹, making $Y_{g(5)}^T = 2$ Mg ha⁻¹ (Table 3.5). Total yield reduction by YCC = 10 years was 2.6 Mg ha⁻¹, a relative yield loss of 30%. About 40% of the yield loss was explained by properties other than nutrient supply.

Table 3.5. Estimated effect of YCC on total yield reduction (Y_g^T); yield reduction due to nutrient supply ($Y_g^{nutrients}$) and due to factors other than the nutrients supply depletion (Y_g^{others}). Relative total yield reduction (RY_g^T) was estimated as ($Y_g^T * 100 / FY_{F(1)}^+$). The fraction of the RY_g^T explained by nutrient supply ($FY_g^{nutrients}$) and due to factors other than the nutrients supply depletion (FY_g^{others}) were estimated as percentage of Y_g^T .

YCC (years)	Y_g^T Mg ha ⁻¹	$Y_g^{nutrients}$	Y_g^{others}	RY_g^T %	$FY_g^{nutrients}$ %	FY_g^{others} %
1	1.47	1.47	0	18	100	0
5	1.95	1.83	0.12	23	94	6
10	2.55	1.53	1.02	30	60	40

3.5.5. Soil properties

Highest INF and PMN were measured during the first three years after pasture (Table 3.6). While PMN showed a gradual reduction rate with YCC, INF was reduced quickly from YCC = 4-6 to YCC = 8-10 years. Soil properties that are temporarily more stable like SOC or fixed as texture, were not altered by YCC, a logical result that indicate no bias due to SOC or texture in the sampling domain.

Table 3.6. Soil properties (top 20 cm) response to years of continuous cropping. Ratio of clay to sand (Cl/Sd) represents soil texture; soil organic carbon (SOC); potentially mineralizable nitrogen (PMN); and water infiltration rate (INF); years of continuous annual cropping after the last perennial pasture in the rotation (YCC). The values are averages for three YCC bins: YCC 1 to 3, 4 to 6 and 9 to 10.

YCC	Cl/Sd ratio	SOC mg kg ⁻¹	PMN mg N-NH4 kg ⁻¹	INF cm d ⁻¹
1 to 3 (n = 40)	0.97 a	28 a	30 a	35 a
4 to 6 (n = 20)	0.99 a	28 a	26 ab	30 a
7 to 10 (n = 20)	0.98 a	26 a	18 b	16 b

Numbers followed by different letter in the same column are significantly different ($P \leq 0.05$).

3.6. DISCUSSION

We confirmed prior results about a measurable reduction of the frontier wheat yield when crop production is intensified by lengthening YCC (Ernst et al., 2016). However, while Y_F^- declined linearly at a rate of $0.12 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ($P \leq 0.05$), Y_F^+ was unaffected during the first 4-5 years after pasture, declining steeply thereafter at a rate of $0.17 \text{ Mg ha}^{-1} \text{ y}^{-1}$ ($P \leq 0.05$) (Fig. 3.4). After 10 years of continuous cropping, Y_F^- and Y_F^+ were reduced from 6.9 to 5.8 Mg ha^{-1} , and from 8.4 to 6.7 Mg ha^{-1} , respectively.

Many abiotic and biotic stresses can affect crop yield. We can discard that the observed wheat yield depression could be explained by biotic stresses attributable to monocultures crop sequences (Carignano et al., 2008) because we chose wheat fields sown after pasture (YCC=1) or winter fallow/soybean sequence. The literature provides evidence about positive effects of crop–pasture rotation on soil properties or, in general terms, soil quality. Compared to continuous cropping, this higher soil quality results from a combination of higher SOC content and better soil physical properties accrued during the pasture phase (Puckridge and French, 1983; Studdert et al. 1997; Díaz-Zorita et al., 2002; García-Préchac et al., 2004). In the long-term, soil properties under continuous no-till annual cropping systems tend to a new equilibrium, normally a step below that of crop-pasture rotations in terms of soil quality, but better

than under conventional tillage (Díaz-Zorita et al., 2002; Ernst and Siri-Prieto, 2009; Fuentes et al., 2009; Sasal et al., 2017). Accordingly, we expected that at least the frontier wheat yield under non-limiting conditions (Y_F^+) would reach a new equilibrium rapidly, yet it declined steadily after YCC = 6 years. While several authors had related soil properties with crop yield, no previous study has explored to our knowledge the relationship between soil properties and frontier wheat yield.

We quantified two components of the Y_g : one attributable to nutrient limitations ($Y_g^{nutrients}$), and another attributable to soil limitations other than nutrients (Y_g^{others}). The Y_g estimated the first year after the pasture phase can be attributed entirely to the nutrient supply (1.5 Mg ha^{-1}). As YCC increased, so did Y_g due to both, a widening of the $Y_g^{nutrients}$, and the expression of Y_g^{others} after five years of continuous cropping (Table 3.5).

There was no relationship between P and K application rates under limited nutrient supply and YCC. However, on average, the N fertilization rate increased by about 5 kg y^{-1} under limited nutrient supply (Fig.3. 2), indicating that while the current N recommendation captured changes in the soil N supply generated by YCC (we recommend higher N fertilization rates with increasing YCC), N use efficiency was negatively affected because the yield was decreasing. After 10 years of continuous cropping, the Y_F^- was reduced by 1.1 Mg ha^{-1} (from 6.9 to 5.8 Mg ha^{-1}), but the N fertilization rate increased by 50 kg ha^{-1} (from 75 to 125 kg ha^{-1} , Fig 3.2). We applied 162 kg ha^{-1} more N under non-limiting than under limiting nutrient supply ($30, 46, 46$ and 40 kg ha^{-1} at sowing, Z22, Z30 and heading stage respectively, Table 3.1). Thus, a reduced soil nutrient supply capacity, partially quantified as PMN (Table 3.6), would be the most limiting soil property during the first four to five years of continuous cropping after pastures (YCC<5). In that period, $Y_g^{nutrients}$ explained 94% of the increase in Y_g^T (from 1.5 to 2.0 Mg ha^{-1} , Table 5). When YCC exceeded five years, a second phase in soil quality deterioration started, where soil nutrient supply (PMN) declined further, but the detrimental effect of YCC could not be compensated for by adding more nutrients (Table 3.6; Fig. 3.4). Comparing YCC = 1 vs YCC = 10, Y_g^T increased from 1.5 to 2.6 Mg ha^{-1} , but only 60% of Y_g^T (1.5 Mg ha^{-1}) corresponded to

$Y_g^{nutrients}$, with the remaining 40% (1 Mg ha^{-1}) explained by Y_g^{others} (Table 3.5). Additionally, the progressively reducing frontier yield required incremental inputs of N, so that for YCC = 10, 50 kg ha^{-1} of additional N were applied compared with YCC = 1 at limited nutrient supply condition, which represents the current ‘best practice’ in terms of fertilization recommendations (Table 3.1; Fig. 3.2). Higher nutrient input with lesser productivity (and lesser fertilizer recovery) is symptomatic of systems prone to nutrient losses.

Increasing fertilization rates to achieve decreasing yields contradicts the pillars of ecological intensification proposed by Cassman (1999). We argue that reduced Y_F^- due to increasing YCC is explained by a progressive loss in soil quality under continuous annual cropping under no-till. When the annual cropping phase is restricted to three to four years and is rotated with a perennial pasture, the system retains soil quality as indicated by higher PMN (Table 3.6, Fabrizzi et al., 2003; Hurisso et al., 2014). According to our results, lengthening the annual cropping phase from three to six years reduced PMN from 30 to $26 \text{ mg N-NH}_4 \text{ kg}^{-1}$ (Table 3.6). Therefore, a gradual loss of soil nutrient supply capacity, partially quantified as PMN (Table 3.6), could be a plausible explanation for the increase in $Y_g^{nutrients}$ from 1.5 (YCC = 1) to $1.8 \text{ (YCC = 5) Mg ha}^{-1}$ (Fig. 3.4; Table 3.5).

When YCC exceeded five years, it seems that a threshold was surpassed and a second phase in soil quality deterioration started, where soil nutrient supply (PMN) continued declining but the detrimental effect of YCC could not be compensated by increased nutrient supply (Table 3.6; Fig. 3.4). We represented the yield gap that is not attributable to nutrients limitations as Y_g^{others} , and calculated that it explained 40% of the Y_g^T . We identified reduced INF as a possible indicator of this second phase of soil quality deterioration (Table 3.6).

Our results align with those obtained by Novelli et al., (2013) and Sasal et al., (2017). While these authors did not quantify the effect of YCC on crop performance, they found a relationship between the YCC under no-till and the proportion of “platy structure” in the topsoil of CC_{NT} systems in the Argentinean Pampas. The platy structure increased from zero to a maximum of 51% of the total depth of the top

horizon (10 cm) in 15 years, increasing runoff and reducing the penetration depth of a dye tracer. These conditions can limit growth due to decreased water infiltration but also due to a poorer environment for root growth. Reduced soil hydraulic conductivity (Aparicio and Costa, 2007) and infiltration rate (Álvarez et al., 2014) under no-till annual cropping can be associated with a poor soil environment for the roots. Better soil water infiltration improves not only water capture but reduces waterlogging due to improved aeration (Cannell and Hawes, 1994). Therefore, a gradual loss of INF from 30 to 16 cm d⁻¹ after 10 years of continuous no-till cropping could indicate a gradual degradation of soil physical properties, which would explain the increase of Y_g^{others} (Table 3.6) and the reduction in nutrient use efficiency.

To test if PMN and INF would completely represent the YCC effect, we produced random forest models alternatively removing these variables individually or in pairs. Clearly, the variance explained by YCC could not be absorbed by PMN and INF, but YCC absorbed most of the variance attributable to these variables, particularly INF. Similarly, when all variables were included in the SFPF regression (Table 3.4), INF was strongly significant, PMN showed a weak response, but YCC remains statistically significant. Both analyses imply that YCC captured more than just the INF and PMN effects, surrogating most likely for multiple soil properties (or related soil functions) that are modified by the cropping system. For example, Novelli et al., (2017) related higher soil water aggregate stability and lesser SOC depletion under CC_{NT} to the fraction of annual time occupied by a crop (as oppose to fallow) and low soybean frequency within the cropping sequence. Typically, CC_{NT} systems in this region have had a high frequency of soybean in the last 15 years. While the variable YCC needs to be interpreted in a local context, meaning that YCC = 5 *per se* might be of little significance in cooler or dryer climates, it seems to be a credible aggregator of the collective changes in the biological and physical properties of the soil. As indicated by our analysis, however, it does not discriminate which portion of the decay in productivity can be attributed to the nutrient supply or to the cumulative changes in other properties.

Our analysis here and that of Ernst et al., (2016) revealed a loss of soil quality due to CC_{NT} that can be detected in the wheat phase of the rotation. Ignoring

externalities such as increased N pollution, it is plausible that producers shifting cropping systems from ROT_{NT} to CC_{NT} (increasing YCC) were making a logical decision in a Ricardian sense. Three elements need to be considered to address this issue. First, while we detected a loss in wheat yield, we did so at relatively high yield levels since the average Y_F^- was 6.5 Mg ha⁻¹. Ernst et al., (2016) calculated a mean frontier yield (referred to as attainable yield) of 4.9 Mg ha⁻¹ from a survey of 1,072 producers. The lower yield may reflect other limitations to crop growth that lessen the YCC's detrimental effect. Second, the yield loss due to YCC could express differently for crops other than wheat. And third, it is the balance between the economic return during the pasture and annual cropping phase that may determine the economically optimal or reasonable length of the rotation. To address this question in a simplified form, we calculated the economic return of plausible crop-pasture rotations with varying length of the annual cropping phase using 2008 – 2016 summary agronomic and economic records from producers of the Uruguayan Federation of Regional Consortia of Agricultural Experimentation (FUCREA using its Spanish acronym Kal).

The annual cropping phase implemented by FUCREA producers during this period was on average composed by 21% double cropped wheat/soybean, 42 % winter fallow/soybean, 8% winter fallow/corn, and 8% other annual crops under both, CC_{NT} and ROT_{NT}. Considering the wheat mean yield reported by Ernst et al., (2016) of 4 Mg ha⁻¹ when sown after the pasture phase (YCC=1), and a relative annual yield depression equivalent to 2% estimated for Y_F^- (this paper, 0.12 Mg ha⁻¹ y⁻¹ / 6 Mg ha⁻¹ y⁻¹), we assumed an annual wheat yield depression of 67 kg ha⁻¹ y⁻¹ under production conditions. This figure is similar to that obtained by Ernst et al., (2016). We further assumed a similar relative yield depression for maize, rendering an absolute yield depression of 100 kg ha⁻¹ y⁻¹, and no yield loss for soybean (Ernst and Siri-Prieto, 2013). The N fertilization was also adjusted accordingly, increasing with the length of the cropping phase. Assuming a three-year fixed length of the pasture phase (on average after three years, perennial pastures need to be replanted) and an annual cropping sequence of wheat / soybean - winter fallow / corn - winter fallow /soybean, we estimated the economic return of rotations with different lengths of the annual cropping phase. All production costs and production value for both grain and livestock

used information summarized from FUCREA producers. These calculations render the “reference” response in Figure 3.5.

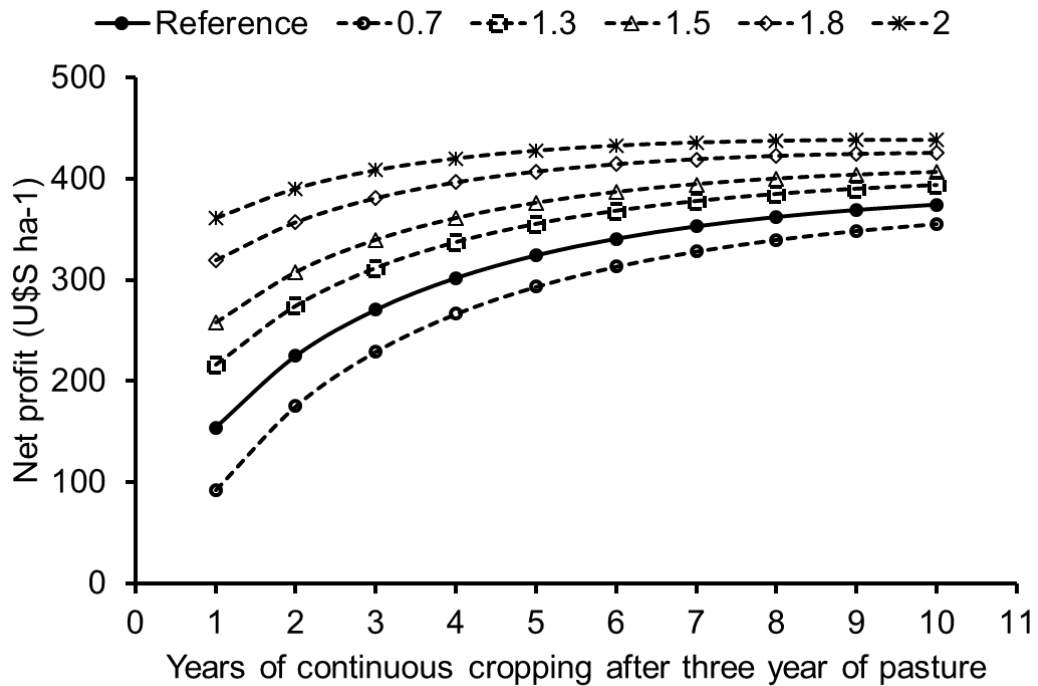


Figure 3.5. Net profit variation for an enterprise caused by a lengthening years of annual cropping after 3 year of pasture at five levels of livestock production. Annual cropping sequence corresponds to 21% wheat/soybean; 42% winter fallow/soybean; 8% winter fallow/corn. Reference: Gross profit using mean crop yield, livestock production and mean prices obtained by FUCREA producer’s (2008-2016). Dotted lines: livestock production variation over Reference.

According to these results, the shift of production systems from ROT_{NT} to CC_{NT} systems described by Franzluebbbers et al., (2014) and Wingeyer et al., (2015) is economically justified. The yield penalty and the increase in N fertilizer rates when the annual cropping phase lengthens explain the decreasing increment of gross profit. Under the prices and mean livestock production obtained during 2009-2016, displacing ROT_{NT} in favor of CC_{NT} was the logical economic choice. Interestingly,

however, there is no advantage of an overly long cropping phase because the proportion of the pasture area becomes small.

The analysis in this paper indicates that Y_g^{others} turns relevant when $YCC > 5$. A ROT_{NT} system composed of three years of a pasture and five years of annual cropping would relinquish about 9% in profit (374 versus 340 U\$S ha⁻¹ y⁻¹ under $YCC = 10$ and $YCC = 5$, respectively). This result depends on the performance of the pasture phase: an increase in livestock profit of 1.3-fold over our reference value would compensate for that 9% loss (Fig. 3.5). Furthermore, doubling livestock production may tilt the system towards a balanced pasture / annual cropping share. But even under the reference condition, it seems reasonable to preserve the ROT_{NT} system with a long cropping phase, to allow for a recovery of soil properties, for we do not know when soil quality may collapse irreversibly.

3.7. CONCLUSIONS

Lengthening the annual cropping phase of a no-till rotation decreased wheat yield. In the first five years of continuous annual cropping, the yield loss was due to a loss in the soil capacity to supply nutrients (expressed through a reduced PMN), which can be compensated with additional fertilizer inputs. Thereafter, an intrinsic loss of soil quality associated to soil physical properties (expressed through INF), further limited wheat yield. This yield loss could not be compensated with increased nutrient supply. The variable YCC captured more than just the INF and PMN effects, surrogating for multiple soil properties that are modified during the annual cropping phase. While economic considerations may justify lengthening the annual cropping phase as an agricultural intensification strategy, the consequences of such lengthening are lower wheat yields obtained with decreasing nutrient use efficiency and a cumulative loss of soil quality

3.8. REFERENCES

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4. TWO DECADES OF CONTINUOUS CROPPING REDUCES SOIL QUALITY, WHEAT YIELD AND NITROGEN USE EFFICIENCY[‡]

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4.1. RESUMEN

Cuando la rotación pasturas-cultivos se sustituye por un sistema de cultivos anuales continuo, el rendimiento de trigo se mantiene o reduce en respuesta a dos procesos: i) reducción de la capacidad de suministrar nutrientes; ii) sutil pero acumulativa degradación de propiedades físicas del suelo. Estudiamos estos procesos en respuesta a 20 años de diferentes sistemas de cultivos (CS) por tres niveles de fertilización nitrogenada N (N0, N80 and N190 kg ha⁻¹) y dos ofertas de agua (lluvia y riego): i) Rotación cultivos-pastura con laboreo convencional (ROT_CT); ii) Rotación cultivos-pastura sin laboreo (ROT_NT); iii) Cultivos anuales continuo sin laboreo con alta frecuencia de sorgo y maíz (CC_NT_{C4}); iv) Cultivos anuales continuo sin laboreo con alta frecuencia de soja y girasol (CC_NT_{C3}); v) Cultivos anuales continuo sin laboreo con alta frecuencia de barbecho invernal (CC_NT_F); vi) Cultivos anuales continuo con laboreo convencional (CC_CT). La calidad del suelo fue relevada en base a su concentración de carbono orgánico (SOC) y nitrógeno total (TSN), tasa de infiltración de agua (INF), tamaño medio ponderado de agregados del suelo estables al agua (MWD) y potencial de mineralización de nitrógeno (PMN). Estimamos la brecha de rendimiento de trigo atribuible a nitrógeno como la diferencia entre el rendimiento obtenido con N190 y con N0 ($Y_{g(x)}^N = Y_{N190(x)} - Y_{N0(x)}$). La brecha generada por cada CS por otras propiedades del suelo, no directamente asociadas a suministro de N se estimó como la diferencia entre el rendimiento máximo (Y_{max}) y rendimiento con N190 ($Y_{g(x)}^{others} = (Y_{max} - Y_{N190(x)})$). La brecha total de rendimiento corresponde a la suma de ambos componentes ($Y_{g(x)}^T = Y_{g(x)}^N + Y_{g(x)}^{others}$). Para estimar la eficiencia de uso del suministro de nitrógeno (N_{seff}), el rendimiento en grano fue corregido ($Y_{2\%}$) a una concentración constante de nitrógeno en grano (Ng) de 20 g kg⁻¹. Calculamos la brecha de rendimiento a $Ng=20$ g kg⁻¹ para cada CS ($Y_{g2\%}^T$); la reducción en N_{seff} a un mismo nivel de Ns ($Y_{g2\%}^{Ns eff}$); la brecha de rendimiento atribuible a cambio en Ng ($Y_g^{\Delta q}$) como la diferencia entre $Y_{g2\%}^T$ and Y_g^T . Solamente ROT_NT y CC_NT_{C4} lograron el Y_{max} (7,2 Mg ha⁻¹), siendo 100% del Y_g^T explicado por Y_g^N . Bajo otros CS, la fracción de Y_g^{others} incrementó desde 32% bajo CC_NT_F a 50% bajo CC_CT,

mientras que fue solamente 23% bajo r ROT_CT. Dependiendo del CS, $Y_{g2\%}^T$ varió desde 3,7 (ROT_NT) a 6,0 Mg ha⁻¹ (CC_CT) cuando $N_s = 125$ kg ha⁻¹. Bajo máximo N_s (315 kg ha⁻¹), $Y_{g2\%}^T$ fue totalmente compensado en ROT_NT y CC_NT_{C4}, fue reducido a 0,6 Mg ha⁻¹ en ROT_CT, pero permaneció entre 1,2 and 1,5 Mg ha⁻¹ en CC_NT_F y CC_NT_{C3}, sobre 2 Mg ha⁻¹ en CC_CT. La eficiencia de uso del N del fertilizante en ROT_NT fue 45 kg de trigo por kg⁻¹ N agregado. El N adicional necesario bajo otras alternativas sin labranza y en ROT_CT, variaría entre 41 to 87 kg ha⁻¹, reduciendo $N_{fert\ use\ eff}$ a entre 31 y 37 kg ha⁻¹ of de trigo por kg⁻¹ N agregado. El peor resultado ocurrió en CC_CT, donde la fertilización N debería aumentar en 118 kg ha⁻¹, (totalizando 308 kg ha⁻¹), lo que reduciría la eficiencia de uso del N del fertilizante a 28 kg de trigo por kg⁻¹ N agregado.

Palabras claves: Brecha de rendimiento; Rotación de cultivos; Secuencia de cultivos; Trigo

4.2. SUMMARY

When crop-pasture rotation is converted to annual cropping, grain yield of wheat stagnates or decline in response to two different process: i) soil nutrient supply capacity depletion; ii) subtle but accumulative soil physical degradation. We studied these processes in response to 20 years of cropping systems(CS) by three N level (N0, N80 and N190 kg ha⁻¹) and two water regimen (rainfed and irrigated): i) Crop-pasture rotation with conventional tillage (ROT_CT); ii) Crop-pasture rotation with no-till (ROT_NT); iii) Continuous cropping with no-till incorporating high frequency of sorghum and maize (CC_NT_{C4}); iv) Continuous cropping with no-till incorporating high frequency of soybean and sunflower (CC_NT_{C3}); v) Continuous cropping with high frequency of winter fallow (CC_NT_F); vi) Continuous annual cropping under conventional tillage (CC_CT). Soil quality was assessed based on soil organic carbon (SOC), total soil nitrogen concentration, field water infiltration rate (INF), soil water aggregate stability (MWD) and potentially mineralizable nitrogen (PMN). We estimate yield reduction due to nitrogen supply as the difference between yield under

N190 and yield under N0 ($Y_{g(x)}^N = Y_{N190(x)} - Y_{N0(x)}$). Yield reduction due to the effect of CS on other soil properties than N supply was calculated as the difference between maximum yield and yield under N190 ($Y_{g(x)}^{others} = (Y_{max} - Y_{N190(x)})$). Total yield gap summing both Yg components ($Y_{g(x)}^T = Y_{g(x)}^N + Y_{g(x)}^{others}$). To estimate Ns efficiency use ($N_{s\ eff}$), grain yield ($Y_{2\%}$) was corrected to a constant N grain concentration (Ng) equal to 20 g kg⁻¹. We calculated total yield gap at constant Ng of each CS ($Y_{g2\%}^T$); yield reduction due $N_{s\ eff}$ at the same level of Ns ($Y_{g2\%}^{Ns\ eff}$); yield reduction attributed to changes in Ng ($Y_g^{\Delta q}$) was calculated as the difference between $Y_{g2\%}^T$ and Y_g^T . Only ROT_NT and CC_NT_{C4} achieved the Y_{max} (7.2 Mg ha⁻¹), being 100% Y_g^T explained by Y_g^N . Under other CS, the fraction of Y_g^{others} increased from 32% under CC_NT_F to 50% under CC_CT , while it was only 23% under ROT_CT . Depending on CS, $Y_{g2\%}^T$ varied from 3.7 (ROT_NT) to 6.0 Mg ha⁻¹ (CC_CT) under 125 kg ha⁻¹ of Ns . Under maximum Ns (315 kg ha⁻¹), $Y_{g2\%}^T$ was totally compensated under ROT_NT and CC_NT_{C4} , it was reduced to 0.6 Mg ha⁻¹ under ROT_CT , but it remained between 1.2 and 1.5 Mg ha⁻¹ under CC_NT_F and CC_NT_{C3} , and over 2 Mg ha⁻¹ under CC_CT . N fertilizer use efficiency under ROT_NT was 45 kg of wheat per kg⁻¹ N added. Additional N needed under alternative no-till CS and under ROT_CT , would varied between 41 to 87 kg ha⁻¹, reducing $N\ fert\ use\ eff$ to about 31 to 37 kg ha⁻¹ of wheat per kg⁻¹ N added. The worst scenario occurred under CC_CT , were N fertilization would be increased by 118 kg ha⁻¹ (total N added would be 308 kg ha⁻¹), reducing N fertilizer efficiency use to 28 kg of wheat kg⁻¹ N added.

Keywords: Cropping system; Yield gap; Crop Rotation; Crop sequence; Wheat

4.3. INTRODUCTION

Huge changes in land use have occurred during the last 20 years in the Rio de la Plata Grasslands, a region that covers more than 700 thousand km² in central-east Argentina, southern Brazil, and Uruguay (Baldi and Paruelo, 2008; Modernel et al., 2016). From 2000 till 2010 soybean area increased by 210% and the total arable cropping area by 28%, while the native grassland area decreased by 5% (Redo et al., 2012). Following this regional trend in land use change, the annual cropped area in Uruguay increased from 400 thousand to 2 million ha in the same period, with soybean and wheat as the main crops (DIEA, 2013). This increase in cropped area was achieved mainly by shifting cropping systems from crop-pasture rotations to continuous annual cropping under no-till (Franzluebbbers et al., 2014), contributing to soil degradation through wind and water erosion, soil organic matter depletion, soil compaction, nutrient loss and reduced biodiversity (Wingeyer et al., 2015). The amount of fertilizer applied, and agrochemicals needed to control yield reducing factors increased when measured per unit of land and per unit of product (Bolsa de Cereales, 2017; Hoffman and Ernst, 2017), representing a negative impact in terms of global and local environmental considerations. Moreover, there is evidence indicating that this intensification strategy is affecting the capacity of soils to sustain production (Ernst et al., 2016; Ernst et al., 2018).

Sustainable intensification of agriculture (SI) is a guiding concept that entails increasing food production from existing farmland in ways that have lower environmental impact, and which do not undermine our capacity to continue producing food in the future (Garnett et al., 2013). SI is associated with concepts such as eco-efficiency, or producing more value with less environmental impact. Applying this concept requires to identify and reduce inefficient use of resources, while maintaining soil fertility and biodiversity and reducing offsite environmental consequences of agriculture.

At global level, regional production inefficiencies have been estimated applying yield gap analysis (van Ittersum et al., 2013), based on estimations using crop growth simulation models of a yield potential (Yp) defined by crop physiology and phenology, temperature and radiation under unlimited water or nutrient supply and no

biotic stress; a water limited yield (Y_w), which is similar to potential but limited by water supply; and a water and nutrient limited yield (Y_{wn}), which is similar to Y_w but also limited by nutrient supply (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013). Another reference yield used to estimate inefficiencies is “Attainable Yield (Y_{att}) or maximum producers’ yield, defined as the yield achieved by a skillful producer using locally optimized agricultural best management practices and adapted cultivars, while taking into account production risks and economics (Fischer and Edmaedes, 2010; Lobell et al., 2009).

Applying yield gap analysis, nutrients have been found to be the most important yield restriction under actual wheat management in the eastern Pampa region (Neumann, 2010; Müller et al., 2012). However, this approach do not have the ability to estimate the effects on crop yield and nutrient use efficiency of gradual changes in soil quality that might occur over time in response to cropping systems. For example, cropping systems in this region changed from a 4-year annual crops and 3-4 years perennial pasture rotation using conventional tillage, to continuous annual cropping under no-till (Franzluebbers et al., 2014; Wingeyer et al., 2015). Compared to crop-pasture rotations, agricultural intensification by lengthening the annual cropping phase decreased wheat attainable yield and increased yield gap when weather conditions were unfavorable for wheat growth (Ernst et al., 2016). This increase in yield gap could be explained by a reduction in soil nutrient supply capacity and by deteriorating soil quality, other than nutrients, while years of cropping after pasture increase (Ernst et al., 2018). During the first 4 or 5 years after pasture, more than 90% of yield reduction could be attributed to nutrient supply and overcame by increased fertilization rates. However, after ten years of continuous annual cropping more than 60% of yield reduction was explained by loss in soil quality, other than nutrient supply capacity (Ernst et al., 2018). Soil quality loss associated to soil physical properties cannot be compensated with increased fertilization rates, and reflects a progressive loss of the soil capacity to sustain biological productivity (Kumar et al., 2012).

Cumulative effects of cropping systems on soil properties and attainable crop yield require time to build up and be measured. Long-term cropping system experiments provide an opportunity to evaluate the impact of changes in soil properties

induced by cropping systems on wheat attainable yield, yield gap and input use efficiency. In this study, we used a 20 year crop rotations and soil tillage experiment to test hypotheses pertaining to the effect of cropping system on soil properties, wheat yield, yield gap and nitrogen use efficiency. The experiment included crop–pasture rotation and continuous cropping under conventional tillage and no tillage, and different crop sequences under continuous no-till. These variables have demonstrated effects on soil quality components, affecting soil organic carbon dynamic (Studdert et al., 1997; Álvarez and Steinbach, 2009), soil structure (Novelli et al., 2013; Álvarez et al., 2014), soil erosion rates (i.e. Díaz-Zorita et al., 2002 in Argentina; García-Préchac et al., 2004, and Ernst and Siri-Prieto, 2009 in Uruguay; Boeni et al., 2014 in Brazil). However, while pastures in the rotation may maintain or improve soil quality under both, conventional and no till systems, crop sequence is a key factor under continuous no-till cropping systems. Under continuous no-till cropping systems, the strategies for enhancing soil quality include intensification of cropping, by elimination of fallow periods (double annual cropping or cover crops), improved residue inputs by increased yield (N fertilization), incorporating crops with highest biomass production level (maize or sorghum) and/or greater and deep root systems (Janzen et al., 1998; Varvel, 2006; Salvo et al., 2010; Jackson et al., 2017; Novelli et al., 2017).

Our hypotheses were: (1) long term cropping system influences soil properties and therefore soil functioning, limiting wheat yield even under no-till; (2) this yield loss can be apportioned to nutrient and non-nutrient limitations, modifying N use efficiency.

The objectives of this study were to: (i) quantify long-term effects of cropping systems on soil properties and wheat yield; (ii) quantify to which extent the yield loss observed under continuous no till cropping systems could be attributed to nitrogen depletion; iii) investigate which soil properties could explain the observed reduction in wheat yield and N use efficiency.

4.4. MATERIALS AND METHODS

4.4.1 Description of study area and experimental setup

The ongoing long-term experiment is located 10 km south of Paysandú (32° 21' S and 58° 02' W; 61 m elevation) in the northwest of Uruguay, which corresponds broadly with the eastern edge of the South American Pampas. The climate is meso-thermal sub-humid with a mean daily temperature of 25°C and 13°C for summer and winter, respectively, and annual precipitation of 1200 mm distributed on average uniformly within the year, but with large intra- and inter-annual variation. Water deficits occur frequently between October and March and water surpluses between May and August. The soil at this site is a fine, mixed, active, thermic Typic Argiudoll (USDA), with a slope of 1%, an A horizon 18 cm deep, pH (H_2O) 5.7 soil water relation v:v = 1:2.5), and clay, silt and sand contents of 289, 437, 273 g kg⁻¹, respectively.

The experiment started in autumn 1993, combining two tillage systems, conventional tillage (CT) and no-till (NT), by two rotation systems, continuous cropping (CC) and crop-pasture rotation (ROT). These resulted in four cropping systems (CS) arranged in a randomized block design with three replications:

Continuous annual cropping under conventional tillage (CC_CT): soil tillage included a combination of moldboard or chisel plow (depending on the year) to a depth of 20-25 cm followed by disking to a depth of 10-15 cm applied during April, before sowing each winter crop. Immediately after winter crop harvest, soil was tilled using disk harrow to a depth of 15-20 cm, followed by field cultivator to a depth of 10-15 cm and then, a summer crop was sown (sunflower, soybean, maize or sorghum) during December.

Crop – pasture rotation with conventional tillage (ROT_CT). The rotation was 3.5 years crops-2.5 years grass and legume pasture. The pasture was under-seeded with the winter crop in the same planting operation in 1995 and 2002. The sod-legume pasture consisted of birdsfoot trefoil, white clover, and tall fescue. Tillage operations for crops were similar to CC_CT.

Continuous cropping with no – till (CC_NT): the same crop sequence than CC_CT but sown with no-till, substituting tillage by application of Glyphosate at the rate of 1.5 to 2.0 kg a.i. ha⁻¹ depending on weed infestation and weather conditions.

Crop – pasture rotation with no – till (ROT_NT). The same crop sequence and pasture than ROT_CT, but both crops and pasture sown under no-till. Glyphosate applications were similar to CC_NT.

From 1993 to 1999 the double annual crops sequence was composed by wheat or barley during winter season (June to November) followed by sunflower or sorghum during summer season (December to April) sown immediately after winter crop harvest. A detailed description of cropping system treatments was published by Ernst and Siri-Prieto (2009).

From 2000 to 2010, both No-Till cropping systems were split combining summer crops with different photosynthetic pathways: soybean and sunflower (C3) (CC_NT_{C3}; ROT_NT_{C3}) versus sorghum and maize (C4) (CC_NT_{C4}; ROT_NT_{C4}). Eleven C3 or C4 summer crops were sown under CC_NT, and seven under ROT_NT. All summer crops were sown following the same previous winter crop. Detailed description of cropping system treatments after 2000, was published by Salvo *et al.*, (2010).

In 2008, ROT_NT_{C3} was transformed to continuous winter fallow/soybean under no-till (CC_NT_{WF}). Winter fallow period occurred each year from end of April to beginning of November (harvest of the soybean to sowing of the next soybean). Soil during winter was maintained free of weeds applying glyphosate.

Cropping systems treatments evaluated until 2014 are shown in Table 4.1, and Table 4.2 summarizes soil use indicators of each treatment till 2012. In this study we evaluated the performance of wheat crops during 2013 and 2014 seasons. To avoid possible wheat yield reduction promoted by sowing wheat into straw of a previous wheat crop (Carignano *et al.*, 2008; Mazzilli *et al.*, 2016), all experimental plots were under a winter cover crop and soybean during 2012, except for CC_NT_{WF} plots (Table 4.1). During winter of 2013, blocks were split in two sequences: wheat (current study)/soybean or Colza_CANOLA/soybean.

Table 4.1. Schematic diagram of cropping system treatments, over 1993-2012 period, used in the long term experiment carried-out in a Mollisol at Paysandú, Uruguay (31510 S; 60320 W). “P” represents periods with perennial sod-legume pasture growing (grey). “wc/sc” represents periods with annual crop growing (one winter crop followed by one summer crop per year). “wc/sc_C3” represents periods with a winter crop and soybean or sunflower during summer seasons. “wc/sc_C4” represents period with a winter crop and maize or sorghum grain during summer seasons. “CC” corresponds to oat growing during winter as cover crop (June to September).

“C” represents Colza-CANOLA

Period	Cropping system name after 2008											
	<i>CC_CT</i>		<i>ROT_CT</i>		<i>ROT_NT</i>		<i>CC_NT_F</i>		<i>CC_NT_{C4}</i>		<i>CC_NT_{C3}</i>	
1993/95	wc/sc		wc/sc		wc/sc		wc/sc		wc/sc		wc/sc	
1996/98	wc/sc		P		P		P		wc/sc		wc/sc	
1999/01	wc/sc		wc/sc		wc/sc		wc/sc		wc/sc_C4		wc/sc_C3	
2002/04	wc/sc		P		P		P		wc/sc_C4		wc/sc_C3	
2005/07	wc/sc		wc/sc		wc/sc		wc/sc		wc/sc_C4		wc/sc_C3	
2008/10	wc/sc		P		P		F/Sy		wc/sc_C4		wc/sc_C3	
2011	W/Sy		W/Sy		W/Sy		F/Sy		W/Sy		W/Sy	
2012	CC/Sy		CC/Sy		CC/Sy		F/Sy		CC/Sy		CC/Sy	
2013	W /Sy	C/Sy	W /Sy	C/Sy	W /Sy	C/Sy	W /Sy	C/Sy	W /Sy	C/Sy	W /Sy	C/Sy
2014	C	W	C	W	C	W	C	W	C	W	C	W

Wheat crops evaluated in this paper are indicated with bold capital letters.

During 2014 wheat (current study) was sown after Colza_CANOLA/soybean sequence. Consequently, both wheat 2013 and wheat 2014, were sown after soybean and last presence of a previous wheat crop was during winter of 2011 (Table 4.2).

Table 4.2. Soil use indicators for the period 1993 to 2012. “Pasture/crop” ratio represents the proportion of time occupied by pasture; number of annual crops is the amount of crops produced during the period; number of crops per year and Total crop frequency are soil cropping use intensity indicators.

	<i>ROT_NT</i>	<i>CC_NT_{C4}</i>	<i>CC_NT_F</i>	<i>CC_NT_{C3}</i>	<i>ROT_CT</i>	<i>CC_CT</i>
Pasture/Crop ratio (%)	50	0	25	0	50	0
Num. of annual crops in 40 growing seasons*	17	33	22	33	17	33
Num. of annual crops per year	0.85	1.65	1.1	1.65	0.85	1.65
Crop Frequency relative to the number of growing seasons						
Sorghum or maize	.075	.400	.075	.075	.075	.075
Soybean or sunflower	.200	.075	.400	.400	.200	.400
Wheat, Barley or oats	.150	.350	.075	.350	.150	.350
Winter fallow	.075	.175	.300	.175	.075	.175
Total	.500	1.00	.850	1.00	.500	1.00

* Two growing seasons per year

The experiment occupied approximately 2 ha with individual plots of 50×10 m in size, thereby allowing the use of field-scale equipment for all operations. Wheat was maintained free of weeds, insects and diseases with timely applications of herbicides, insecticides and fungicides.

During 2013 and 2014 we studied the effect of these different CS on wheat yield and N use efficiency under three nitrogen rates (N) and two water supply levels (W) in a factorial experiment with split-plot design. Cropping system was the main

plot (60 m²) and minor plot (2*5 m) was a factorial of three nitrogen (N) levels: 0 (N0), 80 (N80) and 190 (N190) kg ha⁻¹ (Table 3) and two water supply levels (W): “Rainfed” (limited by water) and “Irrigated” (no limited by water) conditions (Figure 4.1). Under “Irrigated”, soil relative water content in the top layer (0-40cm) was maintained above 65%. Drip irrigation was applied using plastic pipe transportation system. Amount of water applied was estimated by controlling the duration of irrigation operations.

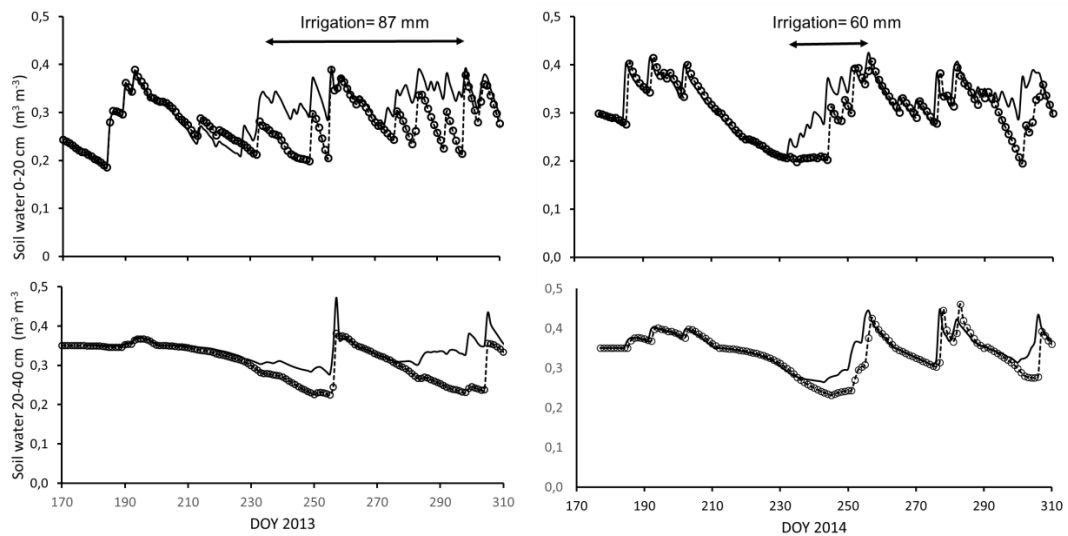


Figure 4.1. Soil water balance in the top 20 cm (above) and between 20 to 40 cm (below) from wheat seeding date to harvest day under rainfed (open circle) and irrigated (continue line) conditions. Left side corresponds to 2013 and right side to 2014.

All treatments were under not limited P, K and S fertilization. We defined the N uptake at physiological maturity under N0 as “soil N supply” and N uptake and wheat yield under N190 as “not limited by N”. The treatment N80 corresponds to average amount of N applied by wheat producers under ROT_NT cropping systems in the region (Ernst et al., 2016).

To quantify accumulated effects of cropping systems on top soil properties on wheat yield, all treatments were sown under no-till. Seeding date was July 6th of 2013 and June 27th of 2014, using cultivar “Baguette 501”, ranked in the top five yielding

cultivars in the trials of the National Testing Network of Wheat Cultivars (INASE 2015).

Table 4.3. Nitrogen fertilizer rates applied (kg ha^{-1}) at seeding date, Z22*, Z30* and heading phenological growth stages under N80 and N190 nitrogen levels.

	Nitrogen application (kg ha^{-1})	
	N80	N190
Seeding	25	40
Z22	25	50
Z30	30	60
Heading		40
Total	80	190

* Corresponds to Zadoks scale (Zadoks et al., 1974).

4.4.2 Soil quality assessment and meteorological data

All soil properties were measured on samples collected from each main plot in June 2013. Soil organic carbon (SOC) (Nelson and Sommers, 1996), and soil total nitrogen concentration (STN) were analyzed after dried sieved through a 2 mm mesh composite samples of 10 sub-samples of top 0-5 and 5-20cm soil layers. Treatment effects were analyzed separately for each soil depth profile. Potentially mineralizable nitrogen in the top 10 cm (PMN, $\text{mg of N-NH}_4 \text{ kg}^{-1}$) was estimated following Waring and Bremner, (1964). Additionally, N-NO_3^- in 0-20 cm was measured at seeding date and when wheat was at Z 2.2 stage (second tiller visible, or when the tip of the fifth leaf is visible). Field water infiltration rate (INF) was determined using the method developed by the Soil Quality Institute (1999). A 15-cm in diameter ring was pressed 8 cm vertically into the topsoil. The ring was lined with plastic wrap and a 2.54 cm sheet of distilled water applied. The plastic wrap was then removed to begin wetting and to homogenize soil moisture. After infiltration was completed, the procedure was repeated, recording the time required for all water to infiltrate into the soil. Three replicates were taken at each site. To evaluate wet aggregate stability we used the wet sieving procedure of Yoder (1936), modified by Kemper and Rosenau (1986). Three

samples for the 0–10 cm layer were collected from each main plot. Immediately after collection, aggregates between 4.5 and 9.5 mm were separated from the composite sample, by gently massaging large clouds to free aggregates of the preferred size. Moist aggregates (30 g) of between 4.5 and 9.5 mm were spread evenly on the uppermost sieve of a nest of 4.5, 2.8, 2.0, 1.0, 0.6 and 0.3 mm diameter. To avoid sudden rupture of the aggregates, the screens were lowered to wet the base of the topmost sieve to allow aggregates to become completely wet (10 min) by capillarity. The water level in the shaking apparatus was adjusted so that aggregates on the uppermost sieve were just submerged on the highest point of the cycle. Samples were oscillated for 15 min at 40 strokes per minute with the amplitude of the action set at 8 cm. The soil remaining on every sieve after 15 min was transferred into a beaker and oven-dried at 105°C for 48 h and then weighed. The strength of aggregates in water was calculated as mean weight diameter (MWD).

$$MWD = \sum_{i=0.15}^{i=7} Xi * Wi$$

Where,

Xi is the average diameter of the openings of two consecutive sieves, and

Wi is the weight ratio of aggregates remained on the ith sieve.

The multipliers used in our study after wet sieving were 7, 3.65, 2.4, 1.5, 0.8, and 0.45 mm for the sieves, respectively, and 0.15 mm for the remaining soil.

4.4.3 Grain yield and N uptake

At physiological maturity, 1 m² per plot was sampled to measure above-ground dry matter production, dry matter partitioning between grain and straw and N concentration (Kjeldhal) in grain and straw. Grain yield (0% grain moisture) was quantified over 6 m² per plot using a plot combined harvester.

4.4.3.1. Quantifying the effect of cropping system on yield gap

To quantify wheat yield reduction in response to long term CS, we used as maximum yield or benchmark (Y_{max}) the wheat yield obtained by the best CS, under N190. We estimated yield reduction due to nitrogen supply as the difference between yield under N190 and yield under N0 ($Y_{g(x)}^N = Y_{N190(x)} - Y_{N0(x)}$). Yield reduction

due the effect of CS on other soil properties than N supply was calculated as the difference between maximum yield and yield under N190 ($Y_{g(x)}^{others} = (Y_{max} - Y_{N190(x)})$). We estimated total yield gap as the sum of yield reduction due to N supply and due to the effect of CS on other soil properties ($Y_{g(x)}^T = Y_{g(x)}^N + Y_{g(x)}^{others}$).

To compare Y_{max} with wheat potential yield (Y_p), we estimated Y_p using Cropsyst simulation model (Stöckle et al., 2003, version 4.19.06), calibrated and validated to local conditions (Mazzilli et al., 2013). Daily weather data, including solar radiation ($Mj\ m^2\ d^{-1}$), minimum and maximum temperature ($^{\circ}C$), relative humidity (%), wind speed ($m\ s^{-1}$) and precipitation (mm), were retrieved from an automatic weather station located nearby the experimental site. Soil parameters required to estimate soil water balance were derived by inputting of soil texture and SOC of whole soil profile composed by five layers of 20 cm each one.

4.4.4. N use efficiency components

N use efficiency under different CS and N application treatments is affected by soil and plant factors related to N supply, N uptake, efficiency with which N is utilized to produce grain, and grain N content (Moll et al., 1982). We solved differences in efficiency produced by changes in grain N content (N_g) by correcting measured grain yield to a constant N grain concentration (N_g) equal to $20\ g\ kg^{-1}$ ($Y_{2\%}$) as follows:

$$Y_{2\%} = \frac{Y * N_g}{0.02}$$

Nitrogen supply use efficiency ($N_{s\ eff}$) was defined as the ratio of $Y_{2\%}$ to total N supply (N_s) (Moll et al., 1982).

$$N_{s\ eff} = Y_{2\%} / N_s$$

Where;

N_s was estimated as the sum of N applied as fertilizer (N_f) plus total aboveground crop N uptake (N_{up}) at physiological maturity on control plots (N_0). N_{up} from N_0 plots is an indicator of soil N supply capacity ($soilN_s$).

Yield reduction attributed to changes in grain nitrogen content ($Y_g^{\Delta q}$) was calculated as the difference between $Y_{g2\%}^T$ and Y_g^T .

Differences in grain yield ($Y_{g2\%}^T$) among CS and N application treatments can be attributed to differences in N_s ($Y_{g2\%}^{Ns}$) and efficiency with which N is utilized to produce grain ($Y_{g2\%}^{Ns\ eff}$). We applied a procedure similar to that suggested by Huggins and Pan (1993) to estimate how much of $Y_{g2\%}^T$ could be attributed to $Y_{g2\%}^{Ns}$ and $Y_{g2\%}^{Ns\ eff}$ at an equivalent N_s amount. For this purpose, we defined *ROT_NT* as the reference CS, and wheat yield under *ROT_NT* at N190 as the reference treatment ($Y_{2\%}^{Ref}$). We proceeded as follows:

- i) We adjusted a regression equation between $Y_{2\%}$ against N_s under *ROT_NT* ($Y_{g2\%}^{Ns\ Ref}$ and N_s^{Ref} respectively).

$$Y_{2\%}^{Ns\ Ref} = a + bN_s^{Ref}$$

- ii) We calculated the difference in N supply (ΔN_s) between each combination of CS and N fertilization level ($N_s(x,z)$) and the reference treatment (N_s^{Ref}):

$$\Delta N_s(x,z) = N_s^{Ref} - N_s(x,z)$$

- iii) We quantified $Y_{g2\%}^{Ns}$ of each combination of CS and N fertilization level ($Y_{2\%(x)}^{Ns(z)}$) by substituting $\Delta N_s(x,z)$ in the $Y_{2\%}^{Ns\ Ref}$ equation.

- iv) We calculated total yield gap at 2% N grain concentration of each combination of CS and N fertilization level ($Y_{g2\%(x,z)}^T$) as follows:

$$Y_{g2\%(x,z)}^T = Y_{2\%}^{Ref} - Y_{2\%(x)}^{Ns(z)}$$

- v) We quantified the yield reduction due N supply use efficiency ($Y_{g2\%(x,z)}^{Ns\ eff}$) at the same level of N_s , subtracting $Y_{g2\%(x)}^{Ns(z)}$ from $Y_{g2\%(x,z)}^T$

$$Y_{g2\%(x,z)}^{Ns\ eff} = Y_{g2\%(x,z)}^T - Y_{g2\%(x)}^{Ns(z)}$$

Assuming that is possible that every CS could reach $Y_{2\%}^{Ref}$ just by increasing N_s , we estimated for each CS-N0 treatment the additional N fertilization needed to

reach $Y_{2\%}^{Ref}$ (*Nf increase*) using the slope of the regression equation between $Y_{2\%}$ against Ns under ROT_NT , as follows:

$$Nf\ increase_x = \left(\frac{Y_{2\%}^{Ref}(x,0)}{b}\right) - 190$$

Under the same assumption, we also estimated the N fertilizer use efficiency (*Nfert use eff*) that would result from applying *Nf increase* to reach $Y_{2\%}^{Ref}$ for each CS-N0 treatment, as follows:

$$Nfert\ use\ eff_x = Y_{2\%}^{Ref} / (190 + \Delta N\ increase_x)$$

4.4.5. Statistical analysis

Wheat yield, N uptake, N efficiency components were analyzed using a linear mixed model, where Year (Y) CS, N, W and its interactions as fixed effects; blocks*year and blocks as random effects. Soil properties were analyzed using a linear mixed model, with fixed effects of CS and random effects of blocks. Mean were compared using Fisher's protected least significant difference (LSD) test at the 5% probability level.

4.5. RESULTS

4.5.1. Soil properties

After 20 years, we observed significant effects of cropping systems on SOC only in the top layer (0-5cm) and small but significant effects in total N in both layers (0-5 and 5-20 cm) (Table 4.4). All CS under no till had $SOC > 27\ g\ kg^{-1}$ in the top 5cm. However, only *ROT_NT* system had the highest values in both physical properties, INF and MWD. During the last 20yr, this system was only 10yr under agriculture (Table 4.4). All CS showed reduced INF compared to *ROT_NT*. PMN and MWD were reduced under *CC_NT_{C4}* and *CC_NT_F*. *ROT_CT* had lower $SOC_{(0-5)}$ than all no-till cropping systems, but also showed the highest PMN level and similar INF than NT systems. Under this CS, $N_{(0-5)}$ was as high as the best CS and $N_{(5-20)}$ as low as the worst CS. The worst values in soil quality indicators were observed after 20 years under *CC_CT*.

Table 4.4 Top soil properties after 20 year of crop-pasture rotation under no-till (*ROT_NT*), crop-pasture rotation under conventional tillage (*ROT_CT*), three alternatives of continuous annual crop under no-till (*CC_NT_{C4}*, *CC_NT_{C3}*, *CC_NT_F*) and continuous annual crop under conventional tillage (*CC_CT*): soil organic carbon content in 0-5 and 5-20 cm (SOC), total nitrogen in 0-5 and 5-20 cm (TSN), potentially mineralizable nitrogen (PMN) (0-10 cm), water infiltration rate (INF) and soil aggregate stability measured as mean weight diameter (MWD) (0-10).

Cropping system	<i>ROT_NT</i>	<i>CC_NT_{C4}</i>	<i>CC_NT_F</i>	<i>CC_NT_{C3}</i>	<i>ROT_CT</i>	<i>CC_CT</i>
SOC ₍₀₋₅₎ (g kg ⁻¹)	28 a	28 a	27 ab	30 a	25 b	18 c
SOC ₍₅₋₂₀₎ (g kg ⁻¹)	19 a	19 a	19 a	18 a	18 a	17 a
TSN ₍₀₋₅₎ (g kg ⁻¹)	2.0 ab	2.1 a	2.0 ab	1.9 b	2.1 a	1.9 b
TSN ₍₅₋₂₀₎ (g kg ⁻¹)	1.7 a	1.7 a	1.6 ab	1.6 ab	1.5 b	1.5 b
PMN mg kg ⁻¹)	20 b	16 c	16 c	22 b	28 a	17 c
INF (cm h ⁻¹)	3.1 a	2.5 b	1.8 c	1.7c	2.0 bc	1.3 d
MWD (mm)	2.13 a	1.29 b	1.34 b	2.08 a	1.47 b	0.64 c

4.5.2. Wheat yield

The mean wheat yield was significantly influenced by Year (5.7 vs 4.7 Mg ha⁻¹ for 2013 and 2014, respectively), CS, N application and CS by N interaction ($P \leq 0.05$). Not limited water conditions were obtained irrigating with 87mm and 60 mm of during 2013 and 2014, respectively (Figure 4.1). However, we observed no significant difference between Rainfed and Irrigated treatments (5.1 vs 5.2 Mg ha⁻¹), and no significant interactions with other factors. So, we removed water availability as a factor from further analysis.

4.5.2.1. Effect of cropping system and N supply on wheat yield and yield gap

Cropping system affected Y_{N0} , Y_{N80} and Y_{N190} differently ($P \leq 0.05$) (Figure 4.2). The Y_{max} measured in our experiment (7.2 Mg ha⁻¹) compares well with wheat Y_p (7.0 Mg ha⁻¹) estimated using the Cropsyst model (7.5 and 6.5 Mg ha⁻¹ under 2013

and 2014 weather conditions, respectively). Only two CS achieved Y_{max} , double annual cropping rotating with pasture (ROT_NT) and continuous double annual cropping under no-till including high frequency of grain sorghum and maize during summer season, (CC_NT_{C4}). Two no-till alternatives (CC_NT_F and CC_NT_{C3}), reduced Y_{N190} to a similar level than traditional ROT_CT , from 7.2 to 6.1 $Mg\ ha^{-1}$ ($p \leq 0.05$).

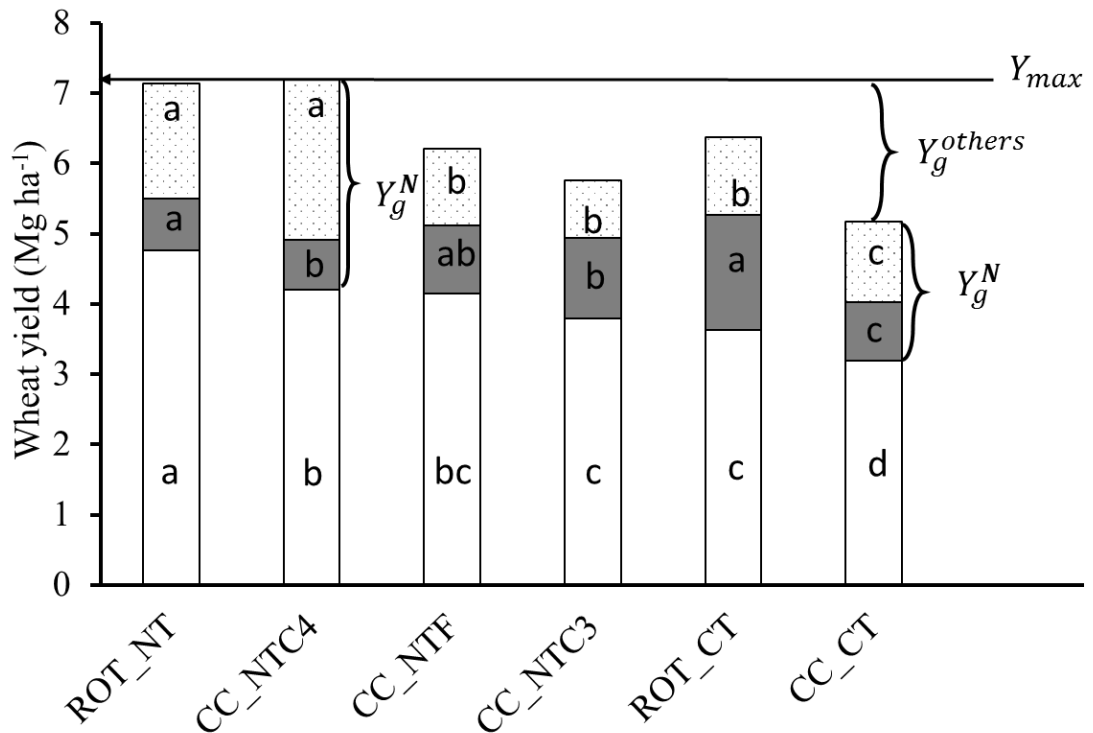


Figure 4.2. Wheat yield under N190 (dotted area), N80 (shadow), and N0 (white) in response to 20 years of crop-pasture rotation under no-till (ROT_NT), crop-pasture rotation under conventional tillage (ROT_CT), three alternatives of continuous annual crop under no-till (CC_NT_{C4}); CC_NT_{C3} ; CC_NT_F and continuous annual crop under conventional tillage (CC_CT). Y_g^N = yield reduction due to soil nitrogen supply capacity; Y_g^{others} = yield reduction due to other soil properties than nitrogen supply capacity; Y_g^T = total yield reduction. Y_{max} = maximum yield obtained under not-limited nitrogen and water conditions. Results are the average of two years under not-limited water conditions. Different letters indicate significant differences in wheat yield between CS treatments, within each N application level (N190, N80 and N0).

On average, grain yield of wheat was significantly improved under N80 compared to N0 management in all CS treatments ($p \leq 0.05$). However, Y_{N80} was reduced from 5.3 Mg ha⁻¹ under *ROT_NT*, and *ROT_CT*, to 4.9 Mg ha⁻¹ under *CC_NT_{C4}* and *CC_NT_{C3}*, and to 4.0 Mg ha⁻¹ under *CC_CT* ($p \leq 0.05$).

The highest Y_{N0} was obtained under *ROT_NT* (4.7 Mg ha⁻¹). Two continuous cropping systems under NT (*CC_NT_{C4}* and *CC_NT_F*) reduced Y_{N0} to 4.1 Mg ha⁻¹ ($p \leq 0.05$). When soybean was a frequent summer crop (*CC_NT_{C3}*) and under *ROT_CT* Y_{N0} was reduced to 3.7 Mg ha⁻¹ ($p \leq 0.05$). The lowest Y_{N0} was obtained under *CC_CT* (3.2 Mg ha⁻¹). The yield gap explained by Ns (Y_g^N) was 2.4 and 3.0 Mg ha⁻¹ for *ROT_NT* and *CC_NT_{C4}*, respectively, while Y_g^N was 2.7 Mg ha⁻¹ for *ROT_CT* and 2.0 Mg ha⁻¹ for the rest (Table 4.5).

Table 4.5. Estimated effect of cropping system (CS) on total yield reduction (Y_g^T); yield reduction due to nitrogen supply (Y_g^N), due to N80 (Y_g^{N80}) and due to other factors than nitrogen supply (Y_g^{others}). Relative total yield reduction (RY_g^T) was estimated as $Y_g^T * 100/Y^{max}$. The fraction of the RY_g^T explained by nitrogen supply (FY_g^N), and due to other than nitrogen supply (FY_g^{others}) were estimated as percentage of Y_g^T . The fraction of Y_g^N explained by N80 (FY_g^{N80}) was estimated as $(Y_g^N - Y_g^{N80})/Y_g^N$.

CS	Y_g^N Mg ha ⁻¹	Y_g^{others}	Y_g^T	Y_g^{N80}	RY_g^T %	FY_g^N	FY_g^{others}	FY_g^{N80}
<i>ROT_NT</i>	2.4	0.07	2.5	1.6	34.7	96.0	4.0	33.3
<i>CC_NT_{C4}</i>	3.0	0.00	3.0	2.3	41.7	100.0	0.0	23.3
<i>CC_NT_F</i>	2.1	1.0	3.1	1.1	43.0	67.7	32.3	47.6
<i>CC_NT_{C3}</i>	2.0	1.4	3.4	0.8	47.2	58.8	41.2	60.0
<i>ROT_CT</i>	2.7	0.8	3.5	1.1	48.6	77.1	22.9	59.9
<i>CC_CT</i>	2.0	2.0	4.0	1.2	55.6	50.0	50.0	40.0

Under *ROT_NT* and *CC_NT_{C4}*, all of Y_g^T was explained by Y_g^N . Under other continuous cropping systems, the fraction of yield gap explained by other factors than soil nitrogen supply, increased from 32.3% under *CC_NT_F* to 50% under *CC_CT*, while

it was only 22.9% under ROT_CT. Applying 80 kg ha⁻¹ of N under ROT_NT reduced Y_g^N by 33%, and the RY_g^T was reduced from about 35% to 22%. This implies that a producer applying the average amount of N currently used would be reaching approximately 80% of Y_{max} . Under CC_NT_{C4}, N80 reduced only 23% of the Y_g^N and RY_g^T remained over 30%. Under CC_NT_F and CC_NT_{C3}, N80 reduced 48 and 60% of the Y_g^N .

4.5.3. N uptake and N efficiency use components

Cropping systems and N fertilization rate modified significantly N_s , grain yield, Ng , $Y_{2\%}$ and $N_{s\ eff}$ (Table 4.6).

ROT_NT showed highest values in N uptake, N_s , Ng , $Y_{2\%}$ and $N_{s\ eff}$ at all N application levels. Compared to ROT_NT, N_{up} under N0 was reduced an average by 20% under the three continuous no till cropping systems (125 vs 100 kg ha⁻¹, $P \leq 0.05$). Under conventional tillage reduction reached 28% when crops were rotating with pasture (ROT_CT) and by 46% under continuous agriculture (CC_CT) (125 vs 89 and 67 kg ha⁻¹, $P \leq 0.05$). There was a significant CS* N application interaction on Ng . While Ng was significantly ($P \leq 0.05$) modified by CS under N0, differences were reduced under N80 and they were no significant differences under N190. $N_{s\ eff}$ decreased with increasing N application rate in all CS.

Grain yield of wheat under the reference CS was strongly related to N supply (soil + fertilizer) ($Y_{2\%}^{Ref} = 2.3 + 0.0195 N_s^{Ref}$). Both, intercept and regression coefficients were significant ($p \leq 0.05$).

Table 4.6. Effect of Crop-pasture rotation under no-till (*ROT_NT*), crop-pasture rotation under conventional tillage (*ROT_CT*), three alternatives of continuous annual crop under no-till (*CC_NT_{C4}*); *CC_NT_{C3}*; *CC_NT_F* and continuous annual crop under conventional tillage (*CC_CT*) on nitrogen uptake at physiological maturity (N uptake), nitrogen supply (Ns), nitrogen concentration in the wheat grain (N grain), wheat yield corrected at N grain equal 20 g kg⁻¹ (*Y_{2%}*), and nitrogen use efficiency (*Ns eff*), under three different nitrogen fertilizer levels (N0, N80 and N190). Ns corresponds to N uptake at physiological maturity under N0 plus N added as fertilizer.

	<i>ROT_NT</i>	<i>CC_NT_{C4}</i>	<i>CC_NT_F</i>	<i>CC_NT_{C3}</i>	<i>ROT_CT</i>	<i>CC_CT</i>
<u>N uptake (kg ha⁻¹)</u>						
N0	125 a	101 b	105 b	94 b	89 bc	67 c
N80	153 a	131 b	134 b	140 a	157 a	113 c
N190	233 a	239 a	197 bc	189 cd	216 b	169 d
<u>N supply (kg ha⁻¹)</u>						
N0	125 a	101 b	105 b	94 b	89 c	67 d
N80	205 a	181 b	185 b	174 b	169 bc	147 c
N190	315 a	291 b	295 b	284 b	279 bc	257 c
<u>N grain (g kg⁻¹)</u>						
N0	21 a	17 c	20 a	17 c	20 b	16 c
N80	23 a	21 b	21 b	22 b	21 b	21 b
N190	24 a	24 a	24 a	25 a	25 a	24 a
<u><i>Y_{2%}</i> (Mg ha⁻¹)</u>						
N0	4.90 a	3.58 bc	4.06 b	3.13 c	3.57 bc	2.59 d
N80	6.05 a	5.06 b	5.27 b	5.44 b	5.48 b	4.22 c
N190	8.56 a	8.75 a	7.33 b	7.09 b	7.93 ab	6.21 c
<u>Ns use efficiency (kg kg⁻¹ Ns)</u>						
N0	39 a	36 ab	39 a	33 b	40 a	39 a
N80	30 a	28 b	28 b	31 a	32 a	29 ab
N190	27 a	30 a	25 bc	25 bc	28 ab	24 c

Numbers followed by different letter in the same row are significantly different ($P \leq 0.05$).

All differences among N rates in the same column are significant ($P \leq 0.05$).

Table 4.7. Total yield difference ($Y_{g2\%}^T$) between each cropping systems and the reference CS (*ROT_NT* under N190), partitioned in yield difference attributed to N supply ($Y_{g2\%}^{Ns}$) and yield difference attributed to N supply use efficiency ($Y_{g2\%}^{Ns\,eff}$). Differences are expressed in Mg ha^{-1} .

N supply under <i>ROT_NT</i> (kg ha^{-1})									
125			205			315			
	$Y_{g2\%}^T$	$Y_{g2\%}^{Ns}$	$Y_{g2\%}^{Ns\,eff}$						
CS	Mg ha^{-1}			Mg ha^{-1}			Mg ha^{-1}		
<i>ROT_NT</i>	3.7	3.7	0.0	2.5	2.1	0.4	0.0	0.0	0.0
<i>CC_NT</i> _{C4}	5.0	4.2	0.8	3.5	2.6	0.9	-0.2	0.5	-0.7
<i>CC_NT</i> _F	4.5	4.1	0.4	3.3	2.5	0.8	1.2	0.4	0.8
<i>CC_NT</i> _{C3}	5.4	4.3	1.1	3.1	2.7	0.4	1.5	0.6	0.9
<i>ROT_CT</i>	5.0	4.4	0.6	3.1	2.8	0.2	0.6	0.7	-0.1
<i>CC_CT</i>	6.0	4.8	1.1	4.3	3.3	1.1	2.3	1.1	1.2

$$Y_{g2\%(x,z)}^T = Y_{2\%}^{Ref} - Y_{2\%(x)}^{Ns(z)}; \quad Y_{g2\%}^{Ns} = 0.0195 * \Delta N_{s(x)}; \quad Y_{g2\%}^{Ns\,eff} = Y_{g2\%}^T - Y_{g2\%}^{Ns}$$

Negative value implies that $Y_{g2\%}^T$ and $Y_{g2\%}^{Ns\,eff}$ were increased relative to *ROT_NT*.

Depending on CS, $Y_{g2\%}^T$ varied from 3.7 (*ROT_NT*) to 6.0 Mg ha^{-1} (*CC_CT*) under 125 kg ha^{-1} of N_s . Excepting *ROT_CT*, more than 50% of the $Y_{g2\%}^T$ was explained by $Y_{g2\%}^{Ns}$, reaching more than 60% under *CC_NT*_{C4} and *CC_NT*_{C3}. Increasing N_s to 205 kg ha^{-1} adding N fertilizer, mean $Y_{g2\%}^T$ was reduced by 1.7 Mg ha^{-1} . Under maximum N_s (315 kg ha^{-1}), $Y_{g2\%}^T$ was totally compensated under *ROT_NT* and *CC_NT*_{C4}, it was reduced to 0.6 Mg ha^{-1} under *ROT_CT*, but it remained between 1.2 and 1.5 Mg ha^{-1} under *CC_NT*_F and *CC_NT*_{C3}, and over 2 Mg ha^{-1} under *CC_CT*. Adding N190

reduced $Y_{g2\%}^T$ and increased the relative importance of $Y_{g2\%}^{Ns\,eff}$. Although N_s was 24 kg ha⁻¹ lower under CC_NT_{C4} , than ROT_NT , the $Y_{g2\%}^T$ was negative. Such behavior suggests: i) surplus of N_s under ROT_NT ; ii) highest $Y_{g2\%}^{Ns\,eff}$ under CC_NT_{C4} (0.5 vs 0.7 Mg ha⁻¹), compensating 100% of $Y_{g2\%}^N$. While $Y_{g2\%}^{Ns\,eff}$ explained more than 50% of the $Y_{g2\%}^T$ under other CC than CC_NT_{C4} , $Y_{g2\%}^T$ quantified under ROT_CT was explained by $Y_{g2\%}^N$ only.

4.5.4. N fertilizer increase required to reach $Y_{2\%}^{Ref}$ and N fertilizer use efficiency

$Nf\,increase$ (assuming that is possible that every CS could reach $Y_{2\%}^{Ref}$ just by increasing N_s), and $N\,fert\,use\,eff$ under such condition, is shown in Table 4.8.

Table 4.8. N fertilization increase needed to reach the $Y_{2\%}^{Ref}$ ($Nf\,increase = (Y_{g2\%}^T/0.0195) - 190$)) and N fertilizer use efficiency ($N\,fert\,use\,eff = Y_{2\%}^{Ref}/(Nf\,increase + 190)$) estimated under equivalent grain yield and N grain content after 20 year of different cropping systems.

CS	$Nf\,increase$ (kg ha ⁻¹)	$N\,fert\,use\,eff$ (kg kg ⁻¹)
ROT_NT	0.0	45
CC_NT_{C4}	66	33
CC_NT_F	41	37
CC_NT_{C3}	87	31
ROT_CT	66	33
CC_CT	118	28

The $Y_{g2\%}^{ref}$ was obtained using N190, implying an estimated $N\,fert\,use\,eff$ of 45 kg of wheat per kg⁻¹ N added. $Nf\,increase$ needed to reach $Y_{g2\%}^{ref}$ under alternative no-till CS would varied between 41 to 87 kg ha⁻¹, reducing $N\,fert\,use\,eff$ to about

31 to 37 kg ha⁻¹ of wheat per kg⁻¹ N added. ROT_CT had similar *Nf increase* and *N fert use eff* than CC_NT_{C4}. The worst scenario occurred under CC_CT, where N fertilization would be increased by 118 kg ha⁻¹ (total N added would be 308 kg ha⁻¹), reducing N fertilizer efficiency use to 28 kg of wheat kg⁻¹ N added.

4.6. DISCUSSION

The wheat Y_p estimated using the CropSyst model matched well our measured maximum wheat yield (Y_{N190} under ROT_NT and CC_NT_{C4}). Under other cropping systems, we quantified a yield gap between Y_p and the corresponding Y_{N190}. We interpret this result as a change in original soil properties' of a given soil series, defined as a *genoform*, caused by 20 years under different cropping systems, resulting in soils with different properties and productivity, defined as *phenofoms*, (Droogers and Bouma, 1997). By definition, potential yield is achieved under no-limited water and nutrient availability and no biotic stress. Consequently it should not be affected by soil quality, provided there is an ample supply of water and nutrients. However, in our study, when cropping systems reduced physical (MWD and water infiltration rate) and chemical properties (SOC, N and PMN), Y_{N190} was gradually reduced, from 7.1 Mg ha⁻¹ (ROT_NT and CC_NT_{C4}) to 6.1 Mg ha⁻¹ (CC_NT_F, CC_NT_{C3} and ROT_CT) and finally to 5.2 Mg ha⁻¹ (CC_CT) (Fig 4.2). When long-term cropping system affected only soil N concentration and PMN, 100% of Y_g^T could be attributed to nitrogen supply. However, when soil physical properties were affected, Y_g^{others} explained up to 50% of Y_g^T (ROT_NT and CC_NT_{C4} vs CC_CT, Table 4.5).

According to Neumann (2010) and Müller et al., (2012), nitrogen is the most important yield restriction under actual wheat management in the eastern Pampa region. However, Ernst et al., (2018) found that a loss of soil quality in response to long term CS can be detected by decomposing the yield gap in two components, one attributable to nutrient supply (Y_g^N) and one attributable to soil limitations other than nutrients (Y_g^{others}). Our analysis confirmed such yield gap components and added new elements to be considered to address this issue. First, we estimate a Y_{g2%}^T resulting from comparing CS at the same level of N_g. Yield difference between Y_{g2%}^T and Y_g^T

correspond to *available grain N accumulation efficiency* (Huggins and Pan, 1993). We decided an alternative way to include it, correcting measured wheat yield at a given Ng content of 2% ($Y_{2\%}$). Therefore, we estimated a gap resulting from grain quality change. Second, $Y_{g2\%}^T$ has two different components, Y_g^{Ns} and $Y_g^{Ns\,eff}$. Third, the analysis allowed us to estimate the additional N fertilization needed to reach $Y_{2\%}$ obtained under the Reference CS. Forth, it provided an opportunity to quantify the impact of changing soil properties due to long term CS management on *Nf use eff*.

Without Ng content correction, Y_g^T was 1.2, 1.4 and 1.8 Mg ha⁻¹ lower than $Y_{g2\%}^T$, under *ROT_NT*, *CC_NT_F* and averaging *ROT_CT*, *CC_NT_{C3}* and *CC_NT_{C4}*, respectively (Table 4.5 vs Table 4.7). While Y_g^T under estimation under the reference management (*ROT_NT*) resulted from highest Ng content independently from Ns, the other cropping systems showed reduced grain quality (Ng content) at N0 and N80 (Table 4.6). This process implies that reducing soil quality are affecting both, grain yield and food quality.

By decomposing $Y_{g2\%}^T$ in N use efficiency components, we confirm that differences in Ns and *Ns eff* were involved in wheat yield response to soil properties' resulting from long-term cropping systems effect yet under no water restrictions (Table 4.7). The $Y_{g2\%}^T$ under N0, corresponds to differences estimated in *soilNs* and *soilNs eff* only. Under such condition, our analysis attributed 100% of the $Y_{g2\%}^T$ estimated under *ROT_NT* to *soilNs* ($Y_{g2\%}^{Ns}$) (Table 4.7). $Y_{g2\%}^{Ns}$ and $Y_{g2\%}^{Ns\,eff}$ under N0 estimated under the other cropping systems had two components: i) yield difference due to *soilNs* difference (ΔNs); ii) yield difference due to *Ns use eff*. For example, the difference in $Y_{g2\%}^T$ between *ROT_NT* and *CC_NT_{C4}* under N0 was 1.3 Mg ha⁻¹ (4.9 vs 3.6 Mg ha⁻¹, Table 4.6) from which only 0.5 Mg ha⁻¹ can be attributed to 24 kg ha⁻¹ of difference in *soilNs* (125 vs 101 kg ha⁻¹ for *ROT_NT* and *CC_NT_{C4}*, respectively). The rest (0.8 Mg ha⁻¹) would correspond to $Y_{g2\%}^{soilNs\,eff}$. Taking into account only the *soilNs* under *CC_CT* (67 kg ha⁻¹), corresponding $Y_{2\%}$ would be only 1.1 Mg ha⁻¹ lower than the reference CS. However, we measured an additional difference estimated in 1.2 Mg ha⁻¹, attributable to $Y_{g2\%}^{soilNs\,eff}$ (2.3 vs 1.1

Mg ha⁻¹). Increasing *Ns* by applying the most frequent N fertilizer dose currently used by wheat producers in the region (N80), resulted in a reduction of $Y_{g2\%}^T$ explained mainly by the decrease of $Y_{g2\%}^{Ns}$, while $Y_{g2\%}^{soilNs\ eff}$ was maintained or increased in most cropping systems (Table 4.7). It is remarkable that $Y_{g2\%}^T$ under ROT_NT N80, was 30% below the benchmark yield (8.56 vs 6.05 Mg ha⁻¹). Considering the “exploitable yield” definition as 80% of *Yp* (Cassman et al., 2003; Lobell et al., 2009), the exploitable yield in our study would be 6.8 Mg ha⁻¹, which is only 0.79 Mg ha⁻¹ more than the ROT_NT N80 yield. N fertilization rates currently used by most producers (N80) would be operating as a wheat yield restriction even under our reference CS, but more severely under the most frequent cropping systems implemented by wheat producers in the region during the last 15 years (*CC_NT_F* and *CC_NT_{C3}*). Our results agree with those reported by Müller et al., (2012), who found that nitrogen is the most important yield restriction under actual wheat management in the eastern Pampa region. We quantified that the N fertilization rate required to reach *Ymax* increased when long term cropping systems reduced soil quality (Table 4.8). Such effect cannot be explained only by reduced *soilNs* since we estimated a strong reduction in N fertilizer use efficiency (Table 4.8). To close the exploitable yield gap, the amount of N fertilizer applied would have to increase by at least 80 kg ha⁻¹ above the current rate of 80 kg ha⁻¹ under *CC_NT_F* and *CC_NT_{C3}*, while under ROT_NT just adding 40 kg ha⁻¹ more would be enough. Increased N fertilizer required to reach the same yield implies increased N losses risk by leaching and/or N emissions.

Crop rotation is an ancient cultural management practice (Russell et al., 1987) that maintains or improves soil quality. Our reference CS (*ROT_NT*), maintained soil aggregates stability and water infiltration rate at highest levels, which summed to PMN > 20 mg *NH₄⁺* provided more N from the soil, requiring less N fertilizer to reach the *Ymax*. Compared to the traditional *ROT_CT*, widely used until the end of the 20th century in the eastern Pampa region, ROT_NT represents a step towards sustainable intensification, from soil conservation and nutrient use efficiency point of view. However, driven by increasing soybean prices, soybean became the dominant crop in Uruguay, Argentina, Bolivia, Paraguay and Southern Brazil (Rio Grande do Sul, Santa

Catarina, and Parana States), representing 63% of total cultivated area versus 19% and 12% of maize and wheat respectively (FAOSTAT 2016). This new dominant CS is well represented by CC_NT_F and CC_NT_{C3} treatments in this study. Our results suggest that this shift of production systems described by Franzluebbers et al., (2014) and Wingeyer et al., (2015), despite its economic justification (Ernst et al., 2018), implied an intensification pathway that cannot be qualified as sustainable.

One of the pillars of ecological intensification proposed by Cassman (1999) is the maintenance or improvement of soil quality, defined as the capacity of soils to sustain biological productivity (soil productivity function), while ensuring environmental, plant and animal health (Doran and Parkin, 1994; Blum. 2005). Our results suggest that progress towards a sustainable intensification of agriculture under a continuous no-till cropping system, requires that at least part of actual proportion of soybean (CC_NT_{C3}) must be substituted by sorghum and corn (CC_NT_{C4}). Although it is true that soil N supply (estimated by PMN) would be reduced, soil physical properties, well represented by INF and MWD, would remain above a critical level, and Y_{max} could still be reached by adjusting N fertilization rates. Stable soil aggregates are critical for sustainable agroecosystems, due to their influence on several soil biological and physical processes such as root growth and water and air movement that, in turn, directly affect crop productivity (Kasper et al., 2009). Our results provides evidence that INF and MWD should be maintained approximately over 2.0 cm day⁻¹ and 1.3 mm, respectively (Table 4.4).

4.7. CONCLUSIONS

Only two continuous no_till systems reached the Y_{max} , double annual cropping rotating with a three year of pasture, and continuous double annual cropping under no-till including high frequency of grain sorghum and maize during summer season (ROT_NT and CC_NT_{C4} respectively). However, soil N supply quantified by wheat yield under N0 was highest under ROT_NT , implying an increased yield gap attributed to N supply when pasture was replaced by CC_NT_{C4} . Reduced soil PMN would be the soil property affected negatively by this CS. An intrinsic loss of soil quality associated to soil physical properties (expressed through INF and MWD),

limited wheat yield under other than CC_NT_{C4} , yet adding maximum N fertilizer, generating an additional Y_g no attributable to nutrient supply (Y_g^{others}) directly.

Wheat yield response to soil quality changes generated by long term cropping systems implied reduced grain N concentration, therefore an additional grain gap quality to be compensated by additional N fertilizer. This process implies that reducing soil quality N fertilizer efficiency use is reduced, affecting both, grain yield and food quality. This hidden soil degradation form would be operating under the more frequent CS in the Pampas region.

4.8. REFERENCES

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5. SÍNTESIS Y CONCLUSIONES GENERALES

La calificación de “intensificación” que da marco a esta tesis refiere al aumento de producción de grano por unidad de tiempo que se logra al alargar la fase agrícola (agricultura continua). El indicador utilizado para cuantificar el grado de intensificación es el número de años de agricultura continua después de la última fase con pastura perenne en la rotación (*YCC*). No obstante, aun aumentando la cantidad de producto (grano) por unidad de insumo, el proceso no puede calificarse como sostenible si la base de recursos naturales se degrada en el proceso de producción (Garnett y Godfray, 2012), y nuestros resultados muestran que esto está sucediendo con el suelo en los sistemas de producción agrícola implementados en Uruguay.

El análisis de los registros de productores de trigo (Artículo 1) confirman que el proceso de intensificación implementado generó una reducción cuantificable tanto en el rendimiento alcanzable (Y_{att}) como en el rendimiento actual (Y_a) cuando las condiciones climáticas entorno al período crítico de definición del rendimiento de trigo no fueron favorables para el cultivo. Esta interacción representa un incremento del riesgo de producción frente a la variabilidad climática. El efecto negativo de *YCC* sobre el Y_{att} de trigo se acentuó en condiciones climáticas equivalentes a primaveras con precipitaciones y temperaturas superiores a la media en torno al período crítico de definición del rendimiento y durante el llenado de grano (Cuadro 2.1, Fig. 2.4), desapareciendo bajo condiciones ambientales favorables. Los mayores Y_{att} se lograron cuando el trigo se sembró en chacras con 5 o menos *YCC* (promedio = 6,0 Mg ha⁻¹). En estos casos, el Y_{att} se mantuvo alto de manera independiente de las condiciones climáticas. En tanto, alargando la fase agrícola a más 5 años, el Y_{att} se mantuvo entre 5,5 y 6,0 Mg ha⁻¹ sólo bajo condiciones de ambiente favorables para el cultivo, siendo menor a 4 Mg ha⁻¹ en chacras con *YCC* > 5 y ambiente climático desfavorable. La tendencia prevista en el cambio climático global para esta región implica un incremento de la temperatura media y las precipitaciones del período en el cual se ubica la definición del rendimiento de trigo (Baethgen y Magrini 1995, Baethgen et al., 2003). Tales condiciones implican un aumento de la frecuencia de ocurrencia de ambientes calificados como de bajo rendimiento (*LYE*), por lo que su interacción con

YCC resulta en un atributo negativo para la sostenibilidad del proceso de intensificación, ya que incrementa el riesgo inherente a la producción.

El hecho de que el efecto negativo sobre el Y_a sea reducido significativamente ($p \leq 0,05$) sólo en años en los que las condiciones de lluvia y temperatura determinan menor rendimiento (Cuadro 2.2), es una dificultad para que productores y asesores técnicos identifiquen el efecto negativo de YCC ya que, en general, se tiende a adjudicar el 100% de la reducción del rendimiento a las condiciones climáticas desfavorables del año. Por otro lado, la pérdida de rendimiento resultó importante cuando se comparan fases agrícolas con duración contrastante, lo que implica que las más cortas están en rotación con pasturas. Comparando el Y_a de trigo sembrado como cabeza de rotación ($YCC = 1$) en un año climáticamente desfavorable contra Y_a cuando el cultivo se sembró en un sistema con $YCC = 10$, la diferencia media esperada es de 560 kg ha^{-1} . En tanto, sólo sería de 56 kg ha^{-1} comparando $YCC = 9$ contra $YCC = 10$. Adicionalmente, no hubo diferencias en el Y_a en años con condiciones climáticas favorables, lo cual dificulta aún más la valoración del problema. El rendimiento medio está afectado por otras ineficiencias asociadas, como la fertilización nitrogenada y el antecesor (Figura 2.4). Por tanto, considerando el efecto de YCC sobre los rendimientos máximos (Y_{att}), donde las ineficiencias de producción son las mínimas, la diferencia esperada entre trigo sembrado sobre situaciones con $YCC \leq 4$ contra situaciones con $YCC > 7$ en condiciones de LYE, fue de $1,0 \text{ Mg ha}^{-1}$ ($4,5$ contra $3,5 \text{ Mg ha}^{-1}$ respectivamente, Fig. 2.3).

La reducción en el Y_{att} al aumentar YCC sería la respuesta del cultivo a una progresiva pérdida de calidad del suelo, siendo posible descartar que este efecto se explique por el cultivo antecesor, efecto que sólo se cuantificó bajo HYE (NT4 y NT6, Fig. 2. 4).

Los resultados de los experimentos realizados en chacras de productores de trigo sobre suelos similares, seleccionadas evitando que el cultivo antecesor del invierno previo fuera trigo o cebada y protegiendo el cultivo para evitar enfermedades, malezas y plagas, confirman que el efecto negativo de YCC es independiente de factores bióticos reductores del rendimiento. Tal efecto negativo tiene dos componentes: i) durante los primeros 4-5 años pos pastura, se produciría una reducción

gradual en el aporte de nutrientes del suelo, denominado brecha por nutrientes ($Y_g^{nutrients}$), que puede ser controlado incrementando la fertilización; y ii) cuando $YCC > 5$, se cuantificó una brecha de rendimiento, denominada brecha no directamente atribuible al menor aporte de nutrientes (Y_g^{others}), que no fue posible controlar por aumento en la fertilización. Esta brecha llegó a ser el 40% de la brecha total (Y_g^T) en chacras con $YCC = 10$ (Fig. 3.4, Cuadro 3.5). Los resultados coinciden con los obtenidos a partir de registros de productores de trigo integrantes del movimiento CREA (Artículo 1). La fertilización nitrogenada es una de las variables asociada a la brecha entre Y_{att} y Y_a de manera independiente de las condiciones climáticas, y sería de mayor importancia relativa que YCC (segundo nivel de clasificación en la Fig. 2.4).

La primera etapa de degradación correspondería a menor aporte de nitrógeno del suelo, asociado a la reducción cuantificada en el potencial de mineralización de nitrógeno del suelo (PMN). En tanto, en la segunda etapa, cuando $YCC > 5$, se sumarían efectos sobre condiciones físicas, cuantificada como una reducción significativa en la tasa de infiltración de agua en el suelo (Cuadro 3.6). La Y_g^T cuantificada comparando la frontera de rendimiento de trigo (Y_F^+) sembrado sobre rastrojo de soja de estación completa (de primera) con $YCC = 10$ contra el trigo sembrado como cabeza de rotación ($YCC = 1$) fue de $2,5 \text{ Mg ha}^{-1}$, de los cuales sólo $1,5 \text{ Mg ha}^{-1}$ pueden atribuirse al déficit de nutrientes. Sin tener como referencia el rendimiento de trigo logrado en los primeros años pos pastura, la brecha cuantificada sería sólo de $1,5 \text{ Mg ha}^{-1}$, lo cual enmascara el efecto negativo anual, que acumulado en el período, fue de $1,0 \text{ Mg ha}^{-1}$ adicional (artículo 2, Cuadro 3.5).

El deterioro en las propiedades físicas y menor aporte de nitrógeno desde el suelo explicarían la interacción entre YCC y precipitaciones en torno a espigazón y llenado de grano (Fig. 2.3). También en la región se han cuantificado efectos negativos de esquemas de agricultura continua sin labranza sobre la infiltración (Álvarez et al., 2014), la conductividad hidráulica (Aparicio y Costa, 2007) y estabilidad y tipo de estructura de la capa superficial del suelo (Novelli et al., 2013, Sasal et al., 2017). Tales condiciones, enfrentadas con lluvias excesivas, generarían un ambiente desfavorable

para el crecimiento de raíces y favorecen pérdidas de la ya disminuida capacidad de suministro de nitrógeno.

El PMN y la tasa de infiltración de agua (INF) también estuvieron relacionadas con la brecha de rendimiento atribuida a nitrógeno (Y_g^N) e Y_g^{others} en el experimento de largo plazo, a lo que se sumó la estabilidad de los agregados de la capa superficial del suelo (MWD), una variable cuantificada sólo en este experimento (Artículo 3, Cuadro 4.4).

Es importante distinguir el marco en el cual se obtuvieron los resultados. Los obtenidos a partir de registros (Artículo 1) y experimentación en chacras de productores de trigo (Artículo 2), corresponden a efectos acumulados por la secuencia de cultivos implementada a nivel de producción en los últimos 10 años (período 2003-2013). En tanto, los obtenidos en el experimento de largo plazo (Artículo 3) corresponden al efecto residual de 20 años consecutivos (1993-2013) de manejo diferencial de la labranza, rotación o no con pasturas y cultivos dentro de la fase agrícola sobre las propiedades del suelo. Luego de 20 años todos los tratamientos pasaron a ser manejados sin laboreo, por lo que se cuantificó la respuesta del trigo a suelos con propiedades diferentes, que inicialmente eran iguales, bajo las mismas condiciones de clima. Ni la rotación con pasturas ni la secuencia de cultivos de este experimento representan el escenario de producción dominante a inicios de este proyecto. Bajo esta consideración, la rotación cultivos-pasturas sin laboreo (ROT_NT), en una relación 50% del tiempo para cada componente (3,5 años), y uno de los sistemas de agricultura continua, que tuvo alta frecuencia de cultivos con metabolismo C4 (sorgo y maíz) durante el período (CC_NT_{C4}), fueron los únicos sistemas que lograron mantener las propiedades del suelo a un nivel capaz de no operar como un factor limitante del rendimiento. Por tanto, un sistema con $Y_{CC} = 20$ logró el mismo rendimiento máximo (Y^{max}) que uno que estuvo sólo 10 años con agricultura sin laboreo en igual período, rotando con 10 años de pastura (ROT_NT). La diferencia en el rendimiento entre estos dos sistemas (Y_g^T) corresponde 100% a brecha generada por déficit de nitrógeno (Y_g^N), lo cual implica mayores necesidad de fertilización nitrogenada en agricultura continua para alcanzar un Y^{max} similar a la rotación cultivos-pasturas (Cuadro 4.7 y 4.8). Los demás sistemas evaluados no lograron

mantener la capacidad de producir, generándose una brecha no atribuible directamente a suministro diferencial de nitrógeno (Y_g^{others}), pero sí al efecto que la pérdida de calidad del suelo genera sobre el aporte de nutrientes y su eficiencia de uso.

Los resultados remarcen que el suministro de nitrógeno del suelo está explicando total ($YCC \leq 5$) o parcialmente ($YCC > 5$) el efecto negativo de YCC sobre el rendimiento de trigo, y que la cantidad de nitrógeno agregado como fertilizante, ya sea con los criterios utilizados por los productores CREA (Artículo 1) o aplicando estrictamente los actuales criterios para recomendar la fertilización nitrogenada (Hoffman et al., 2010, Artículo 2), no es suficiente para compensar el incremento de Y_g^N generado por el proceso de intensificación implementado a nivel productivo.

El efecto residual de distintos manejos aplicados sobre un mismo suelo y una misma oferta de factores que definen el rendimiento implica que el rendimiento potencial (Yp) de las seis alternativas evaluadas en el experimento de largo plazo es el mismo. Sin embargo, el Y^{max} fue estadísticamente diferente ($P \leq 0,05$) entre ellos, y sólo dos (ROT_NT y CC_NT_{C4}) lograron un valor cuantitativamente similar al Yp estimado con el modelo de simulación Cropsyst.

Existe una aparente discrepancia entre los resultados obtenidos en los experimentos instalados en chacras de productores, en los que YCC generó una reducción del rendimiento cuantificado como Y_g^{others} y los obtenidos después de 20 años de CC_NT_{C4} , en el que el 100% de Y_g^T se atribuye a nutrientes (Artículo 2, Cuadro 3.5 contra Artículo 3, Cuadro 4.7). Si bien la forma de cálculo tiene un valor de referencia distinto porque en las chacras se trabajó sólo con aporte de agua por precipitaciones y en el experimento con condiciones definidas como “agua no limitante”, 20 años de agricultura continua con alta frecuencia de soja tanto como doble cultivo como con barbecho invernal (CC_NT_{C3} y CC_NT_F respectivamente), que representan de mejor manera los sistemas implementados a nivel productivo, también generaron una Y_g^{others} que explicó entre el 30 y 40% del Y_g^T (Artículo 3, Cuadro 4.5).

Los resultados obtenidos en el proyecto sugieren que: i) Y_g^{others} resulta del efecto que el deterioro de propiedades físicas del suelo tiene sobre: a) la eficiencia de uso de una reducida tasa de aporte de N desde el suelo durante todo el ciclo del cultivo,

b) el control de la dinámica del agua y el oxígeno en el suelo tanto por exceso como por déficit, c) la combinación de ambos; ii) para cualquiera de las alternativas, asumiendo que es posible alcanzar un Y^{max} equivalente al obtenido después de 20 años de *ROT_NT* y *CC_NT_{C4}* sería necesario fertilizar con más de la dosis máxima evaluada (190 kg ha^{-1} de N)(Cuadro 4.8); y iii) que un sistema de agricultura continua sin laboreo capaz de mantener las propiedades físicas del suelo (en nuestro caso, tasa de infiltración y estabilidad de agregados) a un nivel igual o superior a un “valor crítico”, como podría deducirse de la Figura 1.2, no implica una pérdida de la capacidad de producir del suelo, aunque sí afecta la eficiencia de uso de los nutrientes cuantificada como Y_g^N .

La eficiencia media de recuperación del nitrógeno suministrado (N_s), (N absorbido/ nitrógeno suministrado por el suelo más fertilizante), (Cuadro 4.6, Artículo 3) fue del 65%. Considerando la fertilización adicional necesaria bajo *CC_NT_F* y *CC_NT_{C3}* para obtener un rendimiento equivalente a *ROT_NT* (Cuadro 4.8, Artículo 3), se generan 30 kg ha^{-1} de N adicionales no recuperados, lo que supone un riesgo incrementado de contaminación por pérdidas por lixiviación y/o emisiones gaseosas.

La secuencia de cultivos dominante en la superficie agrícola de Uruguay varió a lo largo del período 2002-2013, pero estuvo mayoritariamente compuesta por doble cultivo trigo/soja (25%), barbecho invernal/soja (45 %) y barbecho invernal/maíz (10%). El restante 20% lo compusieron un 7% de superficie sembrada con praderas y otras combinaciones de cultivos.

Nuestros resultados indican que la racionalidad económica que justificó el proceso de intensificación generado por el cambio desde el sistema más frecuente a fines del siglo XX, representado por *ROT_NT*, a agricultura continua (Fig. 3.5, Artículo 2), no puede calificarse como intensificación sostenible, ya que contradice sus pilares fundamentales propuestos por Cassman (1999).

Si bien es esperable que tanto la pérdida de calidad del suelo como la respuesta en reducción del Y_{alc} tiendan a un nuevo equilibrio, esto no parece haber sucedido aun después de $YCC = 10$ (Artículo 2 Fig. 3.4) y después de 20 años podría alcanzar un nivel de la degradación que implicaría que la calidad del suelo, además de un factor

limitante del rendimiento de trigo producido en condiciones de secano, afecte económica y ambientalmente la posibilidad de producirlo.

5.1. INTERPRETANDO EL PROCESO DE INTENSIFICACIÓN EN FUNCIÓN DE LOS RESULTADOS DEL PROYECTO

La historia de la agricultura en Uruguay puede ser vista como un largo proceso de intensificación, en el cual sus principales hitos fueron: máxima superficie agrícola a fines de la década de 1950; adopción generalizada de la rotación cultivos-pasturas con contracción de la superficie agrícola e inicio de la fase de crecimiento de los rendimientos a fines de la década de 1970; incorporación de tecnología asociada a la revolución verde durante la década de 1980 (germoplasma, fertilizantes, defensivos agrícolas); e incorporación de la siembra directa en la última década del siglo XX. Tomando como referencia al cultivo de trigo, entre el primer y último hito el rendimiento medio nacional se triplicó (Ernst y Siri-Prieto 2011).

En el siguiente diagrama se esquematizan sobre una línea de tiempo, los principales cambios cuantificados en la agricultura de Uruguay (Figura 5.1).

	Agricultura continua con laboreo	Agricultura-pastura con laboreo	Agricultura-pastura sin laboreo	Agricultura continua sin laboreo
Período	1940-1955	1970-1980	1990-2002	2002-----
Superficie (ha)	>1.000.000	< 700.000	< 500.000	>1.000.000
Productores (No)	> 20.000	< 3.000	<1500	<1300
Rendimiento (Mg ha ⁻¹)	1000	2500	3000	¿?
Erosión	alta	Control de erosión	Control de erosión	¿?
Carbono del suelo	Pérdida	Incremento	Incremento	¿?
Propiedades físicas	Deterioro	Mejora	Mejora	¿?
Ubicación		Regionalización	Regionalización	Expansión
Insumos		40 kg N /ha	70 kg N /ha Herbicidas Fungicidas	100 kg N /ha Herbicidas Fungicidas Insecticidas

Figura 5.1. Representación esquemática de los cambios en el uso y manejo de suelos en la agricultura de secano de Uruguay y de algunos indicadores que los caracterizan (Ernst y Siri-Prieto 2011).

Hasta mediados del siglo pasado la agricultura se realizó en un sistema de cultivo que se puede definir como “agricultura continua con laboreo”, representado en esta Tesis por *CC_LC*. Se caracterizó por un estancamiento en los niveles de producción, con un rendimiento medio de trigo de menos de $1,0 \text{ Mg ha}^{-1}$ asociado, entre otras causas, al deterioro de la calidad del suelo producido por el propio sistema de producción y manejo del suelo. En las décadas de 1970 y 1980, el esquema cambió a un sistema de rotación de cultivos con pasturas perennes sembradas (*ROT_LC*). Este cambio estuvo asociado a una fuerte reducción del área sembrada (de más de 1.000.000 ha a menos de 700.000 ha), del número de productores (de más de 20.000 a menos de 3.000 productores), y a la regionalización del cultivo en el país. La agricultura se localizó en el litoral sur-oeste, el esquema de producción permitió reducir las pérdidas de suelo por erosión y mejorar la calidad del suelo deteriorada en la etapa anterior. Este cambio, sumado a la incorporación de tecnología en el cultivo, permitió más que duplicar los rendimientos del cultivo tomado como referencia (trigo), el que pasó de $1,0$ a $2,5 \text{ Mg ha}^{-1}$ promedio.

El período siguiente (1990-2002) se caracterizó por la adopción de la siembra sin laboreo (*ROT_NT*), lo que permitió reducir aún más el riesgo de erosión del suelo y pérdida de productividad. El esquema general siguió siendo agrícola-ganadero en rotación, ubicado en las regiones agroecológicas I y II (Corsi 1982). El rendimiento medio de trigo alcanzó en ese período $3,0 \text{ Mg ha}^{-1}$ si no se consideran los bajos rendimientos determinados por los problemas sanitarios y climáticos de los años 2001 y 2002. Nuevamente, el número de productores se redujo y la superficie sembrada llegó a los mínimos registrados desde 1950.

A partir del 2002, y siguiendo la tendencia de la región, la agricultura volvió a expandirse. La superficie afectada a la producción de cultivos anuales creció como resultado de dos procesos: intensificación agrícola, caracterizada por aumento de *YCC* en el zona tradicional (litoral oeste) y expansión hacia nuevas zonas con potencial agrícola, tradicionalmente ganaderas, bajo el mismo sistema de cultivo. Se sustituyó el sistema *ROT_NT*, característico del litoral oeste, por agricultura continua dominada por soja, combinada con trigo en una proporción variable. En nuestro trabajo, este cambio está representado por *CC_NT_F* y *CC_NT_{C3}*. Este cambio se produjo asociado a

la implementación del concepto de agronegocio, con el mínimo histórico de productores, la mayoría de los cuales no existían en el 2002, cuando comenzó el proceso de intensificación (Arbeletche y Carballo 2007).

En la parte inferior de la Figura 5.1, se presentan los cambios en las cantidades medias de fertilizante nitrogenado y agroquímicos utilizadas para producir trigo, lo que refleja que el sistema de producción se hizo más dependiente del ingreso de insumos para sostener el incremento de rendimientos.

5.2. OPCIONES DE INTENSIFICACIÓN Y LA FUNCIÓN “PRODUCTIVIDAD DEL SUELO”

5.2.1. Aportes a la comprensión del problema

El concepto de intensificación sostenible es más amplio que la mirada estrecha que supone intensificar la producción de un cultivo, por lo que tiene puntos de contacto con conceptos como los de “intensificación ecológica” (Bommarco et al., 2013, Tiftonell, 2014), “sistemas agrícolas diversificados” (Diversified farming systems, DFS) (Kremen et al., 2012), y “agricultura climáticamente inteligente” (Climate Smart Agriculture), (Campbell et al., 2014). En cualquiera de éstas definiciones, analizadas y discutidas por estos autores, la construcción del camino de intensificación requiere de sistemas agrícolas diversificados, con adaptación local, planificación y sistemas de gobernanza que se sustenten en la información generada a nivel empírico por parte de los productores y empresas de servicios, y a nivel científico, por parte del sistema regional de investigación e innovación.

A nivel global, el incremento de la demanda de alimentos prevista para los próximos años debe ser logrado en la superficie agrícola actual, ya que la incorporación de nuevas áreas supone costos ambientales altos (Garnett y Godfray 2012). Esto genera conflicto entre objetivos que pueden ser total o parcialmente contrapuestos: incrementar la producción de la superficie actual, diversificar el sistema de producción, reducir el uso de insumos, aumentar su eficiencia de uso, producir lo que se requiere en el mercado mundial, mejorar la equidad social, incrementar la tasa

de ganancia y el ingreso, reducir el impacto ambiental. En la valoración de la sostenibilidad, la producción de alimentos se ubica entre culpable y víctima de los daños ambientales. Por tanto, el desarrollo de estrategias de intensificación sostenible necesita de indicadores de referencia, que guíen tanto el proceso de investigación como su implementación a nivel de los sistemas de producción comerciales. Un indicador provee de información para entender y manejar los sistemas en función de sus impactos, su performance ambiental y su resiliencia (Doran et al., 1996).

Dentro de los nueve atributos deseables para que un proceso de intensificación sea sostenible, (Hochman et al., 2013), está aumentar la producción de alimentos por unidad de área. Su priorización responde a la valoración de que la superficie afectada a la producción es, a nivel global, el recurso limitante. Y la superficie afectada no es un problema de m², sino de captura y uso de recursos (radiación, agua, nutrientes). Por tanto, los procesos que los afecten, condicionan su sostenibilidad. Acoplar este objetivo con los demás atributos es un desafío que requiere establecer “*umbrales de permisividad*” (hasta cuanto se puede afectar una propiedad) y un orden jerárquico de restricciones de prácticas agrícolas a implementar para mantenerse dentro del rango establecido. Los primeros deben surgir de los programas de investigación y las segundas, supone implementar estrategias que promuevan su aplicación, integrando los conceptos guía para la implementación de buenas prácticas agrícolas.

En la Figura 1.2 se presentó un diagrama teórico (Cassman 1999), mostrando la relación entre la calidad del suelo e insumos necesarios para lograr distintos niveles de producción. En su artículo, Cassman (1999) lo utiliza para plantear la necesidad de implementar agricultura de precisión, ajustando la cantidad de insumos a agregar de manera variable, en función del *Yatt* de cada sitio. Posteriormente, y en base a este concepto, Tittonell y Giller (2013) propusieron un esquema sobre los cambios a implementar en las reglas de decisión para la fertilización en base a “nichos de fertilidad del suelo dentro de granjas heterogéneas”, planteando como desafío, identificar tres categorías de suelos: i) fértiles sin respuesta; ii) baja respuesta pero productivo; iii) degradado sin respuesta. Estos tres niveles resultan de la historia del uso del suelo y su gestión actual. En ambos trabajos se propone que la asignación de

insumos se ajuste, para un mismo ambiente biofísico, en base a la restricción impuesta por la calidad del suelo (dotación de recursos).

En esta Tesis se aplican estos conceptos, pero para cuantificar el efecto que tiene el sistema de cultivo aplicado en el mediano plazo (10 a 20 años) a un mismo suelo original, sobre la evolución de su calidad, transformándolo en suelos con propiedades muy diferentes al original. Siguiendo la definición propuesta por Droogers y Bouma (1997), pasar desde un *genoform* a un *fenofom*.

En base a los resultados obtenidos en esta Tesis, la Figura 1.2 se modifica, cuantificando la respuesta al incremento en la necesidad de insumos para lograr un mismo rendimiento como un efecto negativo y no como respuesta positiva con distintas pendientes (Figura 5.2).

El sistema de diagnóstico y recomendación actual es sensible al sistema de manejo del suelo, lo que determina un incremento en la cantidad media de fertilizante nitrogenado a agregar durante el ciclo del cultivo de $5 \text{ kg ha}^{-1} YCC^{-1}$ (Artículo 2, Figura 3.2). En un sistema en que la fase agrícola dura hasta 4 años (Sector I del esquema), implica que el último cultivo recibirá unos 20 kg ha^{-1} más de N que el primero, pero que será capaz de obtener el Y_{att} . En este caso, el 100% del Y_g se neutraliza aumentando la fertilización nitrogenada bajo los criterios de diagnóstico y recomendación actual. Cuando el Y_g^{others} comienza a incrementarse por deterioro de la calidad del suelo, el sistema vuelve a la fase pasturas, reiniciándose el ciclo.

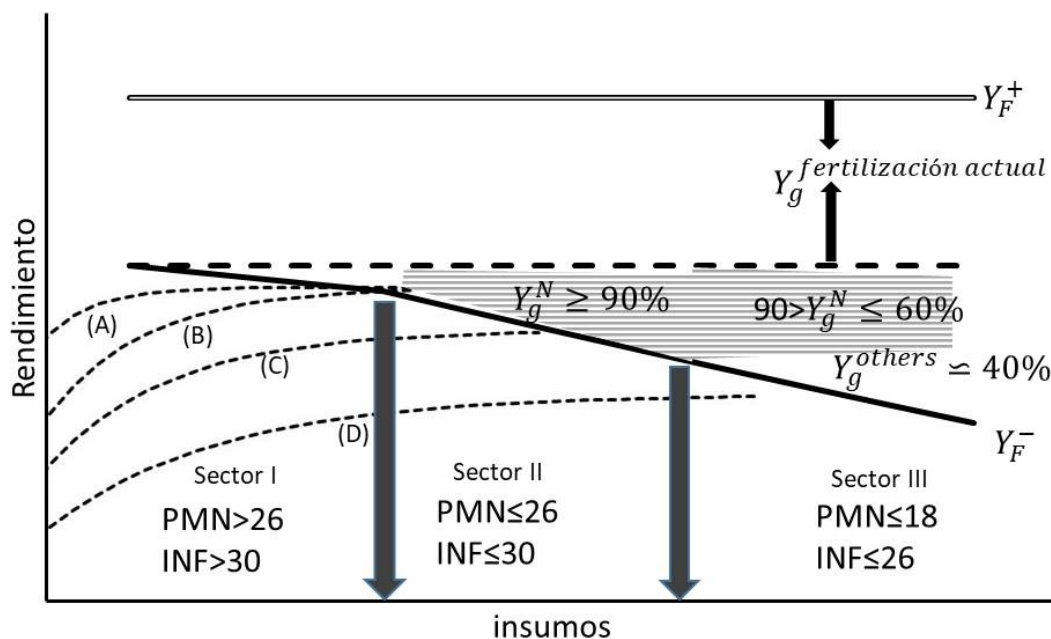


Figura 5.2 Diagrama que describe la relación entre la calidad del suelo afectada por la rotación de cultivos y manejo del suelo y los requerimientos de insumos (N) para el Y_{att} , Y_F^+ o Y_{max} . (A), (B), (C) y (D) corresponden a las curvas de respuestas del esquema propuesto por Cassman, 1999 (Figura 1.2). La línea punteada superior indica el rendimiento objetivo definido como Y_{alc} (Artículo 2 o 3, respectivamente). En la línea de respuesta (A) se ubica el Y_{att} (Artículo 1), equivalente a Y_F^- (Artículo 2) de trigo integrando la fase agrícola de un sistema en que la agricultura rota con pasturas sembradas plurianuales compuestas por gramíneas y leguminosas, sin labranza (ROT_NT). Tal como lo definen Fischer y Edmaedes, (2010), la distancia entre ambas resulta de corregir la oferta de nutrientes (N) fertilizando acorde a los actuales criterios de recomendación (Hoffman et al., 2010), que contemplan el riesgo económico y de producción al definir la dosis a aplicar.

En base a esquema de diagnóstico y fertilización actuales.

Cuando la fase agrícola se prolonga hasta los 5-6 años pos pastura, las necesidades de fertilización nitrogenada continúan creciendo, elevándose a 30 kg ha^{-1} , pero el incremento en la dosis recomendada actualmente no permite alcanzar el Y_{att} (Sector II, curva C). En esta fase, la falla radicaría en la cantidad a agregar, ya que aún

sería posible alcanzar el Y_{att} . ($Y_g^N \geq 90\%$). Por tanto, coincidiendo con Hoffman et al., (2017), el problema radica en que la propuesta actual fue desarrollada en un escenario de producción en que el trigo rotaba con pasturas (ROT_NT) y no se ajusta a sistemas con fases agrícolas más largas. También Angus (2001) y Angus y Peoples (2012) discuten el impacto de la supresión de la fase pastura sobre el aporte de N desde el suelo para las condiciones de Australia.

En sistemas de agricultura continua ($YCC > 6$), se establecen escenarios diferentes en función de: i) manteniendo las propiedades físicas del suelo (INF, MWD) en un nivel superior a un valor crítico; ii) propiedades físicas por debajo del nivel crítico. Para el primer caso, logrado con una rotación de cultivos diversificada, incluyendo alta frecuencia de sorgo y maíz (CC_NT_{C4}), los requerimientos de fertilización nitrogenada para lograr el Y_{att} , crecen en un 35% (Artículo 3, Cuadro 4.8) y, con esta consideración, integraría también el Sector II del esquema. Para el segundo caso, se genera un Y_g^{others} de hasta 40% del Y_g^T (Sector III, entre curvas de respuesta C y D). Asumiendo que sería posible alcanzar el Y_{att} incrementando la fertilización con N, nuestra estimación sugiere que serían necesarios más de 300 kg ha^{-1} , y sólo bajo situaciones en que el rendimiento no es limitado por agua.

Mientras que el camino de intensificación implementado en el pasado reciente, intenta “borrar” los problemas autogenerados incorporando un subsidio de energía (fertilizante nitrogenado fungicidas, herbicidas), existen sistemas alternativos diversificados (ROT_NT y CC_NT_{C4}) que reducen su dependencia.

La magnitud y composición relativa del Y_g son reflejo de servicios ecosistémicos afectados por el sistema de cultivo. El Programa Evaluación de los Ecosistemas del Milenio (2015) define servicios ecosistémicos como beneficios que los seres humanos obtienen desde los ecosistemas, agrupándolos en i) servicios de soporte, como ciclado de nutrientes y formación de suelos; ii) servicios de regulación, como control de enfermedades, polinización de cultivos, regulación del clima y purificación del agua; iii) provisión de servicios, como alimentos, fibras, agua, combustible; y iv) servicios culturales, como educación, recreación y valor estético.

Tomando el esquema conceptual de Bommarco et al., (2013), los cambios determinantes de la intensificación observados en la región desde la rotación con

pasturas sin labranza (*ROT_NT*) a sistemas agrícolas modificaron los servicios ecosistémicos que regulan y soportan el servicio priorizado (o más valorado por el mercado), que es el rendimiento en grano (Figura 5.3).

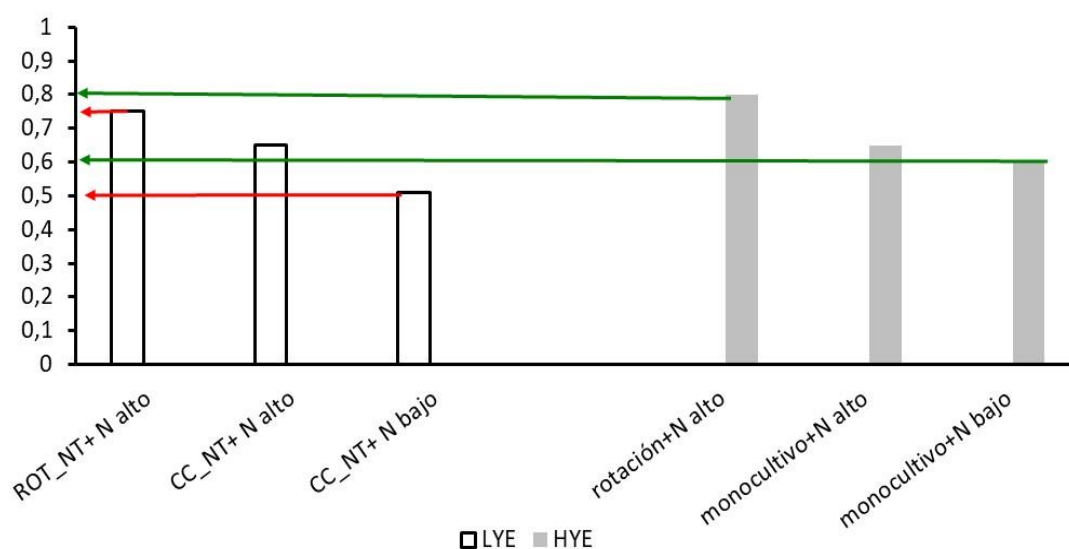


Figura 5.3. Rendimiento actual de trigo relativo al rendimiento alcanzable para ambientes de bajo rendimiento (LYE) y alto rendimiento (HYE) en función de la rotación y la fertilización nitrogenada en sistemas sin labranza. Monocultivo: trigo sembrado sobre rastrojo de trigo o cebada del año anterior de manera independiente al cultivo de verano previo. Rotación: trigo sembrado sobre pasturas, secuencia barbecho invernol/cultivos de verano, cultivo de cobertura invernol/cultivo de verano (break crops); N bajo y N alto refiere a la fertilización nitrogenada total agregada al cultivo. *CC_NT*= agricultura continua sin laboreo. *ROT_NT*: agricultura rotando con pastura sin laboreo. Rendimiento alcanzable en LYE=4,6 Mg ha⁻¹; Rendimiento alcanzable en HYE=5,2 Mg ha⁻¹. Líneas verdes y rojas indican el rango de variación de rendimiento definido el servicio afectado por el sistema de producción. (elaborado a partir de la Figura 2.4, Artículo 1).

En LYE el Y_a está limitado por nitrógeno (servicio de soporte) aunque otros servicios estén a un nivel suficiente para un Y_a mayor, generando la mayor Y_g . En este caso, el servicio afectado no fue atendido por la fertilización nitrogenada

suministrada. El incremento en la fertilización permite incrementar el Y_a (reduce el Y_g), pero hasta el nivel que lo permiten, según nuestra interpretación, las condiciones físicas del suelo afectadas cuando $YCC > 6$, que alteran el suministro de nutrientes y dinámica del agua y el aire en el suelo. La oferta de servicios ecosistémicos es máxima bajo ROT_NT, donde se maximizan los servicios de soporte y regulación (en nuestra interpretación, nutrientes, control de enfermedades y reducción del riesgo climático), logrando el máximo servicio de suministro (Y_a). Bajo esta situación Y_g es mínimo.

En tanto, en HYE, el Y_a está limitado inicialmente por un servicio de regulación (monocultivo), que favorece la expresión de factores reductores del rendimiento (enfermedades). Al igual que en LYE la rotación, pero en este caso contemplando tanto con pasturas como de cultivos, resulta en la mejor oferta de suministro y regulación de servicios, logrando reducir la Y_g a un 20% del Y_{att} . La forma en que se eligieron las chacras de la etapa de investigación realizada en campo de productores y los cambios preparatorios realizados en el experimento de largo plazo (Figura 4.1, Artículo 3), no permite reconocer el impacto de otros servicios que los relacionados al suministro de nutrientes. Pero agrega servicios de suministro y eficiencia de uso afectados por la degradación física del suelo.

5.2.2. Aportes metodológicos

La estrategia de investigación planteada en esta tesis permitió cuantificar (valorar) el impacto negativo del modelo de intensificación desarrollado en Uruguay, cuantificado como YCC , sobre el rendimiento de trigo. Se logró demostrar que el proceso de degradación del suelo subyace aún bajo siembra directa continua, afectando la frontera de producción de trigo. El resultado cuantifica el impacto de “.....satisfacer las necesidades de la presente generación”, pero comprometiendo “...la capacidad de las futuras generaciones para satisfacer las suyas” (WCED, 1987; Waltner-Toews, 1996) o “socavando nuestras posibilidades de producir alimentos en el futuro”, Garnett et al., (2013).

El enfoque metodológico seguido supuso cuantificar el impacto que tiene la implementación del manejo del suelo y la rotación en sistemas de producción

agrícolas, sobre los tres niveles de producción distinguido por van Ittersum y Rabbinge (1997) en función de factores que definen, limitan y reducen el rendimiento de los cultivos. Los efectos negativos de YCC sobre el Y_a promedio, único nivel en el que operan los factores reductores del rendimiento, sólo se cuantificaron cuando las condiciones climáticas entorno al período crítico de definición del rendimiento fueron desfavorables para el cultivo (Artículo 1). A este nivel de rendimiento, los YCC resultaron en un incremento del riesgo de producción o, jerarquizando aspectos positivos, la rotación con pasturas es un sistema de producción que reduce el riesgo de producción de trigo. Por tanto, una variable capaz de aportar al desafío planteado por Hochman et al. (2014) de implementar sistemas de cultivos que maximicen la renta para condiciones de producción en las que el rendimiento está limitado por agua (déficit y/o exceso), pero reduciendo el riesgo.

Los resultados no resultan una novedad en sí mismos. Estos conceptos ya fueron cuantificados por otros autores a nivel nacional (Díaz et al., 2010). La novedad es que operan también cuando los sistemas son bajo no labranza permanente, lo que cuestiona el paradigma utilizado para justificar el proceso de intensificación agrícola implementado en lo que va del siglo XXI (Artículo 1). Bajo condiciones ambientales favorables para el cultivo, YCC no resultó limitante del Y_a , pero sí del Y_{att} (Artículo 1, Cuadro 2.7).

Los efectos cuantificados sobre Y_{att} (Artículo 1), la frontera de rendimiento (Artículo 2) y el Y_{max} (Artículo 3) implican que, dependiendo de la rotación, la calidad del suelo se transforma en un factor limitante del rendimiento, *“perdiendo la capacidad de capturar incrementos futuros de rendimiento como consecuencia de haber afectado funciones del suelo vinculadas a su productividad alcanzable”*. La interpretación *“respuesta a la progresiva pérdida de calidad del suelo que implica YCC bajo el sistema de cultivos predominante implementado”*, implica que la calidad del suelo se modifica de manera tal que se transforma en un factor que limita el rendimiento.

La importancia de los resultados radica en que se generaron utilizando información de registros de productores de trigo, evitando así el sesgo que puede suponer concluir que estamos en un escenario virtual, producto de las condiciones en

las que se realizan los experimentos de largo plazo, “*que a poco de andar se vuelven no representativos de la realidad de producción*” (Ernst 2018). La fase de investigación desarrollada implementando experimentos en campo de productores permitió identificar la proporción del efecto negativo sobre la frontera de producción que puede ser atribuida a fallas en el suministro de nutrientes. El Y_g^{others} permite establecer un valor de referencia del indicador utilizado (YCC) para ubicarse el esquema teórico planteado por Cassman (1999). Nuestros resultados sugieren que durante los primeros 5 años pos pastura el proceso de degradación se ubica entre las curvas A y B de dicho esquema. Por tanto, si bien se estaría afectando el atributo “eficiencia de uso de nutrientes”, no así la producción por unidad de área. Cuando $YCC > 5$, se estaría recorriendo el camino que separa la línea B de las C y D.

5.3. PREGUNTAS EMERGENTES DE LA INVESTIGACIÓN

Haciendo este paralelismo entre el proceso histórico de intensificación de la agricultura y nuestros resultados, podría afirmarse que el escenario actual probable es que un alto porcentaje de la superficie agrícola tenga afectada la calidad del suelo a un nivel tal que compromete tanto el Y_{att} como el Y_a de trigo. Surgen así diferentes líneas de acción.

5.3.1. Cuantificar el impacto en otros cultivos

Siendo soja el cultivo dominante dentro de la secuencia agrícola y al menos 60% del Y_g explicado por $Y_g^{nutrients}$, presumiblemente el efecto de YCC sea menor que el cuantificado en este trabajo. No obstante, las propiedades físicas del suelo afectada por YCC podrían tener un impacto cuantitativamente importante al modificar la captura de agua (MWD, INF) y su disponibilidad. Existen evidencias (Kumar et al., 2012, Gama y Rubio 2012) que muestran el efecto que el deterioro de la calidad física del suelo tiene sobre el intervalo hídrico óptimo, es decir, la posibilidad de utilizar el agua y mantener un nivel mínimo de aire en el suelo en condiciones de excesos hídricos o déficit severos. Estos dos aspectos, que están integrados dentro de Y_g^{others} , podrían ser más importantes en soja (Bacigaluppo et al., 2011). Por tanto, si bien en la justificación del proyecto que da origen a esta Tesis se lo descarta por su posible menor

sensibilidad a los cambios generados por el proceso de intensificación reciente, los resultados permiten suponer un impacto cuantificable en rendimiento atribuible a las mismas causas, pero cuya importancia relativa sea diferente a las encontradas para trigo. Posiblemente no sea el tema de mayor importancia, ya que solo estaría ocultando el efecto por el período en el que el $Y_g^{nutrients}$ es el factor limitante y quizás retardando la manifestación del problema por las características fisiológicas del cultivo.

5.3.2. Corregir/Mitigar el efecto negativo de YCC en sistemas predominantemente agrícolas

Adaptando el esquema propuesto por Silva et al., (2017) para analizar los componentes del Yg , YCC podría asumirse como: i) variable determinante de ineficiencias de producción; ii) como componente de la brecha definida por calidad de la oferta de recursos; iii) como componente de la brecha tecnológica.

La primera opción implica que explica Yg a un mismo nivel de $Yatt$. Como concepto está representado en el análisis por CART del Artículo 1 (Figura 2.4). Implica que es un componente manejable o de opción, como rotar una fase agrícola con pasturas (ROT_NT) o una rotación de cultivos diversificada planificada ($CC_{NT_{C4}}$). La segunda opción implica moverse a la derecha en una misma curva que relaciona $Yatt$ con oferta de insumos. Supone que la diferencia en $Yatt$ generada por YCC resulta de suministro diferencial de nutrientes (ROT_NT contra $CC_{NT_{C4}}$), parcialmente explicado por suministro diferencial de nitrógeno desde el suelo (Y_g^{soilNs}). La tercera opción supone moverse a la derecha en dos curvas diferentes, por lo que Yg resulta de un $Yatt$ incrementado que no puede lograrse aumentando la cantidad de insumos utilizada. En nuestro estudio correspondería al contraste entre ROT_NT y $CC_{NT_{C4}}$ contra el resto de los CS evaluados bajo condiciones de rendimiento limitado por agua. Implica asumir que la calidad del suelo actual no puede mejorarse, generando un Yg entre productores (chacras) según la oferta de recursos de la que disponen. Esta opción está cuantificada como efecto YCC al ser incluido como variable determinante de la frontera de producción (Artículo 1) y como determinante

de una proporción de Y_g^T no atribuida a aporte diferencial de nutrientes (Y_g^{others} , Artículos 2 y 3).

5.3.3. Criterios para diagnosticar el estado nutricional del cultivo, y recomendar la necesidad y cantidad de fertilizante nitrogenado.

Los criterios de diagnóstico y recomendación de momento, dosis y fuente de nitrógeno fueron generados mayoritariamente para *ROT_LC* y *ROT_NT*. Nuestros resultados sugieren que permiten diagnosticar la creciente deficiencia en el suministro de nitrógeno, ya que la dosis recomendada se incrementó a razón de $5 \text{ kg ha}^{-1} \text{ YCC}^{-1}$. Sin embargo, este incremento sólo mitigó parcialmente el incremento del $Y_g^{nutrients}$, aun cuando $\text{YCC} \leq 5$. Tal como lo plantean Hoffman et al., (2017), el desajuste sería el resultado de una demanda creciente por el incremento en Y_p por mejora genética y el disminuido suministro de N generado por YCC . A su vez, la limitante en el suministro de N desde el suelo operaría durante todo el ciclo del cultivo, por lo que es posible que se requieran diagnóstico y recomendación para estadios fenológico posteriores al utilizado en la actualidad (Z30). Nuestros tratamientos de rendimiento no limitado por nutrientes implicó el agregado de fertilizante nitrogenado adicional en Z31 y Z58, manteniendo una relación N/S de 7:1. De esta manera se lograría sincronizar de mejor manera la oferta de nutrientes con la demanda del cultivo, evitando la ineficiencia de uso que supone agregar en etapas tempranas cantidades superiores a las necesarias para cubrir la demanda del cultivo. Evaluar otras fuentes de N, diferentes a la urea, que liberen de manera continua el N podría ser una alternativa a evaluar frente a la necesidad de fraccionar.

5.3.4. Mitigar el efecto negativo de YCC en sistemas agrícolas

Existen antecedentes locales y regionales que demuestran el impacto benéfico que tiene la inclusión sistemática de cultivos de cobertura invernal sobre el suministro de N del suelo cuantificado como PMN (leguminosas) y su propiedades físicas (gramíneas, crucíferas y parcialmente leguminosas) cuantificadas como infiltración y porosidad (Tonitto et al., 2006, Sawchik, et al., 2012, Restovich et al., 2012, Álvarez et al., 2017). La principal limitante que tienen los trabajos es que no permiten

discriminar si la práctica mitiga el problema o es capaz de corregirlo. En el primer caso su aporte resulta de reducir la tasa de pérdida partiendo desde una situación favorable y estabilizándola en un valor de PMN, INF, MWD superior al crítico. Por tanto, sería útil para incorporar en situaciones aun no degradadas. En el segundo caso, debería revertir un proceso ya generado, como presumiblemente es la situación dominante. La estrategia experimental para cuantificar esta segunda opción, de alto interés actual, debería incluir un alto número de experimentos sobre situaciones con el problema ya diagnosticado.

5.3.5. Descompactación mecánica sub superficial

Interpretamos el incremento del Y_g^{others} cuantificado para $YCC > 6$ como la respuesta al deterioro de propiedades físicas del suelo, afectando la dinámica del agua y aire el suelo. La descompactación mecánica sub_superficial del suelo podría aportar una solución de corto plazo que, sumado a cambios en el sistema de cultivos, logre revertir la degradación física en el mediano plazo.

5.3.6. Años y tipo de pasturas a incorporar en la rotación cultivos pasturas

Las ventajas de *ROT_NT* en el experimento de largo plazo resultaron de rotar la fase agrícola con pasturas compuestas por una mezcla de gramíneas perennes y leguminosas, en una relación de 50% tiempo para cada fase. Este tipo de pasturas integra los tratamientos que evalúan la rotación cultivos_pasturas en los experimentos de largo plazo de Uruguay y Argentina, son las más frecuentes en los sistemas productivos comerciales y fundamentan el eslogan planteado por Bautes (1986): “la pastura tiene el mando en los sistemas agrícolas_ganderos”. A nivel experimental, relaciones 70% agrícola_30% pasturas, con una composición dominada por leguminosas, también lograron resultados que podrían enmarcarse dentro de los caracterizados por *ROT_NT* (Morón 2003), la inclusión de pasturas anuales son el sustento de sistemas “lavoura-pecuaria integrados” en el sur de Brasil (Balbino et al., 2011) y muchos de los sistemas agrícolas australianos rotan con leguminosas anuales (Chalk 1998). Asumiendo que la pastura debe integrar la rotación, las preguntas a plantearse son: i) ¿qué relación de tiempo entre la fase agrícola_fase pastura (y su

composición botánica) permite *que el sistema sea tan pastoril como la agricultura lo necesite*?; ii) son de igual duración y composición para mantener la calidad del suelo que para recuperar un suelo ya degradado?

5.3.7. Indicadores de calidad de suelo

Tanto los resultados obtenidos utilizando la función estocástica de frontera de producción como con *random forest* (Artículo 2) indican que *YCC* capturó más que solo su efecto negativo sobre INF y PMN, lo que probablemente se deba a múltiples propiedades del suelo (o funciones de suelo relacionadas) que son modificadas por el sistema de cultivo. En el Artículo 3 se agregó la estabilidad de agregados del suelo (MWD) como indicador de degradación física del suelo. Estas tres variables integran el índice de calidad de suelo generado por la mayoría de los artículos revisados, pero su utilidad requiere de valores de referencia que permitan utilizarlos para valorar la evolución en situaciones particulares (Schiefer et al., 2015). Esta línea de trabajo está siendo desarrollada por el INIA (Morón et al., 2012).

5.3.8. Estrategias de intensificación

La evolución de la población mundial y cambios en los patrones de consumos en los países asiáticos son el sustento del incremento de la demanda de alimentos, fibra y bioenergía para los próximos años. Para cubrir este incremento de la demanda de manera sostenible es necesario intensificar la producción en la superficie ya afectada a la producción, sin generar impactos ambientales negativos. En la literatura, varios nombres refieren a estos objetivos, como intensificación sostenible, intensificación ecológica, intensificación eco_eficiente, agricultura inteligente, intensificación agro_ecológica.

Uruguay integra una región que tuvo el rol (responsabilidad) de producir el alimento necesario en Europa en la década 1940-1950, cuando los europeos estuvieron inmersos en la Segunda Guerra Mundial y sus consecuencias, y a partir del año 2002, respondiendo a la demanda de soja (proteína) desde China. En este caso, porque el occidente del hemisferio norte ya no tiene capacidad de incrementar su superficie agrícola ni sus rendimientos. En Uruguay, en ambos períodos se superó 1.500.000 ha

afectadas a la agricultura en un proceso de *intensificación no sostenible*. En contraposición a este proceso reciente, el Ministerio de Ganadería Agricultura y Pesca desarrolló una serie de políticas enmarcadas en un programa bajo el eslogan de Intensificación Sostenible.

La definición de “intensificación sostenible” es tan general que, según Tiftonell (2014), “casi cualquier modelo o tecnología se puede etiquetar debajo de él”. En tanto, “.....la intensificación ecológica propone enfoques de paisaje que permiten hacer un uso inteligente de las funcionalidades naturales que ofrecen los ecosistemas”. La intensificación debe resultar de “diseñar agroecosistemas multifuncionales que, por ser sostenidos por la naturaleza, son sostenibles en su naturaleza”. De esta manera, la agricultura capitaliza servicios ecológicos que brinda la planificación del uso del paisaje (Bommarco et al., 2013).

En este marco, Uruguay tiene la posibilidad de promover un proceso de intensificación ecológica. Dispone de 1.534. 800 ha con aptitud de uso principalmente agrícola y 910.300 ha con capacidad de uso agrícola de baja intensidad (Molfino 2013). Están geográficamente dispersas en el paisaje, por lo que no hay una zona agrícola pura, normalmente denominada núcleo o cinturón y, por su tamaño, los predios agrícolas incluyen esta variabilidad. Por tanto, existe una oportunidad para la intensificación ecológica (Tiftonell 2014) o agro-ecológica (Fonte et al., 2012) o sistemas de cultivos diversificados (Kremen et al., 2012). El desafío está en reducir la brecha de rendimientos existente, pero evitando el camino que llevó a plantear la necesidad de “des-intensificar” sistemas de producción con baja brecha de rendimiento, pero alto costos ambientales (Struik y Kuyper 2017). Producir más por unidad de insumo agregado es un proceso de intensificación, pero la sustentabilidad depende de una valoración holística del cambio. Incrementando la fertilización nitrogenada en trigo en el sistema de cultivo CC_NT_{C3} aumentó el rendimiento, por lo que se mejora la eficiencia de uso del recurso suelo y la eficiencia de uso del N agregado, sin contemplar diferencias en el aporte de N desde el suelo, se mantuvo relativamente constante. Por tanto, se cumple la premisa de “producir con más eficiencia”. Hasta podría concluirse que hay un negocio rentable en agregar fertilizante nitrogenado en suelos con baja capacidad de aporte de N como el generado por

$CC_{NT_{C4}}$, o los degradados por 20 años de CC_{LC} . La conclusión es diferente al comparar sistemas de cultivos distintos. Los resultados de esta Tesis plantean la necesidad de valorar este enfoque. Implementar un sistema de cultivos en que $YCC \leq 6$, supone que hay una fase de pasturas perennes. Que en la secuencia no se siembra trigo siguiendo a trigo o cebada del año anterior, requiere producir cultivos con capacidad de cortar el ciclo de enfermedades, plagas, malezas y/o incorporar cultivos de cobertura. Por tanto, de un sistema diversificado, no solo espacialmente, sino temporalmente dentro de cada unidad de manejo.

Uno de los desafíos más importantes para la investigación es reconocer y cuantificar los impactos positivos de los servicios ecosistémicos para valorarlos en términos económicos. La diversificación se contrapone con el objetivo de captura de la renta máxima definida por el cultivo principal. Un agricultor que implementa un sistema de producción diversificado reduce su escala como productor agrícola (bajo la premisa de que no aumenta su escala). Este proceso fue identificado como una de las causas de la reducción del número de productores agrícolas asociado a la implementación del sistema de rotación cultivos_pasturas, ya que limitó la capacidad de acceder a innovaciones tecnológicas como la maquinaria, que requieren un tamaño mínimo para ser justificadas económicamente. Por tanto, la construcción de estos caminos de intensificación requiere de generación de conocimiento e innovaciones tecnológicas, pero también de innovaciones institucionales y sistemas de gobernanza alineados con sus objetivos.

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