UNIVERSIDAD DE LA REPÚBLICA
FACULTAD DE AGRONOMÍA

CAMPO NATURAL: PROPUESTA DE MODELO DE ESTADOS Y TRANSICIONES PARA CARACTERIZAR SU DEGRADACIÓN BAJO PASTOREO Y SU MONITOREO SATELITAL

por

Guadalupe TISCORNIA TOSAR

TESIS presentada como uno de los requisitos para obtener el título de Doctora en Ciencias Agrarias

MONTEVIDEO
URUGUAY
Diciembre 2019

Tesis aprobada por el tribunal integrado por Ing. Agr. (PhD.) José Paruelo (Presidente), Lic (Dr.) Marcel Achkar (Relator), Dr. Carlos Nabinger (Relator) y Ing. Agr. (PhD.) Walter Baethgen (Director, con voz y sin voto), el 18 de diciembre de 2019. Autora: Lic. Biol. (Mag.) Guadalupe Tiscornia. Director Ing. Agr. (PhD.) Walter Baethgen.

AGRADECIMIENTOS

Quisiera agradecer especialmente:
A mi FAMILIA, por el constante apoyo, paciencia y hasta revisión de algunos documentos.
Al Instituto Nacional de Investigación Agropecuaria (INIA), a La Estación Experimental "Wilson Ferreira Aldunate" (INIA Las Brujas), y en particular a la Unidad de Agroclima y Sistemas de Información (GRAS), a Agustín Gimenez, ya que sin el apoyo brindado nunca podría haberme embarcado en este desafío y mucho menos haberlo finalizado.
En particular a mi tutor, Walter Baethgen, y al comité de seguimiento integrado por Valentín Picasso, Pietro Ceccato y Pablo Soca, por su guía, contribuciones y enfoques que, sin duda, contribuyeron no solo a mi crecimiento profesional si no a la obtención de un mejor resultado en este trabajo.
A Andrea Ruggia, Martín Do Carmo y Martín Jaurena por las distintas instancias de intercambio, sugerencias y grandes aportes realizados.
Al Instituto de Clima y Sociedad, IRI, de la Universidad de Columbia (NYC, USA) por apoyarme en la realización de mi pasantía.
A la ANII por apoyar la realización de este doctorado mediante el otorgamiento de una beca parcial.
A los miembros del tribunal, por sus comentarios que aportaron mucho en la mejora del documento y la calidad de la tesis.
A todos lo que de alguna manera contribuyeron para que pudiera alcanzar este gran logro profesional y personal.

A todos ellos: ¡MUCHAS GRACIAS!

TABLA DE CONTENIDO

RESUMEN

El campo natural (CN) se viene degradando progresivamente en todo el mundo debido principalmente a la acción del hombre. En Uruguay, donde la producción ganadera extensiva en CN es una de las actividades económicas más importantes, esto cobra real importancia. El objetivo general de esta tesis fue detectar degradación en CN utilizando la teledetección. Para ello, nos basamos en: 1) marco conceptual para abordar el análisis de la degradación y una definición de "degradación de campo natural"; 2) definición de alguna característica estructural del CN que respaldara políticas nacionales y decisiones a nivel predial. Sobre el primer punto, se propuso un marco integral con categorías conceptuales para monitorear la degradación del CN y una nueva definición basada en las ya existentes. Se identificaron "impulsores" como fuerzas externas que causan degradación; “procesos” como cambios medibles en las condiciones del CN (evaluados mediante indicadores); y “consecuencias” como impactos o resultados del proceso de degradación. El punto 2, se basó en la teledetección (sensor MODIS) por su capacidad de cuantificar áreas grandes en un tiempo corto, a bajo costo y con la posibilidad de analizar evolución anual y series temporales. Se seleccionó la altura del tapiz (estimador de biomasa disponible) como variable a ser evaluada considerándola como un indicador de degradación en la medida que permaneciera en rangos bajos por largos períodos de tiempo o en períodos críticos (primavera u otoño). La variabilidad dentro de cada potrero fue extremadamente alta para las observaciones de campo (CV: 70%) y menor a lo esperado cuando se consideró información MODIS (CV: 4% - 6%) y Landsat (CV: 12%). Las correlaciones entre la información satelital y de campo fueron bajas, aunque la banda roja mostró cierto potencial y justifica una mayor exploración. Es necesario trabajo adicional para encontrar un método de detección remota que permita monitorear la condición "instantánea" del CN. Se espera que los resultados de esta tesis contribuyan a promover y mejorar las prácticas de manejo y gestión sostenible, monitoreo y toma de decisión, en este ecosistema tan importante y, a menudo, descuidado.

Palabras clave: campo natural, degradación, teledetección, MODIS, Campos

NATURAL GRASSLANDS: STATES AND TRANSITIONS MODEL PROPOSAL TO CHARACTERIZE ITS DEGRADATION UNDER GRAZING CONDITION AND ITS SATELLITE MONITORING

SUMMARY

Natural grasslands (NG) are being progressively degraded around the world due to human-induced action. In Uruguay where livestock production based on NG is an important economic activity, this takes on real importance. The general objective of this thesis was to detect degradation of NG using remote sensing (RS) techniques. To achieve this, we worked on: 1) a conceptual framework to approach degradation studies and a clear definition of what "NG degradation" is; 2) definition of a structural characteristics of NG, essential to support national policies and decisions at the farm level. Regarding topic 1, we propose a comprehensive framework with different conceptual categories, for monitoring NG degradation, and a new definition based on current ones. We identified "drivers" as external forces that cause degradation; "processes" as measurable changes in NG conditions (evaluated using indicators); and "consequences" as the impacts or results of NG degradation process. Topic 2 was based on RS (MODIS) due to its ability to quantify large areas in a relative short time, at low cost and with the possibility of analyzing annual evolution. The NG height (available biomass estimator) was selected as a variable to be evaluated as an indicator of degradation, as long as it remained in low ranges for a long time frame or in critical periods (spring or autumn). Variability within each paddock was extremely large in field observations (CV: 70%) and smaller than expected when considering MODIS (CV: 4%-6%) and Landsat information (CV: 12%). Correlations between RS info. and field measurements were low, but Red band showed some potential and justifies further exploration. Additional work is needed to find a RS method that can be used to monitor the "instantaneous" condition of NG. The results of this thesis are expected to contribute to promoting and improving sustainable management, monitoring and decision-making, in this very important and often neglected ecosystem.

Keywords: native grasslands, degradation, remote sensing, MODIS, Campos

1. INTRODUCCIÓN

Los pastizales son uno de los ecosistemas más grandes del mundo con un área estimada de 40-50 millones de km^2 (Bilenca y Miñarro, 2004; Suttie et al., 2005), entre el 25% y el 40% de los ecosistemas terrestres (Gibson, 2009; Sala y Paruelo, 1997). Son en su mayoría ambientes limitados por agua, dominados por pastos, leguminosas y otras hierbas, con posible presencia de especies leñosas, que tienen el potencial de ser pastoreadas por animales salvajes o domésticos (Allen et al., 2011).

Los pastizales del Río de la Plata (ubicados entre las latitudes 28ºS y 38º S) son uno de los pastizales templados-subtropicales del mundo, junto con los ubicados en las grandes planicies del centro de América del Norte, las estepas del este de Europa y Mongolia, este de Sudáfrica y las llanuras de Nueva Zelanda. Los pastizales del Río de la Plata cubren la parte centro-este de Argentina, la mayor parte de Uruguay y el sur de Brasil, y se subdividen en "pampas" y "campos" (Soriano et al., 1992). Las "pampas" son pastizales templados, sin árboles, ubicados en el este y el centro de Argentina en llanuras planas y fértiles, clima húmedo a árido con veranos cálidos e inviernos suaves (Allen et al., 2011). Los "campos" son pastizales que consisten principalmente en pastos, junto con otras especies herbáceas, pequeños arbustos y árboles ocasionales. Ocurren en paisajes ondulados, con fertilidad del suelo variable, en clima subtropical húmedo, cálido en verano y suave en invierno, que se presenta en Uruguay, el sur de Brasil y el noreste de Argentina (Allen et al., 2011).

A nivel mundial, los pastizales naturales contribuyen de manera significativa a la seguridad alimentaria, siendo la base de la producción de carne y leche (Lund, 2007; O´Mara, 2012). Adicionalmente, proveen de muchos otros servicios ecosistémicos importantes para el ser humano como conservación de biodiversidad, secuestro de carbono, conservación de suelos, calidad de agua y otros (Sala y Paruelo, 1997; O´Mara, 2012; Petri et al., 2010; Bedunah y Angerer, 2012; Modernel et al, 2016). Los pastizales se encuentran entre los ecosistemas con la mayor riqueza de especies del mundo (Wilson et al., 2012) y son el hábitat de muchas especies animales de vida silvestre. En el caso de Uruguay, se detectaron 47 especies de anfibios, 430-460 especies de aves y 85 especies de mamíferos (Bilenca y Miñaro, 2004; Soutullo et al., 2013). De estas especies, el 34% de los anfibios, el 5% de las aves y el 20% de los mamíferos están amenazados, son vulnerables o están en peligro de extinción (Soutullo et al., 2009; Soutullo et al., 2013).

En Uruguay, el campo natural representa más del 65% del área del país y se desarrolla sobre una amplia diversidad de tipos de suelos (Berretta et al., 2000). Como consecuencia de esto, la vegetación es muy heterogénea y diversa, con decenas de especies por m^2 (Altesor y Pezzani, 1999; Rosengurtt, 1943) y con un total de más de 2000 especies con 350 especies de gramíneas registradas (Boggiano y Berretta, 2006). En estos ambientes se da un predominio de especies estivales (C4) con un aumento de la frecuencia de las especies invernales (C3) durante el otoño e invierno (Berretta et al., 2000).

En esta región, la producción ganadera se ha llevado a cabo durante más de 300 años y el manejo del ganado se considera un factor clave para mantener las características de los pastizales (Overbeck et al., 2007). Por lo tanto, el control de la intensidad del pastoreo a través del manejo de la tasa de acumulación de forraje o tasa de crecimiento es una herramienta importante para regular la cantidad de energía solar captada y convertida en producción de carne (Briske y Heitschmidt, 1991). En este contexto, la asignación de forraje, definida como kg de materia seca de forraje por kg de peso corporal del animal (Allen et al., 2011; Sollenberger et al., 2005), puede ser más útil para manejar el pastoreo que la consideración de la tasa de acumulación de forraje (Do Carmo et al., 2018a). En este sentido, la gestión de la disponibilidad de forraje requiere una estimación de la biomasa o el uso de un proxy como la altura del forraje (Do Carmo et al., 2018b).

El estado de conservación de los pastizales varía alrededor del mundo, pero en general está lejos de ser satisfactoria (Suttie et al., 2005), lo que afecta directamente a los diferentes servicios ecosistémicos que brindan. A nivel global, los pastizales naturales, han mostrado signos de degradación, debido principalmente al sobrepastoreo (Berretta et al., 2000; Akiyama y Kawamura, 2007; Wessels et al., 2007; Harris, 2010; Han et al., 2008; O´Mara, 2012; Mansour et al., 2012ab), otros manejos no deseables (Veldman et al, 2015; Mansour et al., 2012ab; Wick et al., 2016; Zhou et al, 2005; Gang et al, 2014; Liu et al., 2013; Andrade et al., 2018; Zhou et al., 2014) y cambio climático (Han et al., 2008; Veldman et al, 2015; Mansour et al., 2012b; Zhou et al, 2005; Gang et al, 2014; Liu et al., 2013; Zhou et al., 2014). Adicionalmente, muchos de ellos han sufrido procesos de sustitución debido a la expansión de cultivos y plantaciones forestales (Suttie et al., 2005; Paruelo et al., 2006; Tiscornia et al., 2014; Cai et al., 2015). En países como Uruguay, donde la producción ganadera extensiva basada en campo natural es una de las principales actividades económicas, los procesos de degradación cobran real importancia.

Relacionado con esto y a pesar de que muchos autores y organizaciones internacionales demandan por la preservación de los pastizales naturales (Henwood, 1998; de Faccio Carvalho y Batello, 2009; Veldman et al., 2015), no existe una definición consensual de lo que es "degradación" y, según algunos autores, hay pocos temas más polémicos y cargados emocionalmente que la degradación de los pastizales (de Queiroz, 1993).

Tradicionalmente, la caracterización de la vegetación del campo natural y la estimación de parámetros biofísicos que permitan estimar distintos estados, se ha realizado en forma directa, haciendo mediciones a nivel de campo sobre la planta o la cobertura vegetal. Estos métodos son muy demandantes y tiene la limitante de no poder escalarse fácilmente a grandes áreas. Para salvar estas restricciones, desde hace algunos años, se han venido utilizando métodos indirectos basados en respuestas espectrales derivada de imágenes satelitales o fotografías aéreas. En este sentido, tanto a escala mundial como regional, se ha realizado mucha investigación utilizando la teledetección para monitorear el estado de la vegetación (Lawley et al., 2016) y, más específicamente, para caracterizar el funcionamiento de los pastizales.

1.1. DEGRADACIÓN DE CAMPO NATURAL

Una estimación global de Gang et al. (2014) mostró que casi la mitad de los ecosistemas de pastizales estaban degradados y casi el 5% de estos pastizales experimentaron niveles de degradación fuertes a extremos. Dada la relevancia de estos ecosistemas, la degradación del campo natural se ha convertido en un tema emergente en lo relativo a la gestión de los pastizales y la protección del medio ambiente.

En relación al concepto de “degradación del campo natural”, algunas definiciones son muy amplias (Xu et al., 2009) mientras que otras se centran solo en algún aspecto específico (Manssour, 2011; Wessels et al., 2007; Liu et al., 2004; Rosengurtt, 1943; Berretta y do Nascimento, 1991; Behmanesh et al., 2015; Millot et al., 1987; Pallarés et al., 2005; Tácuna et al., 2015). Andrade et al. (2015) resaltan la complejidad del concepto de degradación que integra aspectos ecológicos, de productividad y socioeconómicos, y desarrollaron un marco conceptual de degradación de los pastizales de etapas y umbrales que ayuda a los investigadores a estudiar la degradación, aunque no se propuso una definición general explícita del concepto. El término "degradación" que se refiere a la condición de un pastizal natural, es ampliamente utilizado en diferentes circunstancias por diferentes actores interesados, incluyendo investigadores, agentes de extensión rural, y formuladores de políticas, sin necesariamente coincidir en una definición común.

Esta diversidad de definiciones para la degradación de los pastizales puede deberse a diferentes razones. Una está relacionada con los diferentes antecedentes disciplinarios de los investigadores o partes interesadas involucradas mientras que otras razones pueden ser objetivos diferentes para la utilización de los pastizales (por ejemplo, alimento para ganado, conservación, caza); diferentes regiones del mundo con diferentes condiciones de suelo; diferentes ámbitos de estudio, métodos y estándares de clasificación (Xu et al. 2009). Suttie et al. (2005) sostienen que el "sobrepastoreo", la "degradación" y la "desertificación" son conceptos muy controvertidos y problemáticos y están de acuerdo con de Queiroz (1993) en que las definiciones de degradación son diferentes según los objetivos de gestión. Dado que estos objetivos pueden diferir, las definiciones de lo que constituye degradación también difieren.

Por otro lado, el concepto de degradación no denota el mismo conjunto de condiciones para diferentes partes interesadas. Bedunah y Angerer (2012) destacaron la complejidad del término degradación al afirmar que los científicos de los pastizales deben desempeñar un papel clave en la recopilación, la comprensión y los comentarios sobre las definiciones de degradación utilizadas por las partes interesadas. Existe una fuerte demanda de la comunidad internacional de pastizales por la uniformidad en la terminología utilizada en los sistemas de pastoreo (Allen et al., 2011). En este sentido, Smith (1979) alentó a "usar una terminología de condición de rango que signifique lo mismo para todos". Las definiciones consensuales son importantes para mejorar la comunicación entre los investigadores y los productores y se vuelven imperativas cuando involucramos a los responsables de la formulación de políticas y al público en general. Acordar una definición de un concepto complejo como la degradación de los pastizales también es importante para la investigación, ya que contribuye a identificar qué procesos deben describirse y qué variables deben medirse para evaluar sistemáticamente el grado de degradación.

A pesar de esto y teniendo en cuenta que las definiciones de lo que es un campo natural degradado difieren entre los diferentes contextos, entendemos que todas ellas pueden ser agrupadas en diferentes categorías conceptuales relacionadas con la degradación: como son los impulsores, los procesos o las consecuencias. Entendiendo a los "impulsores" como fuerzas externas o cambios que causan degradación, los "procesos" como cambios medibles en las condiciones de los pastizales que pueden evaluarse utilizando indicadores y las “consecuencias” como los impactos o resultados del proceso de degradación de los pastizales.

La importancia de los pastizales naturales para la seguridad alimentaria de muchos países en desarrollo y para la economía de otros como Uruguay, Argentina y Brasil, implica que su degradación es un importante problema político, económico y ambiental. Dados estos aspectos diversos y potencialmente conflictivos, y la necesidad de preservar los pastizales naturales para la producción ganadera y la diversidad, es esencial alcanzar un marco de análisis común para estudiar los procesos de degradación del campo natural y definir indicadores de monitoreo apropiados.

Considerando la afirmación de Queiroz (1993) de que la degradación está intrínsecamente relacionada con los objetivos de manejo, creemos que es necesaria una revisión de los estudios realizados en campo. En este contexto, surgen preguntas importantes: ¿Cuál es la condición de un campo natural degradado? ¿Cuáles son los principales impulsores que influyen en la degradación? ¿Cómo se ven afectados los procesos ecológicos debido a la degradación? ¿Cuáles son las principales consecuencias de la degradación?

Para definir un campo natural de referencias nos basamos en los trabajos de de Faccio Carvalho et al. (2017). Este sería un pastizal que presente el suelo cubierto, que esté compuestos por especies nativas con una alta biodiversidad específica tanto vegetal como animal (lo que favorece los procesos de ciclado de nutrientes, por ejemplo) y una alta heterogeneidad de especies y de estructura (que lo hacen sistemas más resilientes). Lo consideramos como un sistema que se encuentre bajo herbivoría, pero de intensidad media, lo que favorece la biodiversidad de especies y permite la existencia de algunas menos tolerantes al pastoreo (no se llega a producir selectividad, lo que podría llevar a la eliminación de algun grupo funcional en condiciones de pastoreo más intenso).

1.2. LA TELEDETECCIÓN

La información relacionada con las características estructurales (altura o masa de forraje) del campo natural, es esencial para respaldar las decisiones de manejo, no solo a nivel nacional sino también a escala de establecimiento o potrero. Esto presiona a la investigación para generar "información de bajo costo, adecuada y oportuna, que pueda apoyar a los productores en la toma de decisiones" (Wachendorf et al., 2017). Teniendo en cuenta que los métodos de campo actuales son laboriosos y requieren mucho tiempo, es difícil extender el monitoreo de la asignación de forraje a grandes áreas, y la utilización de la teledetección se evidencia como una opción prometedora al monitorear grandes áreas en un tiempo relativamente corto, a relativamente bajo costo y con la posibilidad de analizar un período histórico.

La teledetección o sensoramiento remoto se ha utilizado desde hace varios años para estimar la producción primaria neta aérea (An et al., 2013; Baeza et al., 2010; Baldassini et al., 2012; Guerschman et al., 2003; Li et al., 2016; Piñeiro et al., 2006) o la biomasa anual o estacional (Jia et al., 2016; Olsen et al., 2015).

Los atributos de la estructura y función de estos ecosistemas también se han relacionado con los índices de vegetación provenientes de la teledetección, en lugares como la Patagonia, donde se evaluó la relación entre la cobertura y la riqueza de especies con nueve indicadores de vegetación diferentes. Gaitán et al. (2013) mostraron que el NDVI explicaba alrededor del 30% al 40% de la variabilidad encontrada en estos atributos del ecosistema. En las praderas áridas del suroeste de América del Norte, la cobertura de vegetación herbácea total (verde y senescente), la altura y la biomasa, se estimaron utilizando un Índice de Vegetación (SATVI) estimado a partir de Landsat, obteniendo buenos resultados (Marsett et al., 2006).

Los parámetros biofísicos de los pastizales, en su mayoría considerados en base estacional o anual, se han monitoreado con teledetección durante muchos años y, recientemente, han evolucionado hacia enfoques de modelación más complejos, robustos y eficientes (Ali et al., 2016). Sin embargo, se debe hacer más investigación para estimar con precisión el rendimiento intra anual de algunas variables biofísicas como la biomasa o la altura.

El objetivo general de esta tesis fue detectar, mediante técnicas de teledetección, degradación en el campo natural. Pero, para poder monitorear los pastizales haciendo foco en la degradación, es necesario definir en primer lugar indicadores plausibles de ser monitoreados. Para ello, se trabajó en base a dos ejes principales:

- La necesidad de un marco conceptual consensuado para abordar el análisis de la degradación y de una definición clara de lo que es la "degradación de campo natural". En base a esto, definir variable que pudiera ser monitoreada con teledetección;
- La posibilidad de monitorear características estructurales del campo natural, necesaria para respaldar políticas nacionales y decisiones a nivel de establecimiento.

En relación al primer punto, el objetivo fue el de elaborar un marco integral con diferentes categorías conceptuales para monitorear la degradación de los pastizales y, adicionalmente, proponer una nueva definición práctica de "degradación del campo natural" basada en las ya existentes. Esto procura contribuir con programas de monitoreo, a respaldar las decisiones de manejo, a diseñar medidas de conservación y gestión sostenible, comunicar la importancia de la conservación de los pastizales y evidenciar los diferentes conceptos involucrados.

Para abordar el segundo punto, se intentó estimar, con información satelital, el comportamiento observado del campo natural como una "fotografía" de la altura disponible del forraje, en diferentes momentos del año. Este enfoque parece ser particularmente importante en la gestión de los sistemas de producción pecuaria de modo de estimar la biomasa disponible en un momento dado, y no solo biomasa acumulada anual o estacionalmente.

2. FACTORES, PROCESOS Y CONSECUENCIAS DE LA DEGRADACIÓN DEL CAMPO NATURAL: PERCEPCIÓN DESDE UNA REVISIÓN BIBLIOGRÁFICA Y UNA ENCUESTA EN LOS PASTIZALES DEL RÍO DE LA PLATA

2.1. RESUMEN

Los pastizales naturales se están degradando progresivamente en todo el mundo debido a la acción humana (por ejemplo, el sobrepastoreo), pero no existe un marco conceptual ampliamente aceptado para abordar los estudios de degradación, ni una definición clara de lo que es la "degradación del campo natural". La mayoría de los factores, procesos y consecuencias relacionadas con la degradación de los pastizales están muy difundidos y, por lo general, se citan de forma separada en la literatura. En este trabajo, proponemos un marco integral con diferentes categorías conceptuales, para monitorear la degradación de los pastizales, y una nueva definición basada en las ya existentes. Se realizó una actualización conceptual de la degradación de los pastizales basada en una revisión bibliográfica y una encuesta a expertos, centrada en los pastizales del Río de la Plata (RPG). Identificamos los "impulsores" como fuerzas externas o cambios que causan degradación, los "procesos" como cambios medibles en las condiciones de los pastizales que pueden evaluarse utilizando indicadores y las “consecuencias” como los impactos o resultados del proceso de degradación de los pastizales. Entendemos que este marco conceptual puede contribuir al diseño de programas de monitoreo, en respaldar las decisiones de manejo, a diseñar medidas de conservación y a comunicar la importancia de la conservación de los pastizales y los diferentes conceptos involucrados. Particularmente para RPG, esperamos que este documento contribuya a promover prácticas de gestión sostenible en este importante, pero a menudo, descuidado ecosistema.

Palabras clave: productividad, forraje, biomasa, diversidad de especies, indicadores, pastoreo agronomy

MDPI

Review

Drivers, Process, and Consequences of Native Grassland Degradation: Insights from a Literature Review and a Survey in Río de la Plata Grasslands

Guadalupe Tiscornia [1,*], Martín Jaurena [2] and Walter Baethgen [3]

1 Agro-Climate and Information System Unit (GRAS), National Institute of Agricultural Research (INIA Uruguay), Ruta 48 KM.10, Canelones 90200, Uruguay
2 Pastures and Forages National Research Program, National Institute of Agricultural Research (INIA Uruguay), Ruta 5 KM.386, Tacuarembó 45000, Uruguay; mjaurena@inia.org.uy
3 International Research Institute for Climate and Society (IRI), Columbia University, 61 Route 9W, Palisades, NY 10964, USA; baethgen@iri.columbia.edu
* Correspondence: gtiscornia@inia.org.uy; Tel.: +598-2367-7641

Received: 23 March 2019; Accepted: 5 May 2019; Published: 10 May 2019

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Abstract: Natural grasslands are being progressively degraded around the world due to human-induced action (e.g., overgrazing), but there is neither a widely accepted conceptual framework to approach degradation studies nor a clear definition of what "grassland degradation" is. Most of the drivers, processes, and consequences related to grassland degradation are widespread and are usually separately quoted in the literature. In this paper, we propose a comprehensive framework with different conceptual categories, for monitoring grassland degradation, and a new definition based on current ones. We provide a conceptual update of grassland degradation based on a literature review and an expert survey, focused on the Río de la Plata grasslands (RPG). We identified "drivers" as external forces or changes that cause degradation; "processes" as measurable changes in grasslands conditions that can be evaluated using indicators; and "consequences" as the impacts or results of the process of grassland degradation. We expect that this conceptual framework will contribute to monitoring programs, to support management decisions, to design conservation measures, and to communicate the importance of grasslands conservation and the different concepts involved. Particularly for RPG, we expect that this paper will contribute to promote sustainable management practices in this important and often neglected ecosystem.

Keywords: productivity; forage; biomass; species diversity; indicators; grazing

1. Introduction

Grasslands cover an estimated area of 40% of the land surface [1]. There are different types of native grasslands, with communities determined mainly by climate and soil conditions, by grazing animals and by fire [2]. Globally, grasslands make a significant contribution to food security, providing forage for ruminants used for meat and milk production [3,4] and by the provision of many other important ecosystem services for human well-being [5,6]. However, the status of grasslands conservation varies around the world, but it is generally far from satisfactory [7]: they have shown signs of degradation, due primarily to overgrazing [2,8–12], other improper management practices [13–20], and climate change [12–14,16–18,20]. In fact, grasslands are among the ecosystems with the highest species richness in the world [21]. A global estimation of Gang et al. [17] showed that almost half of grassland ecosystems were degraded and almost 5% of these grasslands experiences strong to extreme levels of degradation.

Given its relevance, grassland degradation has become an emerging topic in the fields of grassland management and environmental protection. Even though many authors and international organizations call for preservation of natural grasslands [13,22,23], there is not a consensual definition of what natural grassland degradation is. The conceptual definitions of degradation are very broad, involving the deterioration of grassland quality, productivity, economic potential, service function, recovery ability, and diversity [24]. Others focus only on the decline of forage production or grassland productivity [9,25–28], and others incorporate invasion of non-native plant species [29,30], dominance of non-palatable species [31] or functions related to biogeochemical and water cycle [12,32–34]. In summary, the term "degradation" referring to the condition of a natural grassland, is widely used in different circumstances by different stakeholders, from researchers and rural extension agents, to policy makers, without a common agreed definition. These extremely variable definitions of grassland degradation reflect the wide variety of services expected from this ecosystem, with each definition corresponding to one or a few services.

Although definitions differ across human and environmental contexts, we argue that all of them can be grouped in conceptual categories related to degradation: e.g., drivers, process, or consequences. Many research reports focus on the process indicators of grassland degradation: e.g., Cao et al. [35] define the degradation as "an adverse reduction in biodiversity and biomass production, increased soil erosion, and nutrient loss". Wick et al. [15] in contrast, focus on consequences and define grassland degradation as the reduction in their ability to provide ecosystem goods and services. Other studies combine different conceptual categories, such as consequences and process indicators: "degradation (...) leads to desertification, reduces grassland productivity and biodiversity" [36]; others combine drivers and process indicators: overgrazing, woody-plant encroachment, and invasion by non-native plant species, led to the reduction in the quantity or nutritional quality of the vegetation available for grazing" [29]. Clarifying these conceptual categories is crucial to build conceptual models that can explain the dynamics of grassland degradation and restoration.

Understanding the forces that drive the state of grasslands ecosystems, is an important first step for preventing their degradation. For this task, the State and Transition Model (STM) [37], simple diagrams that conceptualize the complex dynamic of the vegetation, which has been proposed as a useful tool to assess grassland management and conservation [38]. According to these models, there are "normal" or non-degraded vegetation states that are known to be very stable, since they rapidly return to its original condition after a small perturbation. However, discontinuous and irreversible changes (at least in the medium term) occur after a major disturbance, when the thresholds are exceeded and, a "normal" stable state is replaced by an alternative stable but unwanted (degraded) one [15,39]. It is frequently reported in the literature that primary driving forces of grassland degradation, which can be grouped into natural events (e.g., the increase in the frequency of extreme drought) and anthropogenic (management) factors (e.g., overgrazing or grazing abandonment) or by the interaction of both factors, can cause discontinuous changes in vegetation compositions that are non-reversible. These transitions to degraded communities are triggered when the driving forces overcome the resilience of the reference community [40,41]. However, the dividing line between what is considered "normal" and what is considered degraded is far from absolute.

Much has been studied about degradation in water-limited grasslands [8,12,42–44], which are ecosystems very prone to soil desertification. In these grasslands, prolonged droughts and overgrazing are commonly recognized as the two common underlying drivers that lead to degradation. However, in mesic and humid grasslands, which are alternatively limited by temperature, water and nutrients, an in-depth synthesis of knowledge is needed to understand driving forces, process, and consequences of grassland degradation.

Given the importance and the need for preserving natural grasslands for livestock production and diversity, it is essential to reach a conceptual framework to study the process of grassland degradation. Considering de Quiroz [45] statement that degradation is intrinsically related to human management objectives, we believe that there is a need for a review of the studies conducted in grasslands used for livestock production. In this context, important questions arise: what is the condition of a degraded natural grassland? Which are the main drivers that influence grassland degradation? How ecological process are affected by grassland degradation? What are the main consequences of grassland degradation? The goal of this paper is to provide a conceptual update of grassland degradation based on an extensive worldwide literature review and an expert survey focused on the Río de la Plata region.

2. Methodology

2.1. Literature Review

A literature search was conducted in December 2016 with the main objectives of identifying the drivers, process indicators, and consequences related to degradation. We first used the free search engine Google Scholar (https://scholar.google.com/) to search across a wide range of academic sources and not only peer-reviewed literature. We searched by the terms "natural grassland degradation" and "rangeland degradation" related exclusively to livestock production; a complementary search in Spanish was conducted with the terms: "degradación", "campo natural" and "pastizales". Search in Portuguese was omitted, even though it is a very important language and the "Campos" region includes Brazil, due to the fact that in general the Brazilian journals have abstracts in English. Although there are many uses of natural grasslands such as recreation, hunting, and conservation, we address the issue of degradation of natural grassland, not of those intensively farmed.

A total of 5910 results were obtained: 5345 from the English-language search and another 565 from the Spanish-language search. Since we wanted to conduct an in-depth analysis of the concepts and indicators used to describe grassland degradation around the world, we limited our analysis to the most-cited 100 papers, though substitutions were made to ensure that at least one paper from each of the major grassland regions was represented (South American, North America, East Europe, Asia, Australia, and South Africa). Out of these 100 papers, we identified and systematized 27 papers that provided an explicit definition of grasslands degradation (see Supporting material in supplementary file).

Additionally, and to enrich and reinforce drivers, process indicators, and consequences and the conceptual framework, we updated the literature review by specifically searching in different scientific databases (Scopus, Science Direct, Springer, JSTOR, among others). As a result of this new search, an additional 40 papers were also systematized.

2.2. Expert Survey

To adapt our propose conceptual framework to the focus region, we center the expert survey on a regional level. We then conducted a regional survey focused on the Río de la Plata Grasslands (RPG).

This survey was first sent to the regional authors with more citations on "Río de la Plata Grasslands" research, and to take advantage of the expert network, we applied a "snowball sampling" technique [46]: we asked the experts to recommend three more people to whom the survey should be sent. This second group of experts was added to the expert list and surveys were sent to them as well. The survey was first conducted via email or phone, between July 2014 and March 2016.

The survey target population [47] consisted of 39 experts from different institutions: 54% from universities (Departments of Agronomy or Natural Sciences/Ecology), 13% from the private sector (agronomic advisors and/or farmers), 33% from other institutions (research institutes, extension institutes or the government, and non-profit organizations). The respondent's disciplinary backgrounds were 85% Grassland management scientists and 15% Botany/Ecology. Only 8% were women. In terms of nationality, 22 were Uruguayans, 11 Argentineans, and 6 Brazilians.

Five purposely open-ended questions were included in the survey: 1. What do you consider to be a degraded natural grassland and how can you define it? 2. Mention three relevant indicators that you would use to characterize a degraded natural grassland. 3. How do you define a non-degraded natural grassland? 4. Mention three relevant indicators that you would use to characterize a non-degraded natural grassland. 5. Identify two or three of the most relevant characteristics that could be used to differentiate the two conditions.

3. Conceptual Framework for Grassland Degradation

In the present study, we established a framework that identified three distinct conceptual categories: drivers, processes, and consequences of natural grasslands degradation (Figure 1). For this work, we define "drivers" as the external forces or changes that can cause degradation, such as overgrazing or land use change. "Processes" are the conditions that create a sequence of changes in the properties of the grassland ecosystem, and can be evaluated using indicators, such as reduction in plant growth. We use the term "process indicator" as a variable used to measure and infer a conclusion from the phenomenon of degradation [48], such as vegetation height or bare ground cover. Finally, we consider "consequences" as the impacts or results of the process of grassland degradation, such as reduction in the Aboveground Net Primary Productivity (ANPP).

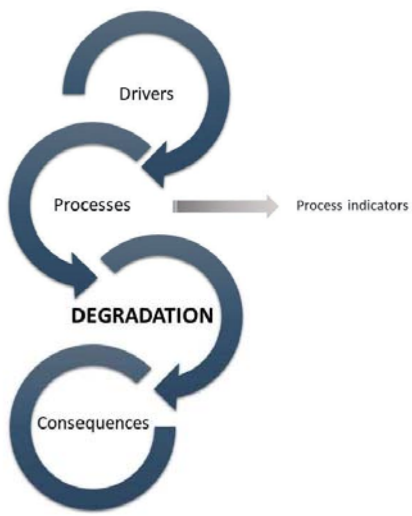

Figure 1. Conceptual framework of drivers, processes, and consequences of natural grasslands degradation.

3.1. Which Are the Main Drivers that Influence Grassland Degradation?

In Akiyama and Kawamura [9] review, they discussed several mechanisms of grassland degradation highlighting climate change and anthropogenic disturbances as the two main underlying factors that lead to degradation. Globally, the factors of climate change most related to grassland degradation are warming and the increase in the frequency of prolonged droughts [13,16,17,33,35,49]. Liu et al. [18], Gang et al. [17], Yang et al. [50], and Zhou et al. [20,51] presented quantitative assessments of the relative roles of climate change and anthropogenic perturbations, revealing that any of them can be the dominant driver of degradation depending on the study context. However, most of these studies did not consider the interactions between drivers. In this sense, Sala et al. [52] shows that there is clear evidence to support nonlinear responses of ecosystems and synergistic interactions among many global drivers of biodiversity change (e.g., invasions of alien species that are promoted by both human disturbances and climatic changes). On the other hand, Klein et al. [53] evince a decrease on ANPP and forage quality (for a of 1.0–2.0 °C warming) but also showed an interaction with grazing that could mitigate that decline. Additionally, Carlyle et al. [54] analyzed different grasslands types and found, by manipulating temperature, water, and grazing conditions, that biomass production depends on the interaction between the three variables under site-specific conditions.

Overgrazing, which occurs when stocking rates exceed the carrying capacity of grasslands, is the most widespread anthropogenic driver of degradation [9,55,56]. In fact, stocking rates are less variable than the carrying capacity, and this is ultimately related to primary production and, therefore, to the climatic conditions. In this way, overgrazing clearly interacts with climate variability. In this regard, Liu et al. [18] report that Mongolian steppe degradation can be attributed both to climate change (decreasing precipitation and increasing temperature) and to the increase in the stocking rate. On the other hand, extreme under-grazing (or grazing abandonment) could also be a source of degradation affecting productivity and species composition. Although long term livestock exclosures increased standing biomass and vegetation cover, and they may be a useful management tool to restore the vegetation in degraded grassland of arid regions [57,58], they sometimes decreased grassland biodiversity [59,60] and ANPP [59].

Regarding grassland degradation, there is a long-standing controversy about the use of fire. On one hand, Snyman [61] suggested that fire may potentially degrade semiarid grassland based on the fact that the recovery of the above and below ground biomass production and water use efficiency, took at least two years after burning. On the other hand, the use of fire appears to be relevant in fire-prone communities (e.g., mesic grasslands) where fire is an evolutionary force that has been used for hundreds of years to maintain grassland structure and function [62].

Finally, the improper fertilization and/or exotic species introduction [63–65] and invasive alien species [66] are also other important factor influencing grassland degradation.

3.2. How Ecological Process Are Affected by Grassland Degradation?

3.2.1. Energy Flux

The most direct signs of grassland degradation are the change in vegetation parameters such as the decrease in litter mass, vegetation cover and height [12,31,67,68]. At the same time, the decline in vegetation vigor in degraded grasslands is also reflected in the decrease of the canopy leaf area index. This is highly relevant, since the leaf area index is one of the main controllers of the primary production through its role in the photosynthesis [69–71]. On the other hand, the decrease in vigor of the vegetation could be accompanied by the substitution of high forage quality species for low forage quality ones [8,31,35,67]. This species turnover could lead to a lower leaf area efficiency than non-degraded grasslands and, therefore, to a greater reduction in plant growth.

3.2.2. Biogeochemical Cycles

Grasslands have a high potential for carbon storage; however, this capacity strongly depends on how grasslands are managed [72]. The decrease in litter and plant cover in degraded grasslands can lead to a slowdown of the nutrient cycling [67,73,74] and to a significant reduction of soil organic carbon [12,74–79] and nitrogen [80]. Additionally, the reduction in plant cover also results in a reduced infiltration, which in turn, increases soil erosion [81] and reduced soil water content [82]. This process can also slow down even more the nutrient cycling process via feedback cycles.

3.2.3. Water Cycle

The hydrological functioning of grasslands could change dramatically by the decrease in plant and litter cover. The decline in plant cover can lead to an increase in soil bulk density and a decline in the soil structural stability [67,83,84]. The degradation of grasslands increases evaporation rates [85,86] and surface runoff [83,87], reducing soil-water infiltration capacity [67,83,84]. This in turn reduces the effective soil water content [43] and increases soil loss due to erosion [88], leading to greater risks of degradation [89]. This process is highly relevant in semiarid regions, where plant and litter cover are scare per se.

3.3. What are the Main Consequences of Grassland Degradation?

In countries with most of the territory occupied by grasslands and where extensive livestock production is an important economic activity, grassland degradation can cause significant economic and environmental problems. Some economic consequences arise, such as the decreased capacity to produce commodities [24,45,90] (e.g., meat and wool). This occur because degraded grasslands have a decreased capacity to provide forage for livestock (e.g., decreased ANPP) [8,18,24,26,35,55,91,92]. In addition, in degraded grasslands, high forage quality species could be replaced by low productive species [8,31,35,67], with the consequent loss of forage nutritional value [31]. Such changes imply a reduction in the carrying capacity and, therefore, a reduction in livestock production [9,56].

The degradation of the ecosystem services (benefits that society receives from ecosystems) involving water and nutrient cycle, energy flow, climate regulation, biodiversity and erosion control among others [6], has been repeatedly reported as one of the main consequences. Wen et al. [93] reported that primary production and other ecosystem services (carbon storage, nitrogen recycling, and plant diversity) of degraded grassland were always lower than those provided by non-degraded ones.

Changes in surface properties of the ecosystems, could severely affect the energy balance, which may affect the regional climate [94–96]. The decrease in litter quantity, vegetation height and biomass [12,31,67,68]; the replacement of high forage quality species by low quality ones [8,31,35,67]; the increase in runoff and soil losses [88]; and the decrease in litter [73], are key processes that, separately or together, can lead to a reduced plant growth which results in a lower secondary production.

Grassland degradation decrease soil organic carbon and nitrogen stocks and promote the emission of greenhouse gases into the atmosphere [12,80,93]. According to the two-year study of Zhang et al. [80], total carbon and nitrogen stored in a semiarid grassland ecosystem was reduced, under severe degradation conditions, by 16% and 10% respectively. Indeed, in a comprehensive meta-analysis Dlamini et al. [79] showed that grassland degradation reduced soil organic carbon by 16% and 8% in dry and wet climates, respectively. In some regions, degradation goes beyond its effects on ecosystem services, as it can lead to the completely loss of grassland habitat or to desertification [97].

Other important consequence of grassland degradation is the loss of animal and/or plant biodiversity [24,35,65]. Grazing usually increases species richness in mesic grasslands, while it generally reduces species richness in semiarid and arid grassland [98–100]. Even though there are some analysis as the one reported by Eldridge et al. [101], where grazing reduces ecosystem structure, function, and composition on different bioclimatic conditions (arid to humid and sub- humid) in Australia, the negative effects of grazing were greater in drier environments. Nevertheless, the way in which species decrease in overgrazed grasslands is mostly dependent on the grazing history and the position on the moisture gradient [102]. In mesic grasslands with long history of grazing, the peak of species richness generally occurs under moderate grazing intensities [102–104], meanwhile in sites with short history of grazing this peak happen at light grazing intensities. On the other hand, in semiarid grasslands with a long history of grazing, this peak take place at light grazing intensities, and then, as grazing intensity increases, species richness should decline slightly; meanwhile in sites with short history of grazing the species richness decrease linearly with the increase of grazing from non-grazed to severe grazing intensities [102,103].

4. Conceptual Framework Adapted to RPG

The South American RPG are one of the largest temperate and subtropical grasslands regions in the world. The RPG cover the central-eastern part of Argentina, most of Uruguay and southern Brazil [105] (Figure 2).

In the RPG, extensive livestock production has taken place for more than 300 years and therefore stocking rate management is a key factor for grassland conservation [106]. Specifically, the RPG have a predominance of C4 grasses, and C3 grasses to a lesser extent, and are the habitat of 4864 plant species [19]; 385 bird species and 90 mammal species [107].

Figure 2. Map of South America highlighting the Río de la Plata grasslands region. Adapted from Miñarro and Bilenca [43].

Causes for degradation in RPG extensive livestock-based systems have been reported by many researchers, such as: (i) overgrazing by animals [56]; (ii) invasive alien species [108]; and (iii) nutrient addition and/or the introduction of exotic forage species into native grassland [63–65].

In RPG, animals graze all year round at relatively constant stocking rates [31], while ANPP of these grasslands shows large seasonal and inter-annual variations [109]. Under these conditions, grasslands can become recurrently overgrazed, mainly when periods of low forage production (e.g., severe droughts) coincide with high stocking rates. Indeed, the decreased forage biomass and the substitution of palatable species by unpalatable ones that can lead to a reduced plant growth and forage quality [8,31] are some of the processes that most concern in RPG. Besides that, weed invasions [108,110] and degradation promoted by fertilization and exotic forage species over-seeded in native grasslands are also concern. In these cases, the invasive weeds and the over-seeded species often weaken native species as they compete them for resources, such as space and light. However, as the over-seeded species do not persist, they end up facilitating the colonization and dominance of invasive species [65].

The consequences of overgrazing by livestock in RPG are strongly dependent on grassland type. Studies of Altesor et al. [59] in Southern Campos in Uruguay, Jaurena et al. [111] in northern Campos in Uruguay, and Fedrigo et al. [56] in Campos in Río Grande do Sul-Brazil indicate that these grasslands are particularly resistant to overgrazing. Meanwhile, in the Flooding Pampa in Argentina, the increase of grazing intensity induces a quick replacement of C3 and C4 native grasses by exotic annual forbs and grasses [112]. In addition, the most problematic invasive weed in the RPG is *Eragrostis plana* Nees, which has already invaded 20% of the native grassland in Río Grande do Sul, decreasing native plant diversity and livestock production [113].

4.1. How Did Experts Percived the Degradation of Natural Grassland?

According to the expert survey, in most cases, the experts recognized that the grassland degradation is strongly dependent on grassland community, related mainly to different soil types. They referred to degradation as a complex process that have diverse dynamics on each specific community or specific region. Most of the experts focused on the importance of the primary (plant) and secondary (animal) productivity. Some of grassland management specialist mentioned that the dominance of some exotic forage species, if they are palatable and nutritious for livestock, they did not consider the presence of these species (e.g., ryegrass *Lolium multiflorum* Lam.) to be an indicator of degradation. On the other hand, others defined the degradation problem related to the abiotic conditions that cause a change in the community state which is not reversible after the disturbance occurs.

4.2. *Which Indicators Are the Most Important to Characterize Degradation?*

According to the conceptual framework previously described (Figure 1), we identified the drivers, process indicators, and consequences related to degradation from the literature review and experts survey. It is noteworthy that 63% of papers alluded to process indicators, 50% mentioned at least one driver, and 36% referred to consequences. The most commonly cited drivers (46% of the papers) were related to human-induced processes (mainly overgrazing). Loss of ecosystem processes, service and function (24%) and soil erosion (10%) were the most frequently declared consequences.

Half of the experts identified overgrazing in specific communities as the most mentioned driver. The most commonly cited consequences increased soil erosion (41%) followed by reduction of resilience (including drought resistance) and the reduction of livestock production (28% each).

The most frequently mentioned indicators were vegetation or bare soil cover, productivity (ANPP related to the potential of the community), plant species or functional groups diversity, and species and functional type composition.

It is worth noticing that climate change was not considered to be an important driver for the experts but is was cited on the 15% pf the papers. Although drought resistance and resilience were mention as important consequences in the expert survey.

A comparison of the most relevant indicators extracted from the two different scales addressed in the study (regional and global) is shown in Table 1.

Table 1. Frequency (%) of the most relevant indicator mentioned in the literature review (from a total of 67 analyzed papers) and expert survey (from 29 experts who answered the survey). Some papers or experts mention more than one indicator. The "+" and "−" signs indicate the effect of the natural grassland's degradation on that indicator: a decrease (−) or an increase (+). Indicators are grouped following the conceptual framework present in Figure 1. *1 (overgrazing, under-grazing, fragmentation); *2 (high forage value: quality and stability in time); *3 (related to livestock preference); *4 (mainly livestock production); *5 (water cycle, nutrient cycle, energy flow, species dynamic).

Conceptual Category	Subtopic	Indicator	Effect	% of Papers (Literature)	% of Experts (Survey)
Drivers		Human–induced processes *1 [6,8–10,13–16,25,29,34,35,52,55,56,63–65,91,92,106,114–122]		46	52
		Result of natural events (drought, climate change) [13,14,16,17,25,33,35,49,55,115]		15	
Process indicators	Productivity	Productivity (ANPP related to the potential in a specific soil type) [12,15,24,25,29,32,34,36,45,55,90–92,115,123,124]	−	24	55
		Vegetation and/or bare soil cover [12,24,25,32,34,55,108,110,114,116,125–127]	− or +	19	72
		Productivity indicator species % *2 [4,123,124]	−	4	45
		Plant height [12,92,125]	−	4	31
		Biomass or Forage availability [9,10,14,35,55,92,115,126]	−	12	7
		Quality indicator species (%) *3 [14,24,25,29,31,128]	−	10	10
	Biodiversity	Plant species richness, plant or functional groups diversity [8,12,24,26,29,34,35,65,123,125]	−	15	55
		Species and functional type composition [8,29,115,123,126]	− or +	7	55
		Weeds (%) [8]	+	1	41
		Structural heterogeneity [29]	−	1	48
		Non–native plant species % [65,108,110,127]	+	6	41
		Key, endemic or rare species [32]	−	1	28
	Soil process	Soil bulk density [32,87]	+	3	17
		Soil organic matter [32,74–78,92]	−	10	14
		Soil nutrients [29,35,116]	+	4	21
		Litter presence [67,68,73]	−	4	10

Table 1. *Cont.*

Conceptual Category	Subtopic	Indicator	Effect	% of Papers (Literature)	% of Experts (Survey)
Consequences		Soil erosion [29,34,35,67,87,88,116]	+	10	41
		Drought resistance and resilience [18,24,76,129]	−	6	28
		Secondary production *4 [9,24,34,45,56,90,123,129]	−	12	28
		Ecosystem processes, services and function *5 [12,15,24,29,32,45,56,67,74,75,83,84,87,88,123,124]	−	24	23
		Plant health [15]	−	1	21
		Soil seed bank [130,131]	−	3	3

4.3. Conceptual Framework Proposed of Monitoring Río de la Plata Grassland Degradation

According to the information discussed above, a complete conceptual framework diagram presenting the relation between those concepts is shown in Figure 3.

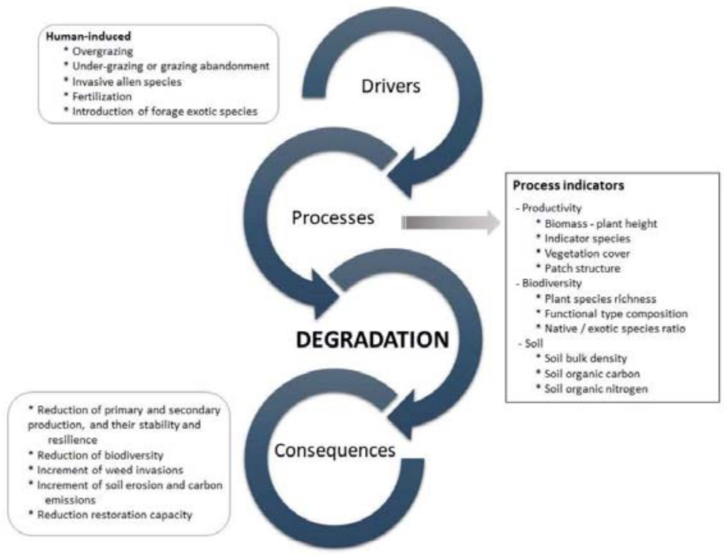

Figure 3. Proposed conceptual framework of RPG degradation with drivers, process indicators, and consequences based on literature review and expert survey.

5. What is a Degraded Native Grassland?

The term "degradation" referring to the condition of a natural grassland, is widely used in different circumstances by different stakeholders (from researchers and rural extension agents to policy makers), without a common agreed definition. Based on our review and considering that the interaction of grassland and herbivorous is the central key of the analysis, we propose as common definition of grassland degradation, a retro-progressive process in which a grassland community changes to a lower quality state, losing its capacity to be grazed by herbivores. Specifically, grassland degradation happens when you have a general decrease in productivity, soil properties, and diversity due to human activities and natural processes. This new definition is based on the fact that as plant communities degrade, above ground standing biomass and plant production decrease [12,18,29,67,68], and soil-vegetation cover and litter amount decrease too [67,74]. These effects could occur in conjunction with changes in species composition [8,29,35,67], reductions in species diversity [24,35,65], increased soil erosion [35,67,87,88] and augmented soil nutrient loss [67,74]; among other important effects. In all cases, different stakeholders agree that the degradation process leads to a lower quality of grassland ecosystem.

6. Discussion

The importance of natural grasslands to food security, to the provision of ecosystem services, and to the economy of many developing countries such as Uruguay, Argentina, and Brazil, imply that their degradation is a major political, economic, and environmental issue. This importance is reinforced by the experts' perception that degradation can be increased by the effects of livestock production intensification and climate change. Although it is widely known and repeatedly reported in the literature that overgrazing is one of the main global drivers of degradation, the experimental evidence of irreversible changes to degraded states in RPG is limited and it is highly dependent on the community type. The STMs developed in the RPG region by Andrade et al. [132] provide a conceptual framework of stages and thresholds that help researchers to study degradation and restoration. In the present review paper, we advance in the theoretical framework detailing the main drivers, process indicators, and consequences. Despite some differences evidence on the global literature review and the regional expert survey, some of the most frequently mentioned topics were the same, and they have some common process indicators, suggesting that the problem of degradation may have a common interpretation. Taking this into consideration, grassland degradation for livestock production could be monitored assessing drivers, process indicators, and consequences as in the propose framework.

From our perspective, to further advance in the knowledge of grassland degradation process in RPG, we represent the interactive effects of rainfall variability and overgrazing, in new conceptual STMs (Figure 4A–D). Specifically, to support the decisions of ecosystem management, these models try to link (i) multiple drivers operating simultaneously, in different site-specific conditions (e.g., soil types bioclimatic zones and evolutionary history of grazing), (ii) the main process affected (e.g., decreased on primary production by a reduced of the leaf area index, or the reduction on plant species diversity by an increment on interspecific competitive exclusion for light) and its indicators, and (iii) the expected consequences of management practices in different climatic scenarios.

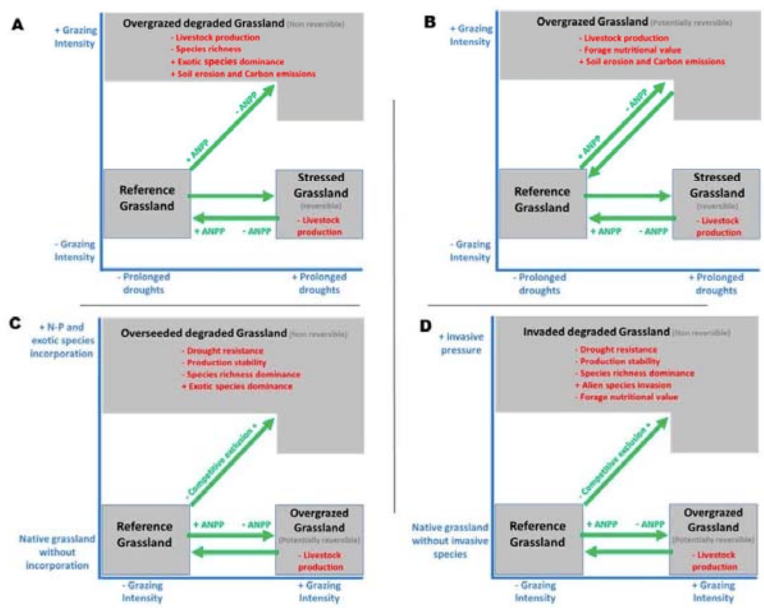

Figure 4. Conceptual framework proposed for the study of grassland degradation in the RPG represented by four state and transition models: (**A**) Grassland degradation by overgrazing and increased rainfall variability in sites with short evolutionary history of grazing; (**B**) Grassland degradation by overgrazing and increased rainfall variability in sites with long evolutionary history of grazing; (**C**) Grassland degradation by intensification (nitrogen and phosphorous incorporation combined with over-seeding of exotic forage species) with different grazing intensities; and (**D**) Grassland degradation by invasive alien species with different grazing intensities. Drivers are remarked in blue, process in green and consequences in red. ANPP (above ground net primary production). The two-sided arrows represent potentially reversible processes when the disturbance is removed, while the one-sided arrows represent an irreversible shift to a degraded state.

Some studies conducted in the Flooding Pampas in Argentina [112,133] reveal that grazing would induce rapid changes to alternative degraded states (Figure 4A). However, on the other hand, studies carried out on Campos grasslands [56,134] suggest that grazing intensity and climate variability would induce phase changes within states (slow, continuous and reversible community changes), but would not cause change into alternative degraded stable states (Figure 4B). Similar results are reported by Porensky et al., [135] in northern mixed-grass prairie in the USA. The differences in responses of plant community to overgrazing, which experts mentioned repeatedly, could be related with the interaction between grassland bioclimatic conditions and the evolutive history of grazing [103]. However, there is a lack of knowledge in that history on a specific region with an adequate spatial-temporal resolution, this has repercussions in being able to capture grassland dynamics (essential to understand short term evolution). To overcome this limitation, Oesterheld and Semmartin [136] propose to consider the regional set of species, the covariation of production and grazing intensity, and the positive biotic interactions that protect plants from herbivores, for a better understanding of why different grasslands communities respond differently to grazing. Additionally, invasive alien species [108] and nutrient addition and/or the introduction of exotic forage species into native grasslands [63–65] in interaction with grazing intensity would induce changes to alternative degraded states (Figure 4C,D).

As we already mentioned, grassland degradation has become a widespread and common problem in different regions of the world and in this review paper we have found that different regions and grassland types have some common drivers, process, and consequences related to degradation and thus, have the potential to be analyzed and monitored by a common framework. However, the reviewed articles also revealed that other drivers, processes and consequences were common within a similar rainfall variability conditions, and different according to a bioclimatic gradient and evolutive history of grazing. Climate change appears to be a significant driver on arid grasslands [20,50,51,137] while it is not mentioned in humidity grasslands analysis. On the other hand, light grazing intensity or grazing exclusion, have different effects depending on the bioclimatic region, with a positive effect on arid environments [57,58], and a negative one on humidity regions [59,60]. Regarding consequences, desertification is exclusively reported on arid and semiarid areas [9].

Although it seems that the responses to the underlying drivers of degradation are different between semiarid, mesic, and humid grasslands, we suggest that this bioclimatic gradient mask the true effect of rainfall variability. The results of Davidowitz [138] showed that more drier grasslands generally are climatically more variable than the humid ones, so inter-annual rainfall variability is inversely related to its mean. For many processes, inter-annual rainfall variability can be a more important climatic parameter than the average precipitations [139]. For instance, where rainfall variability is high in relation to its average, species need to adapt to first survive prolonged drought periods and then, to take advantage of long rainfall periods [140]. Additionally, in arid and semiarid rangelands, the variability in ANPP could be higher than variability in rainfall [141,142].

Although several studies quantified the effects of climate change and anthropogenic management on grassland degradation, simulating actual vs. potential net primary production effects [17,20,50,51,135], their interactions have not been addressed and the effect of frequency and intensity increment of extreme precipitation events on grassland degradation, remains almost unexplored.

In this review, we found that most of grassland degradation studies were conducted in water-limited grasslands. In these grasslands, prolonged droughts and overgrazing are the two common underlying drivers that lead to degradation. Sloat et al. [143] found that grasslands regions with high rainfall variability support lower livestock densities than less-variable areas. Considering that stocking rates are less variable than the carrying capacity and therefore than climatic conditions, overgrazing clearly interacts with the increased rainfall variability. From these non-equilibrium concept of grassland dynamics proposed by Ellis and Swift [144], it has been predicted that the potential degradation by overgrazing is low in environments with relatively high rainfall variability. These studies argue that in periods of drought, herbivores population is reduced, thereby decreasing their potential to degrade grasslands. We consider that this application of the non-equilibrium concept could contribute to understand the dynamic of wildlife-based ecosystems where animals self-regulate their populations during prolonged droughts. However, this is not the general case in extensive livestock-based systems where farmers seek to maximize profit. In this context, farmers have two contrasting scenarios for the application of management practices to mitigate drought effects. On one hand, they could provide supplemental emergency feed (e.g., crop residues or grain by-products), use stockpile forage and facilitate the access to water sources to minimize animal mortality and to avoid weight losses in drought periods, maintaining the stocking rates. This managements practices could lead to a positive feedback that cause further degradation [145]. As a second option, if these same management options are combined with the reduction of the stocking rate to match availability of lower forage and to minimizes the effect of grazing on vegetation, a negative feedback could probably occur that will prevent degradation.

The diversity of grasslands, the differential impacts of climate and management on them, and the variety of uses and human dimensions throughout the world, are the main reasons for the coexistence of different conceptual significances of degradation. de Queiroz [45] state that definitions of degradation are different depending on the human management objectives. Given that these objectives can differ, the definitions of what constitutes degradation also differ. We argue that definitions can also differ due to emphasis on different conceptual categories related to degradation and that is why it is important of clarify these conceptual categories. Moreover, the concept of degradation does not denote the same set of conditions for different stakeholders. Bedunah and Angerer [5] highlighted the complexity of the term degradation by claiming that rangeland scientists need to have a key role in collecting, understanding, and commenting on degradation definitions used by stakeholders. Agreeing on a definition of a complex concept such as grassland degradation is also important for research purposes, since it contributes to identify what processes need to be described and which variables need to be measured to systematically assess the degree of degradation.

7. Conclusions

Grassland degradation has multicausal drivers; however, the complexity of this process remains mostly unexplored, since most of the studies focus on single drivers of vegetation change. From our study, we proposed a new conceptual model which consider the multiple drivers that operate simultaneously and their interactions in different site-specific conditions.

Despite the difference in scale (global and regional), some of the mentioned topics were the same and they have some common process indicators suggesting that the problem of degradation, may have a common interpretation and can be analyzed with a common conceptual framework.

We believe that the proposed conceptual framework for the degradation of grasslands used for livestock production is a valuable contribution to monitoring programs and to support grassland management decisions, by clarifying the different concepts involved in the process (drivers, process indicators, and consequences) and structuring the degradation analysis allowing identifying key aspects. In addition, the framework could be a useful tool to communicate the importance of grasslands conservation, both to a general audience and to specialists in the field.

Despite this, we also found that some drivers, process, and consequences were common within a bioclimatic zone and could be different along a bioclimatic gradient. This gives some particularities to the systems that needs to be abroad and could be also analyzed according to the proposed conceptual framework.

Considering the RPG region, we expect that this paper will contribute to reach a conceptual update of grassland degradation based on the mentioned concepts that can help to promote a dual goal of production and conservation in this important and often neglected ecosystem.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/5/239/s1, supplementary file: Supporting Literature review.pdf.

Funding: This research has been conducted as part of a Ph.D. program (Facultad de Agronomía, Universidad de la República, Uruguay) supported by the Agro-climate and Information System Unit (GRAS) of the National Agricultural Research Institute (INIA Uruguay) and a partial scholarship provided by the National Agency for Research and Innovation (ANII Uruguay).

Acknowledgments: We want to especially thank the experts who took the time to answer the questions or discussed the topic. We also want to thank Cathy Vaughan from IRI (International Research Institute for Climate and Society Columbia University) and Andrea Ruggia from INIA (National Institute of Agricultural Research, Uruguay) for their comments, reviews, and contributions. Finally, a special mention to Valentín Picasso from the Agronomy Department, University of Wisconsin for his great contribution to this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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Supporting Literature review. List of the 100 papers from the literature review. Papers that provide an explicit definition of the concept of "grassland (or rangeland) degradation" are marked in bold.

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3. ¿ES POSIBLE MONITOREAR ALTURA DEL TAPIZ EN CAMPO NATURAL CON INFORMACIÓN SATELITAL EN URUGUAY?

3.1. RESUMEN

En los países donde la producción ganadera, basada en campo natural, es una actividad económica importante, la información sobre las características estructurales del forraje es esencial para respaldar políticas nacionales y decisiones a nivel de establecimiento. La teledetección aparece como una buena opción para cuantificar grandes áreas en un tiempo relativamente corto, con un bajo costo y con la posibilidad de analizar la evolución anual y serie históricas. Este trabajo tuvo como objetivo contribuir a mejorar las decisiones de manejo mediante la evaluación de la capacidad de la información satelital para estimar la altura del forraje, como un estimador de la biomasa disponible. Se analizaron los datos de campo (altura de forraje) de 20 potreros bajo pastoreo (322 muestras) y su relación con variables provenientes del sensor MODIS (FPAR, LAI, MIR, NIR, Red, NDVI y EVI). Los valores de los coeficientes de correlaciones entre ésta variables (satelital y mediciones de campo) fueron bajos. Esto puede deberse a la gran variabilidad encontrada dentro de cada parcela en las observaciones de campo (CV: alrededor del 75%) en relación a la encontrada en la información satelital (MODIS: CV: 4% - 6% y Landsat: CV: 12%). A pesar de esto, la banda roja mostró potencial (con valores significativos de coeficientes de correlación en el 41% de los potreros) y justificaría una mayor exploración. Es claro que se necesita trabajo adicional para encontrar un método basado en teledetección que pueda ser usado para monitorear adecuadamente la altura de los pastizales.

Palabras clave: teledetección, ganadería, forraje, MODIS, campos remote sensing

MDPI

Article

Can we Monitor Height of Native Grasslands in Uruguay with Earth Observation?

Guadalupe Tiscornia [1,*], Walter Baethgen [2], Andrea Ruggia [3], Martín Do Carmo [4] and Pietro Ceccato [2]

1 Agro-climate and Information System Unit (GRAS), National Institute of Agricultural Research (INIA Uruguay), Ruta 48 KM.10, Canelones 90200, Uruguay
2 International Research Institute for Climate and Society (IRI), Columbia University, 61 Route 9W, Palisades, NY 10964, USA
3 National Research Program of Family Farm Production, National Institute of Agricultural Research (INIA Uruguay), Ruta 48 KM.10, Canelones 90200, Uruguay
4 Centro Universitario de la Región Este, Universidad de la República (Uruguay), Ruta 9 y Ruta 15, Rocha 2700, Uruguay
* Correspondence: gtiscornia@inia.org.uy

Received: 4 June 2019; Accepted: 30 July 2019; Published: 1 August 2019

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Abstract: In countries where livestock production based on native grasslands is an important economic activity, information on structural characteristics of forage is essential to support national policies and decisions at the farm level. Remote sensing is a good option for quantifying large areas in a relative short time, with low cost and with the possibility of analyzing annual evolution. This work aims at contributing to improve grazing management, by evaluating the ability of remote sensing information to estimate forage height, as an estimator of available biomass. Field data (forage height) of 20 commercial paddocks under grazing conditions (322 samples), and their relation to MODIS data (FPAR, LAI, MIR, NIR, Red, NDVI and EVI) were analyzed. Correlations between remote sensing information and field measurements were low, probably due to the extremely large variability found within each paddock for field observations (CV: Around 75%) and much lower when considering satellite information (MODIS: CV: 4%–6% and Landsat:CV: 12%). Despite this, the red band showed some potential (with significant correlation coefficient values in 41% of the paddocks) and justifies further exploration. Additional work is needed to find a remote sensing method that can be used to monitor grasslands height.

Keywords: remote sensing; livestock; forage; MODIS; campos

1. Introduction

Native grasslands are one of the largest ecosystems in the world with an estimated cover area of 40 to 50 million square kilometers [1,2]. They are defined as natural ecosystems dominated by naturally occurring grasses and other herbaceous species with the possible presence of woody species, used mainly for grazing by livestock and wildlife [3].

As population increases, grasslands are becoming important contributors to human food supply (meat and milk), while providing other important ecosystem services, such as carbon sequestration, genetic material storage, water quality, and soils conservation [4,5].

The Río de la Plata grasslands (located between 28° S to 38° S) are among the world´s largest temperate-subtropical grasslands, covering the central-eastern part of Argentina, all of Uruguay, and southern Brazil. These grasslands are subdivided into "pampas" and "campos" [6]: The former are temperate treeless grasslands located in eastern and central Argentina on flat and fertile plains, humid to arid climate, with warm summers and mild winters [3]. "Campos" are grasslands consisting mainly of grasses, along with other herbaceous species, small shrubs, and occasional trees. They occur on undulating and hilly landscapes, with variable soil fertility, in sub-tropical humid climate, warm in summer and mild in winter, found in Uruguay, southern Brazil, and north-eastern Argentina [3].

In Uruguay, livestock production is mainly based on extensive grazing of native grasslands, which represent over 65% of the country's total area. Uruguay has a wide diversity of soil types [7] and, as a consequence, its grasslands are heterogeneous including tens of species per m^2 [8,9] and a total of more than 350 registered species [10]. These grasslands have a predominance of summer growing species (C4) with an increase in frequency of cold-season species (C3) during autumn and winter [7]. Considering that warm-season species are responsible of the highest forage production (in spring and summer), and that this is the season with highest rainfall variability, the risks related to drought are very high [7].

In environments with large variation in herbage production, due to seasonal and interannual variability in rainfall and temperature, the optimal stocking rate needed to reach a specific performance target varies widely among seasons and years [11–13]. The control of grazing intensity through the management of stocking rate is an important tool to regulate the amount of solar energy captured and converted into beef production. Within this context, herbage allowance (HA), defined as kilograms of herbage dry matter per kilogram of animal body weight [3,14], may be more useful than stocking rate for managing the grazing process [15]. Managing HA requires herbage mass estimation, or a proxy like herbage height [16].

Information related to structural characteristics (herbage height or biomass) of native grasslands is essential to support management decisions, not only at the farm level but also at national and regional levels, to inform policy making. This results in demands on researchers to generate "low cost, appropriate and timely information that can be provided to farmers to support their decision-making" [17]. Bearing in mind that existing field methods are labor-intensive and time-consuming, it is difficult to extend HA control to large areas. In this context, remote sensing monitoring is a promising option for quantifying large areas in a relative short time at a comparatively low cost and offering the possibility of analyzing historical data series.

Considerable research has been conducted to monitor indicators of the vegetation condition [18] and, more specifically, to characterize grasslands functioning. Thus, remote sensing has been used to estimate above ground net primary production (ANPP), with the advanced very high-resolution radiometer (AVHRR-NOAA) and the moderate-resolution imaging spectroradiometer (MODIS) [19–24]. Annual grassland biomass has also been estimated using different satellite sensors (MODIS, SPOT, and AVHRR) with good results in Northern China [25] and in the Sahel [26].

Other ecosystem's structure and function attributes have also been related to vegetation indexes coming from Earth observation. In the Patagonia steppes, Gaitan et al. [27] assessed the relationship between cover and species richness with nine different vegetation indicators. The authors showed that NDVI explained 30%–40% of the total variability found in these ecosystem attributes. In the arid southwest grasslands of North America, the total herbaceous vegetation cover (green and senescent), height, and biomass estimated using the soil adjusted total vegetation index (SATVI) for cover and the near infrared band from Landsat for height and biomass, was highly correlated with observed information [28].

Grasslands biophysical parameters, mostly considered in a season or in annual base, have been retrieved from Earth observation for many years. Recently, the modelling approaches are evolving to more complex, robust, and efficient ones [29]. Also, some studies included higher-resolution sensors such as Sentinel 2 or modern technologies such as radar (active sensor) [30–32]. However, more research is needed to accurately estimate the intra-annual performance of some biophysical variables as biomass or height.

In this work, we tried to estimate observed grasslands behavior as a "photograph" of what was available in terms of forage height at different time steps along the year. This approach differs from estimating the height as the annual or seasonal accumulation of biomass. Our approach seems to be particularly important for improving management of livestock production systems. We also analyzed intra paddock variability at different spatial scales.

In this context, the objective of this study was to contribute to improve grazing management by evaluating the ability of remote sensing information to estimate forage height (as an estimator of available biomass) at paddock scale.

2. Materials and Methods

2.1. Study Area

The study was carried out on 11 commercial farms located in Uruguay (30°–35° S, 53°–59°W), South America. Seven of them were located in the eastern region and the other four in the central zone of the country (Figure 1).

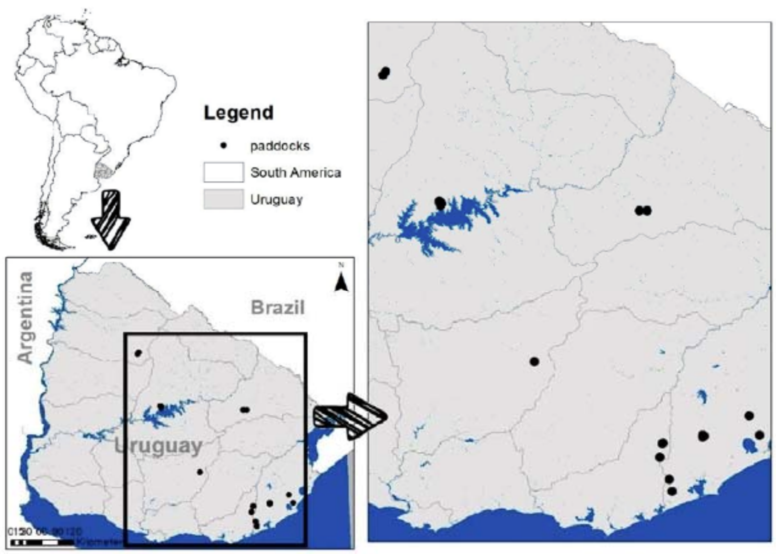

Figure 1. South America map highlighting Uruguay (up-left corner) and paddock´ location in Uruguay (bottom left corner and right).

2.2. Data

2.2.1. Farm Data

A total of 20 natural grasslands paddocks under grazing conditions, identified as 1 to 20, were analyzed. Six of the farms had only 1 analyzed paddock (paddocks 3, 4, 7, 14, 19, and 20), four farms had 2 paddocks, and one farm had 6 evaluated paddocks. The sizes varied between 12 has and 258 has. (Table 1).

Table 1. Area of the 20 paddocks analyzed in this study. Paddocks were designated from 1 to 20. Letters from A to K designate farms.

Paddock Number	Area (has)
3(B), 4(A), 7(C), 9(E), 10 (E), 19(D), 20(F)	12–50
8 (E), 11 (E), 15 (G), 16 (G), 17 (H), 18 (H)	51–100
1 (I), 2 (I), 5 (K), 12 (E), 13 (E), 14(J)	101–150
6 (K)	>151

Farm data (forage height) were collected between October 2012 and December 2015 every 40–50 days, two times per season, in each of the 20 paddocks under grazing conditions, with a total of 322 data points. Each forage height estimation was collected using the standard "comparative yield method" [33] by trained experts, collecting 100 to 300 sampling points in a systematic procedure to evenly cover the paddock area and decreasing the sampling error as the observation number increased. In every case, and in order to avoid biases associated with the different users, every sample was taken by trained assistants and researchers.

Five to seven reference quadrats of 50 cm × 50 cm were located to cover height heterogeneity, and height was measured in five points for every quadrat. In these same quadrats, a five-level scale was defined, where "1" was the lowest height and "5" was the highest. These scale samples were transformed into height measures by applying the linear regression equations resulting from the analysis of the measurements of forage height and estimated scale within the reference quadrats for each paddock. After that, more than 100 points were sampled, and each observer had to assign a scale value to each point. A "0" value was assigned when bare soil was identified. Finally, we used the regression equation explained above to convert scaled values into height.

The forage average height, median, mode, and maximum values were estimated for each paddock at each date.

Each paddock was sampled on average 16 times (between three and 23) during the analysis period. When variables of every paddock were analyzed together, the 20 paddocks were included, but when each paddock was analyzed individually, paddocks with less than 10 sampling dates were discarded (paddocks 6, 8, and 10). Outliers due to annotations mistakes or sampling errors were removed from the analysis.

2.2.2. Satellite Data

Spatial and temporal resolutions are critical when grasslands biophysical parameters have to be monitored. Analyses were conducted based on MODIS information downloaded from Earth Data website (https://search.earthdata.nasa.gov/search). We selected MODIS products because of their good temporal resolution (daily), the relatively good spatial resolution (250 m, 500 m), and the possibility of easily escalating to regional or national level with the same image (only one Path and row for Uruguay). In addition to this, higher-resolution sensors (Landsat or Sentinel 2) have no daily information or had no information available for Uruguay for the period when the field data were obtained (Sentinel 2).

We worked with ESRI®ArcGis 10.4 for Desktop on MODIS sinusoidal coordinate system, reprojecting the farm paddocks originally generated on WGS84.

Relations between spatial data at different temporal and spatial resolutions, and field data, were analyzed to achieve the objective of the research. We used composite images because of the practicality and daily information in order to have the data closest to the field measurement date, to have every pixel of the same date and to be able to choose nearby date due to the assiduous presence of cloud cover in some part of the country and time of the year.

We computed the weighted average of satellite pixels within each paddock. We considered the trade-off between size and purity, trying to select a sufficient number of pure pixels [34]. In some cases, because of the shape of the paddocks, no pure pixels fitted in it. In those cases, we used the weighted average (percentage of the area within the paddock) estimated only with the non-pure pixels, which centroid fitted in that paddock (more than 80% of the pixel was located inside the paddock).

Composite MODIS data

From composite products and for the analyzed period, we used:

- MOD13Q1, 250 m V006 [35]. We selected the middle infrared band (MIR), near infrared band (NIR), and red bands; and the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI).
- MCD15A3H, 500 m V006 [36]. We used fraction of photosynthetically active radiation (FPAR) and leaf area index (LAI). According to Myneni et al. (2015), in this context and for this product, "LAI is defined as the one-sided green leaf area per unit ground area in broadleaf canopies and as one-half the total needle surface area per unit ground area in coniferous canopies. FPAR is defined as the fraction of incident photosynthetically active radiation (400–700 nm) absorbed by the green elements of a vegetation canopy".

Quality bands of composite products were also checked.

Daily MODIS data

We extracted daily information from October 2012 to December 2015 of every paddock. We used the bands and index described as follows:

- MOD09GQ (GQ). MODIS Terra/Aqua Surface Reflectance 250 m [37]. We selected the near infrared (NIR) and red bands; and estimated NDVI (NIR-Red/NIR+Red).
- MOD09GA (GA). MODIS Terra/Aqua Surface Reflectance 500 m. [37]. We selected MIR, NIR, and red bands; and estimated NDVI (NIR-red/NIR+red) and Normalized Difference Water Index, NDWI (NIR-MIR/NIR+MIR).

In order to select the MOD09 daily images, we analyzed zenith and azimuth angles for the sun and sensor positions. For each paddock, we selected cloud-free images that were closest to the field measurement date (no more than 15 days before or 15 days after). Considering that most of the chosen images had similar solar and sensor zenith angles, we avoided dates where sun and sensor were at the same side (azimuth angles with the same sign) because of the hot spot effect. We finally tried to select similar angles to have equivalent images conditions.

We also analyzed quality bands in order to identify the best data for the studied dates and paddocks. In this analysis, we found quality data that indicate good quality values, but when we visually checked the images, clouds were detected. Because of this, we also visually analyzed each selected image, to confirm that no clouds were present over the paddocks, in order to use them properly.

- MCD43A4 (Nbar). MODIS/Terra and Aqua Nadir BRDF (bidirectional reflectance distribution function) adjusted reflectance (NBAR), 500 m, V006 [38]. We selected MIR, NIR, and red bands; and estimated NDVI and NDWI.

Landsat data

Landsat images were only used to verify variability at different spatial scales due to their low temporal resolution (16 days) and the consequent high probability of cloud cover, which makes it more difficult to find available data (cloud free) for each sampling date. We downloaded and analyzed Landsat 8 (30 m spatial resolution) images (OLI/TIRS Level-2 Data Products—Surface Reflectance) from Earth Explorer website (https://earthexplorer.usgs.gov/) [39]. We only considered images visually identified as without clouds over the paddocks, within the period of 15 days before and 15 days after the field measurements date. We arbitrarily selected one band (NIR). Weighted average and standard deviation of Landsat NIR was estimated for each paddock.

We also estimated the standard deviation of NIR from both MOD09 products (GA and GQ) and MOD13Q1 for each paddock.

2.2.3. Data Analysis

We compared and correlated data obtained at paddock level with satellite data in order to identify variables that can predict native grasslands height and/or available biomass. We first analyzed the relationship between the variables by pairs and scatterplot's linearity was checked. An example of the analysis of median height vs. MODIS daily variables for all the paddocks is shown in Figure 2.

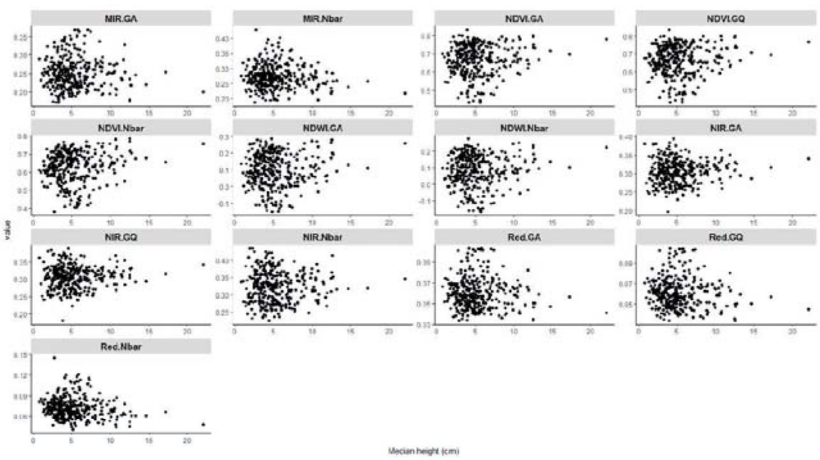

Figure 2. Scatterplot of median height (cm) in the x axes and MODIS satellite information in the y axes for all the analyzed paddocks. MIR: Middle infrared band, NIR: Near infrared band, Red: Red band, NDVI: Normalized difference vegetation index, EVI: Enhanced vegetation index. Nbar (MODIS/Terra and Aqua Nadir BRDF (bidirectional reflectance distribution function) adjusted reflectance (NBAR), 500 m), GA (MODIS Terra/Aqua Surface Reflectance 500 m), and GQ (MODIS Terra/Aqua Surface Reflectance 250 m) refer to the MODIS daily products analyzed.

Pearson coefficient of correlation was estimated for every paddock jointly and for each individual paddock. Spearman coefficient of correlation was also checked, reaching very similar values.

Variability within the paddocks was analyzed as well. Coefficient of variation, for each sampling date within paddocks, was analyzed for height measurement and pixels satellite information.

We worked with ESRI®ArcGis 10.4 for Desktop, R version 3.4.1, and R Studio software (Version1.0.143) to analyze farm measurements distributions and correlations.

3. Results

3.1. Farm Data

Figure 3 presents the results of height measurements for each paddock for the period October 2012–December 2015, showing the seasonal pattern. Regarding the inter-date variability in height, results showed differences in the observed measurements distribution for each paddock within dates. The average inter date coefficient of variation (CV) of the 17 paddocks selected for individual analysis was 76% (range: 53%–100%).

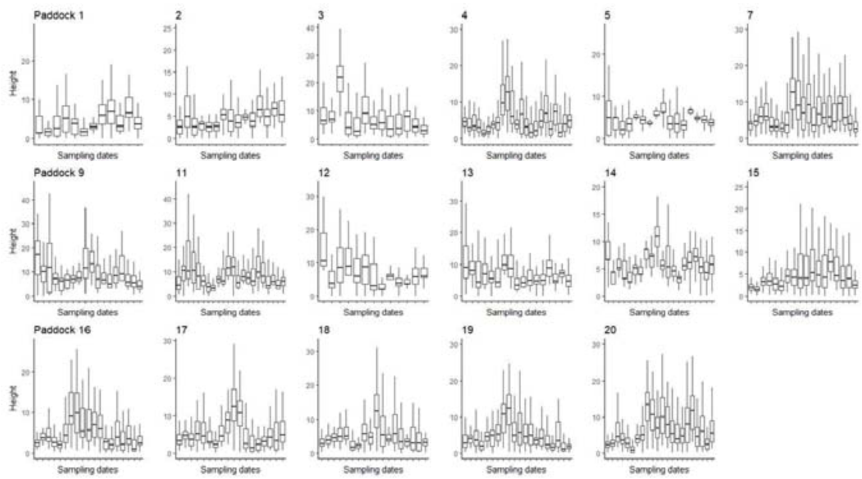

Figure 3. Height (cm) boxplot showing the distribution of observed data of each one of the 17 individually analyzed paddocks. Paddocks with less than 10 sample dates were discarded (paddock 6, 8, and 10). Sampling dates, from October 2012 to December 2015, are different according to each paddock.

3.2. Composite MODIS Data

Regarding composite images, Pearson correlations between median height and satellite information (FPAR, LAI, MIR, NIR, Red channel, NDVI, and EVI) for all the paddocks, showed non-significant values (lower than 0.1).

The correlation between median height and MODIS composite images for each paddock individually evidenced different performances depending on the paddock (Table 2).

Table 2. Pearson correlation coefficient between median height and composite MODIS satellite variables for every analyzed paddock (P). Significant ($p < 0.05$) correlation coefficient values are highlighted in grey. FPAR: Fraction of photosynthetically active radiation, LAI: Leaf area index, MIR: Middle infrared band, NIR: Near infrared band, Red: Red band, NDVI: Normalized difference vegetation index, EVI: Enhanced vegetation index.

P	FPAR	LAI	MIR	NIR	Red	NDVI	EVI
1	0.024	0.204	−0.335	0.041	−0.248	0.201	0.141
2	0.084	0.013	−0.355	0.042	−0.306	0.244	0.200
3	0.217	0.305	−0.606	0.173	−0.514	0.428	0.307
4	−0.605	−0.376	0.030	0.290	0.087	0.076	0.246
5	0.324	0.458	−0.182	0.289	−0.305	0.354	0.349
7	0.180	0.225	−0.094	0.079	0.146	0.029	0.067
9	0.603	0.468	−0.537	0.306	−0.481	0.571	0.543
11	0.555	0.363	−0.499	0.253	−0.323	0.411	0.390
12	−0.076	−0.036	0.091	0.228	0.119	−0.043	0.042
13	0.444	0.274	−0.402	0.229	−0.387	0.409	0.406
14	0.247	0.263	−0.471	0.285	−0.324	0.351	0.353
15	0.328	0.250	−0.407	−0.188	−0.380	0.240	−0.001
16	−0.235	−0.237	−0.728	0.059	−0.528	0.490	0.306
17	−0.478	−0.282	−0.400	0.065	0.130	0.370	0.335
18	−0.574	−0.390	0.003	0.098	0.571	−0.261	−0.002
19	0.447	0.363	−0.163	0.483	−0.190	0.543	0.588
20	−0.367	−0.282	−0.218	−0.063	−0.131	0.083	0.018

The remote-sensed variable that showed largest number of paddocks with significant and consistent (negative) correlation coefficient values, was MIR (Table 2). FPAR, despite having one more significant correlation values, showed no consistent results (positive in some cases and negative in others).

3.3. Daily MODIS Data

We first analyzed the correlation of remote sensing MODIS variables (MIR, NIR, Red channel, NDVI, and NDWI) with field information from all farms considered together. From this analysis, Pearson correlation coefficient indicated no significant correlation between observed data and satellite information (Table 3).

Table 3. Pearson correlation coefficients between height (median, average, mode, and maximum value) and daily MODIS satellite variables for all paddocks.

	H Median	H Average	H Mode	H Maximum
MIR (GA product)	−0.032	−0.018	−0.013	0.034
NIR (GA product)	0.090	0.070	−0.003	0.036
Red (GA product)	−0.085	−0.067	−0.041	0.008
NDVI (GA product)	0.108	0.087	0.037	0.012
NDWI (GA product)	0.079	0.058	0.013	−0.002
NIR (GQ product)	0.083	0.058	0.009	0.029
Red (GQ product)	−0.092	−0.077	−0.047	0.001
NDVI (GQ product)	0.112	0.092	0.047	0.016
MIR (Nbar product)	−0.087	−0.092	−0.008	−0.056
NIR (Nbar product)	0.014	−0.011	0.000	−0.051
Red (Nbar product)	−0.163	−0.156	−0.070	−0.092
NDVI (Nbar product)	0.136	0.121	0.060	0.051
NDWI (Nbar product)	0.081	0.070	0.011	0.016

Although all correlation coefficient values were low, they were higher when the median was considered (Table 3). This justifies the decision to consider the median as the most representative statistic of the observed values in the paddocks.

We then analyzed each paddock individually and assessed the correlation of all the satellite variables (MIR, NIR, Red channel, NDVI, and NDWI) with the field measurements. Pearson correlation coefficients with all satellite variables were generally low and, in some cases, not consistent, with positive correlations in some paddocks and negative in others. Despite this, there were some individual paddocks that had significant correlation ($p < 0.05$) with most of the analyzed satellite information. The highest coefficient was found with NDWI of MODIS GA product ($r = 0.68$, $p = 0.002$) but the Red channel of MODIS Nbar product have the highest number of paddocks with significant correlation values (7 paddocks from a total of 17). A linear relationship between satellite information and height median is shown in Table 4. No daily satellite information had significant correlation in every paddock together (Table 4).

Table 4. Pearson correlation coefficients between height and daily MODIS satellite variables for every analysed paddock (P). Significant ($p < 0.05$) correlation coefficient values are shaded in grey. MIR: Middle infrared band, NIR: Near infrared band, Red: Red band, NDVI: Normalized difference vegetation index, NDWI: Normalized difference water index. Nbar (MODIS/Terra and Aqua Nadir BRDF (bidirectional reflectance distribution function) adjusted reflectance (NBAR), 500 m), GA (MODIS Terra/Aqua Surface Reflectance 500 m), and GQ (MODIS Terra/Aqua Surface Reflectance 250 m) refer to the MODIS daily products analyzed.

P	MIR, GA	NIR, GA	Red, GA	NDVI, GA	NDWI, GA	NIR, GQ	Red, GQ	NDVI, GQ	MIR, Nbar	NIR, Nbar	Red, Nbar	NDVI, Nbar	NDWI, Nbar
1	0.002	−0.074	−0.010	−0.003	−0.027	−0.036	−0.029	0.021	−0.008	0.039	−0.001	0.000	0.014
2	0.246	0.122	−0.002	0.039	−0.105	0.135	−0.012	0.052	−0.214	−0.323	−0.161	0.015	−0.020
3	−0.525	0.314	−0.431	0.377	0.522	0.361	−0.333	0.329	−0.539	0.139	−0.645	0.500	0.492
4	−0.036	0.014	0.014	0.001	0.036	0.018	−0.080	0.069	0.062	0.028	−0.174	0.168	−0.019
5	−0.256	0.383	−0.429	0.464	0.372	0.377	−0.429	0.441	−0.067	0.362	−0.309	0.432	0.359
7	−0.180	0.258	−0.342	0.352	0.290	0.229	−0.293	0.323	0.071	0.137	−0.283	0.225	0.081
9	−0.546	0.519	−0.574	0.615	0.679	0.479	−0.558	0.597	−0.438	0.460	−0.547	0.619	0.600
11	−0.453	0.450	−0.467	0.494	0.520	0.386	−0.445	0.466	−0.349	0.422	−0.445	0.530	0.509
12	0.115	0.074	0.140	−0.106	−0.062	0.022	0.166	−0.140	0.120	0.002	0.040	−0.031	−0.103
13	−0.116	0.523	−0.136	0.246	0.334	0.481	−0.159	0.263	−0.358	0.192	−0.420	0.397	0.397
14	−0.288	0.276	−0.252	0.277	0.323	0.280	−0.226	0.261	−0.519	−0.015	−0.511	0.327	0.309
15	−0.425	−0.160	−0.472	0.257	0.136	−0.121	−0.301	0.167	−0.262	−0.002	−0.351	0.212	0.192
16	−0.482	0.371	−0.272	0.364	0.499	0.366	−0.221	0.315	−0.579	0.160	−0.607	0.533	0.576
17	−0.335	0.295	−0.390	0.469	0.430	0.283	−0.367	0.444	−0.172	0.202	−0.576	0.609	0.504
18	−0.268	0.211	−0.447	0.408	0.288	0.204	−0.475	0.415	−0.278	0.051	−0.420	0.353	0.342
19	−0.482	0.351	−0.555	0.523	0.501	0.328	−0.610	0.556	−0.257	0.250	−0.594	0.584	0.467
20	−0.061	−0.241	0.053	−0.097	−0.059	−0.162	0.020	−0.052	−0.266	−0.346	−0.268	0.008	−0.106

After analyzing these correlations and in order to check if any satellite information could provide an estimate of increase or decrease in height, we also checked for correlations between height and satellite information, estimating the differences between one date and the previous one (delta value). Pearson coefficients for each paddock and their statistical significance are shown in Table 5.

Table 5. Pearson correlation coefficients between delta median height (difference between one date and the previous one) and delta daily MODIS satellite variables for every analyzed paddock (P). Significant ($p < 0.05$) correlation coefficient values are highlighted in grey. MIR: Middle infrared band, NIR: Near infrared band, Red: Red band, NDVI: Normalized difference vegetation index, NDWI: Normalized difference water index. Nbar (MODIS/Terra and Aqua Nadir BRDF (bidirectional reflectance distribution function) adjusted reflectance (NBAR), 500 m), GA (MODIS Terra/Aqua Surface Reflectance 500 m), and GQ (MODIS Terra/Aqua Surface Reflectance 250 m) refer to the MODIS daily products analyzed.

P	MIR, GA	NIR, GA	Red, GA	NDVI, GA	NDWI, GA	NIR, GQ	Red, GQ	NDVI, GQ	MIR, Nbar	NIR, Nbar	Red, Nbar	NDVI, Nbar	NDWI, Nbar
1	−0.316	0.479	−0.323	0.457	0.514	0.522	−0.339	0.476	−0.305	0.412	−0.283	0.410	0.510
2	−0.093	0.597	−0.380	0.458	0.379	0.568	−0.373	0.463	−0.470	−0.031	−0.419	0.379	0.385
3	−0.591	0.201	−0.541	0.392	0.637	0.242	−0.408	0.336	−0.499	0.106	−0.604	0.500	0.550
4	−0.134	0.092	−0.205	0.194	0.143	0.138	−0.216	0.224	−0.001	0.267	−0.331	0.386	0.158
5	−0.223	0.518	−0.314	0.462	0.493	0.552	−0.336	0.462	−0.291	0.386	−0.392	0.527	0.540
7	0.009	0.051	−0.183	0.188	0.047	0.010	−0.093	0.110	0.319	0.027	0.106	−0.125	−0.317
9	−0.225	0.480	−0.301	0.403	0.490	0.447	−0.281	0.380	−0.255	0.320	−0.342	0.378	0.348
11	−0.108	0.506	−0.266	0.374	0.361	0.467	−0.258	0.364	−0.254	0.305	−0.342	0.377	0.329
12	−0.072	0.251	−0.154	0.189	0.195	0.217	−0.139	0.172	−0.015	0.296	−0.272	0.302	0.145
13	−0.425	0.501	−0.444	0.532	0.666	0.485	−0.482	0.567	−0.632	0.366	−0.623	0.629	0.706
14	−0.063	0.404	−0.173	0.281	0.258	0.367	−0.108	0.218	−0.260	−0.045	−0.389	0.279	0.135
15	−0.603	0.019	−0.293	0.232	0.348	0.056	−0.176	0.167	−0.223	0.084	−0.022	0.076	0.270
16	−0.173	0.240	−0.132	0.190	0.293	0.277	−0.147	0.205	−0.143	0.186	−0.254	0.355	0.370
17	−0.181	0.300	−0.282	0.406	0.351	0.251	−0.306	0.409	−0.065	0.301	−0.371	0.539	0.477
18	−0.153	0.369	−0.221	0.296	0.329	0.388	−0.260	0.323	−0.050	0.114	−0.248	0.267	0.188
19	−0.038	0.160	−0.320	0.296	0.133	0.205	−0.350	0.353	0.158	0.286	−0.148	0.363	0.232
20	−0.094	0.075	−0.007	0.012	0.114	0.145	−0.046	0.064	−0.256	−0.105	−0.293	0.145	0.077

There were four indices that showed the largest number of paddocks with significant correlations: Delta NIR (GA) in four paddocks and Delta NDWI (GA), Delta NIR(GQ), and Delta NDVI (Nbar) in three paddocks. These new correlations (delta values, Table 5) were no better than correlation showed in Table 4 despite having the higher correlation value (−0.706, $p < 0.05$).

Considering the information of all paddocks considered together, the delta values presented better results than red channel, NIR, MIR, NDVI, and NDWI values, obtaining the best correlation value between delta height and delta NDWI (MODIS GA product) (Figure 4). It is worth mentioning that these better correlation values are probably due to two delta height values (circled in red in Figure 4), which are likely very influential statistically and resulted in improved correlation.

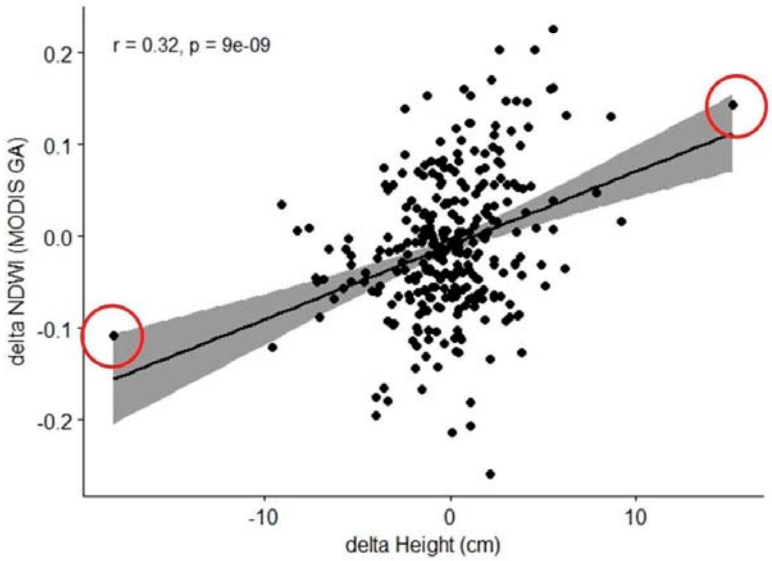

Figure 4. Linear correlation between delta median height and delta NDWI from MODIS GA product, considering the whole field information together. Pearson correlation value and significance are r = 0.32, $p < 0.001$. The tow influential data points are circled in red.

3.4. Variability

Analyzing variability and bearing in mind that farm measurements have coefficients of variation within paddocks of around 75% on height, we estimated the coefficient of variation of the satellite information (Table 6) to check variability at different spatial scales (Landsat and MODIS).

Paddocks 4, 7, and 10 have no MODIS (GA) information because of their shape and size; only one centroid of a pixel fitted the paddock.

Satellite information evidenced much smaller variability than field measurements with coefficients of variation for MODIS around 4% for 500 m resolution products, between 5% or 6% in 250 m resolution products, and 12% for Landsat (30 m spatial resolution).

Table 6. Average of the coefficient of variation (CV) of satellite information within paddocks on the considered dates and the standard deviation (SD) of those estimations for every paddock (P).

P	Dates Considered	Landsat		MODIS GQ		MODIS Comp		MODIS GA	
		CV	SD	CV	SD	CV	SD	CV	SD
1	10	12.04	1.44	6.27	0.95	6.23	0.83	5.89	2.15
2	12	9.89	4.05	4.41	6.59	4.49	2.59	1.56	0.58
3	8	15.32	13.12	2.92	1.74	4.15	1.70	2.88	0.86
4	9	10.89	3.27	5.01	6.75	5.38	1.78		
5	9	18.10	10.67	8.64	1.67	11.43	5.11	6.87	3.52
6	4	11.95	11.49	9.18	2.07	8.09	2.45	8.89	2.55
7	10	15.95	6.78	4.86	1.66	4.75	1.18		
8	8	8.43	3.08	4.23	2.10	5.64	1.37	9.50	8.66
9	12	9.94	7.33	3.15	1.78	3.56	1.56	2.16	1.63
10	2	4.76	1.06	1.62	0.27	2.21	0.09		
11	13	7.79	2.34	3.27	1.53	4.03	2.19	2.04	1.24
12	11	8.95	1.88	2.60	1.28	4.72	2.08	1.35	0.93
13	14	8.63	2.86	3.22	1.10	5.09	1.93	3.23	1.10
14	14	14.98	7.45	7.07	3.20	7.74	2.75	4.01	3.93
15	11	18.44	11.39	3.96	1.04	4.52	0.76	2.86	1.85
16	12	14.78	4.68	6.51	1.37	6.71	1.67	6.00	2.04
17	6	14.12	8.52	5.71	3.60	8.96	5.75	4.52	2.51
18	6	11.94	6.12	6.79	2.94	9.46	5.54	1.97	1.71
19	11	19.57	8.56	6.40	4.10	7.55	3.70		
20	8	8.09	7.92	3.37	1.82	4.46	3.11	1.26	1.01

4. Discussion

In agreement with previous studies that described native grassland variability [40], field measurements were extremely variable within the paddocks for each sampling date, with coefficients of variation around 75%. In most paddocks, this heterogeneity was even higher as the height increased, as shown in Figure 2, where the size of the boxes is larger when the values of the median are higher. This is probably due to the small-scale botanical and structural heterogeneity of this environment, but also because of variation in livestock management and in climate conditions. The amount of variability also showed differences between dates, probably associated with seasonal species composition. On the other hand, as satellite information provides an average value at a pixel resolution (500 m, 250 m, 30 m), it is expected to have much less variability but, differing to what we anticipated, showed no strong differences between these spatial resolutions. Thus, Landsat 8 (with spatial resolution of 30 m), could not represent the variability of native grassland more accurately than MODIS. Therefore, it can be expected that using other sensors with a resolution that is slightly higher, such as Sentinel 2, would not result in a better characterization of this variability either. Although it could be worth to check this fact, we probably must appeal to sensors of much higher resolution (1 m or centimeters) or non-optical ones (radar).

When we compared these extremely variable field measurements with MODIS satellite information, poor correlations were found. MODIS composite or daily variables seem to be not sensitive to grassland height variations. Considering the median height of every date and paddock, the minimum value was 1.4 cm and the maximum was 22 cm (Figure 3 boxplots), while satellite band reflectance values from GA product vary only from 0.17–0.37 for MIR, 0.20–0.39 for NIR, and 0.03–0.1 for the red band. Regarding the vegetation indices, NDVI varied from 0.43 to 0.83 and the NDWI from −0.15 to 0.28. This is consistent with results found in the semi-arid Sahel by Olsen et al. [26], who concluded that an increase in NDVI over time cannot always represent an increase in herbaceous biomass. This could be due to the fact that NDVI saturates at high biomass or leaf area index.

In contrast to what was found on monospecific pastures of alfalfa and grass (tall fescue), where good correlations are reported between height and several vegetation indices [41], our study showed that no daily or composite MODIS satellite information could explain height observed behavior in the natural grasslands of every paddock and date. This could probably be due to the hundreds of species present in native grasslands that result in such a heterogeneous environment, and/or to the presence of non-photosynthetically active plant material that could influence the signal captured by remote sensing sensors. For example, in paddocks 4, 17, and 18 (Table 2), the correlation between height and FPAR was negative, opposing what we expected. A similar situation occurred in paddock 18 with a positive correlation between height and red band. Careful consideration of the results at individual paddocks revealed that in all cases mentioned above, we found one very influential point with a high value of height and low value of FPAR (and high value of red band). This could probably be due to a situation with high biomass and a large proportion of senescent material. In general, MODIS composite information (MOD13Q1 and MCD15A3H) did not show good results either, and only MIR appeared as a variable worthy of further exploration in future work.

Analyzing paddocks individually, red band was the most promising variable (Table 4). Some paddocks had high and significant correlation values with several satellite variables (NIR, MIR, red band, NDVI, NDWI). Paddock 9, 11, and 19 showed significant correlations in more than 9 (out of a total of 13) daily remote sensing variables; paddock 13 a total of 8 with daily delta value; and paddock 9 and 19 more than 4 (from a total of 7) with composite images. Other paddocks had no correlation with any variables (paddock 1, 7, 12, and 20). Taking into consideration only the significant values, the sign (+ or −) of Pearson correlation coefficient values result as we expected for all the plots (positive relation between height and NIR, NDVI, and NDWI; and negative relation with MIR and red band).

On the other hand, changes in height and in satellite variable values from one date to the next (delta values) only showed better results than single date values when NIR (GA) was used (Table 5). There were some paddocks that had relatively good correlations (Person correlation values >0.6) between height and one or more of the different satellite variables such as MIR and NDWI of the GA MODIS product and MIR, red band, and NDVI of Nbar MODIS product, but these cases were isolated and not always with the same paddock involved. As an example, paddock 15 only showed high correlation between delta height and delta MIR (−0.603) but this satellite variable had very poor correlation values in other paddocks (Table 5).

It is worth considering that in the analyzed period, large variability on weather conditions was observed. During the first three years (2012–2014), weather conditions were relatively favorable, which resulted in NDVI values above or close to the average conditions of a 30 years series, while in April–July 2015, an intense drought period occurred [42]. Hence, the low correlation observed in our research cannot be attributed to a lack of variability in the observed values.

During the analysis process, we sought for possible common field characteristics in paddocks, such as size of the paddocks (Table 1), location (Figure 1), or field data CV (Figure 3 boxplots) with the same response to a specific satellite information signal, but no explanatory co-variable was found.

Considering paddocks 9, 11, 12, and 13 (all paddocks from the same farm) and taking into account characteristics that could be detected by remote sensing, the first two paddocks had relatively homogeneous conditions related to soil types, elevation, vegetation, and historical management, and the other two had very different conditions, being more heterogeneous in relation to soils, elevation, water sources, vegetation, and size. These could be the reasons that field measurements in paddocks 9 and 11 have strong correlation with different satellite variables while paddocks 12 and 13 did not (Table 4). On the other hand, paddock 19, the third paddock with significant correlation values with several satellite variables, had no homogeneous conditions and, therefore, this statement cannot be generalized.

Furthermore, the results of Cimbelli and Vitale [30] suggested that higher grass had a bigger component of the red band, but our results could not be explained by that either. Paddocks with higher values of median height (average or median of sampling dates, and maximum observed value) had different spectral response.

As it was shown, the spatial variability (heterogeneity) observed in native grasslands under grazing conditions is extreme, and this makes it difficult to manage, plan, and characterize at the paddock scale with a single average or even median field measurement value. Considering this, it is even more difficult to try to do so based on earth observation information that provides a value for each pixel, no matter how good the information is.

Additionally, more field information, such as density or vegetation cover, water content, chlorophyll level, or percentage of senescent material, needs to be analyzed and monitored in order to explain differences found between spectral information responses in different paddocks.

Most of the studies, including this one, have used a single sensor to analyze a very complex and heterogeneous ecosystem and this could probably be a limitation. Bearing this in mind, Wachendorf et al. [17] propose developing a system with complementary sensors to overcame these limitations and provide better estimations of different grassland characteristics. In addition to this, the integration of different sources of information (remote sensing, field data, air photos, and street-level imagery) to monitor grasslands, also seems to be an auspicious methodology [43,44]. SAR data (radar remote sensing) calculated from X- or C-band were explored too, with promising results [45,46]. On the other hand, some authors propose hyperspectral and high-resolution images as an option to overcome the difficulties at a paddock scale grasslands monitor [47]. Finally, drones and other unmanned aerial vehicles offer an opportunity for new applications, proving higher spatial resolution and customized spectral and temporal resolution [17,48]. It is worth mentioning that as spatial resolution increases, it is more difficult to scale the analysis to a regional or national level. Moreover, a decision support system needs to be simple to be used by different stakeholders.

5. Conclusions

As it was expected, height of native grasslands is extremely variable within paddocks for each sampling date and between dates (seasonal variability). This variability is what we must deal with when we analyze native grassland forage availability and satellite information, and, at least at these spatial resolutions (500 m, 250 m, and 30 m pixel), the estimation of pasture height variability cannot be represented accurately.

We did not find high correlations between field measurements of height and MODIS composite/daily variable when we analyzed all the paddocks considered together or paddock by paddock. However, some areas of future work seem to be justified. The daily red band of Nbar MODIS product seems to be a promising variable to explore, with relatively good correlation values in 41% of the paddocks. When composite MODIS images were considered, MIR had the best performance with 29% of the paddocks showing negative correlation values higher than 0.45.

This work aims to contribute to manage the grazing process on livestock production systems, based on Earth observation information. Our results showed that no MODIS composite/daily variable was able to predict robustly the native grassland height behavior, but some satellite information came out as promising.

Work is needed in order to find remote sensing methods that can be used to monitor the "instantaneous" condition of grasslands (height or available biomass), and this research has evidenced some of the related difficulties and opportunities.

Author Contributions: Conceptualization, G.T., W.B., and P.C.; methodology, G.T., W.B., and P.C.; formal analysis, G.T.; investigation, A.R. and M.D.C.; writing—original draft preparation, G.T.; writing—review and editing, G.T., W.B., A.R., M.D.C., and P.C.

Funding: This research has been conducted as part of a PhD program (Facultad de Agronomía, Universidad de la República, Uruguay) supported by the Agro-climate and Information System Unit (GRAS) of the National Agricultural Research Institute (INIA Uruguay) and a partial scholarship provided by the National Agency for Research and Innovation (ANII Uruguay).

Acknowledgments: We want to specially thank the National Research Programs of Family Farm Production and Pastures and Forages of INIA (National Institute of Agricultural Research, Uruguay) for their contribution with the field data.

Conflicts of Interest: The authors declare no conflict of interest.

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4. DISCUSIÓN

Los pastizales naturales son de gran importancia para la economía de muchos países en desarrollo como Uruguay, Argentina y Brasil, tanto para la seguridad alimentaria como para la provisión de servicios ecosistémicos. Esto implica, que su degradación, es un problema de índole política, económica y ambiental muy importante. En este sentido, cualquier acción que apoye las acciones de monitoreo y permita prever una condición no deseable, es por demás trascendental. Este trabajo de tesis se enfoca en ese tema, y si bien algunos resultados no son lo contundentes que se hubiera querido, aportan a la discusión y brindan líneas de trabajo a explorar.

4.1. CAPÍTULO 1

Aunque es ampliamente conocido y repetidamente informado en la literatura que el sobrepastoreo es uno de los principales impulsores globales de la degradación, la evidencia experimental de cambios irreversibles en los estados degradados en los pastizales del Río de la Plata es limitada y es altamente dependiente del tipo de comunidad que se esté analizando. Si bien para la región existen algunos modelos conceptuales (Andrade et al., 2015) que proporcionan un marco conceptual de estados y umbrales que ayudan a los investigadores a estudiar la degradación y restauración, en esta tesis se detalla un marco conceptual general que describe los principales impulsores, indicadores de proceso y consecuencias, y se describen cuatro modelos de estado y transición para los pastizales del Río de la Plata que colaboren en la toma de decisión.

Analizando la revisión bibliográfica (a nivel global) y la encuesta a expertos regionales (Argentina, Brasil y Uruguay), encontramos que las diferentes regiones y tipos de pastizales tienen algunos impulsores, procesos y consecuencias comunes relacionados con la degradación y, por lo tanto, tienen el potencial para ser analizados y monitoreados por un marco común. Sin embargo, los artículos revisados también revelaron que otros impulsores, procesos y consecuencias eran comunes en condiciones similares de variabilidad de la lluvia, y diferentes según un gradiente bioclimático y un historial evolutivo de pastoreo. El cambio climático parece ser un factor importante en los pastizales áridos (Yang et al., 2016; Zhou et al., 2017; Wang et al., 2016), mientras que no se menciona en el análisis de los pastizales húmedos. Por otro lado, la intensidad del pastoreo ligero o la exclusión del pastoreo, tienen diferentes efectos según la región bioclimática, con un efecto positivo en ambientes áridos (Al-Rowaily et al., 2015; Qasim et al., 2017) y uno negativo en las regiones húmedas (Altesor et al., 2005; Yao et al., 2019). En cuanto a las consecuencias, la desertificación se reporta exclusivamente en áreas áridas y semiáridas (Akiyama y Kawamura, 2007).

Para avanzar aún más en el conocimiento del proceso de degradación de los pastizales del Río de la Plata, se representan los efectos de las interacciones entre la variabilidad de la lluvia y el sobrepastoreo, en cuatro modelos de estados y transiciones donde se indican los distintos impulsores, procesos y consecuencias. Para apoyar las decisiones de gestión, los distintos modelos intentan vincular: i) múltiples impulsores que operan simultáneamente, en diferentes condiciones específicas del sitio, ii) el proceso principal que es afectado y sus indicadores, y iii) las consecuencias esperadas de las medidas de manejo, en diferentes escenarios climáticos.

Adicionalmente, la diversidad de los pastizales, los impactos diferenciales del clima y el manejo, y la diversidad de usos, son las razones principales de la coexistencia de diferentes significados conceptuales de degradación. de Queiroz (1993) afirman que las definiciones de degradación son diferentes según los objetivos de manejo. Dado que estos objetivos pueden diferir, las definiciones de lo que es degradación también difieren. Las definiciones también pueden diferir debido al énfasis en diferentes categorías conceptuales relacionadas con la degradación y es por eso que es importante aclarar estas categorías conceptuales. Acordar una definición de un concepto complejo como la degradación del campo natural también es importante para fines de investigación, ya que contribuye a identificar qué procesos deben describirse y qué variables deben medirse para evaluar y monitorear el grado de degradación.

4.2. CAPÍTULO 2

En función del modelo conceptual desarrollado en el Capítulo 1, la altura del tapiz surge como una variable que se relaciona con la degradación del campo natural cuando se la considera en rangos bajos por un período prolongado de tiempo o en repetidos momentos clave del año y con condiciones ambientales adecuadas. Así mismo, considerando las distintas variables que pueden ser medidas a campo, ésta pareció a priori como plausible de ser evaluada para monitorearse utilizando información satelital.

En concordancia con estudios previos que describen la variabilidad espacial de la altura del tapiz en campo natural (Laca et al., 1989), las medidas de campo observadas fueron extremadamente variables dentro de cada potrero. Inclusive, en varios potreros esta heterogeneidad fue mayor a medida que la altura crecía. Esta variabilidad probablemente se deba a la heterogeneidad botánica y estructural que existe a pequeña escala en el campo natural, pero también a las diferencias en el manejo del ganado y a la variabilidad en las condiciones ambientales y climáticas. Esto hace que sea difícil manejar, planear y caracterizar a escala de potrero con un valor promedio o inclusive considerando la mediana de las mediciones de campo. Teniendo en cuenta esto, parece aún más difícil tratar de hacerlo basándose en información satelital que proporciona un valor integral para cada píxel, sin importar qué tan buena sea la resolución. Y si bien es esperable que la información satelital tenga una variabilidad menor que la de las mediciones de campo, contrario a lo que esperábamos, esta variabilidad no tuvo grandes diferencias cuando se analizaba las distintas escalas (MODIS: 500m y 250m o Landsat: 30m).

Analizando las correlaciones lineales entre los datos de campo y la información satelital, nuestro estudio mostró que ninguna información diaria o compuesta de MODIS (banda del rojo, NIR, MIR, NDVI NDWI, FPAR y LAI) es capaz de explicar el comportamiento de la altura anual observada en campo natural de manera generalizada, para todos los predios. Las variables compuestas o diarias MODIS parecen no ser sensibles a las variaciones de altura de los pastizales. Esto es consistente con los resultados de Olsen et al. (2015) pero contrario a los hallados por Payero et al. (2004) para pasturas monoespecíficas. A pesar de esto, la banda del rojo del producto Nbar de MODIS parece ser una variable prometedora para seguir explorando, ya que se encontraron valores de correlación relativamente buenos en el 41% de los potreros.

Vale la pena considerar que, en el período analizado, se observó una gran variabilidad en las condiciones climáticas. Durante los primeros tres años (2012–2014), las condiciones climáticas fueron relativamente favorables, lo que resultó en valores NDVI superiores o cercanos a las condiciones promedio de una serie de 30 años, mientras que en abril-julio de 2015, ocurrió un intenso período de sequía (INIA-GRAS, 2019). Dado esto, la baja correlación observada en este análisis no puede atribuirse a la falta de variabilidad en los valores observados.

Las bajas correlaciones encontradas podrían deberse a los cientos de especies presentes en este ecosistema que resultan en un ambiente extremadamente heterogéneo, o a la presencia de restos secos (material vegetal no fotosintéticamente activo) que podría influir en la señal capturada por los sensores. Es importante destacar también que las mediciones de altura a nivel de campo se realizaron sobre el estrato bajo sin considerar la presencia de matas (que en algunos potreros existían), lo que incorpora un factor de distorsión más a la señal que reciben los sensores satelitales.

La mayoría de los estudios, incluido este, han utilizado un solo sensor para analizar un ecosistema muy complejo y heterogéneo y esto probablemente podría ser una limitación. Teniendo esto en cuenta, Wachendorf et al. (2017) proponen desarrollar un sistema con sensores complementarios a fin de poder proporcionar mejores estimaciones de las diferentes características de los pastizales. Por otro lado, la integración de diferentes fuentes de información (sensores remotos, datos de campo, fotos aéreas e imágenes terrestres) para monitorear los pastizales, también es una opción interesante a explorar (d´Andrimont et al., 2018; Wood et al., 2012). Otras tecnologías como SAR (sensores radar) se han explorado, obteniendo resultados promisorios (Tamm et al., 2016) que valdría la pena investigar. Por otro lado, el uso de imágenes hiperespectrales y de alta resolución, podrían ser una opción interesante para el monitoreo a escala de potrero (López-Díaz, 2011). Finalmente, los drones y otros vehículos aéreos no tripulados también podrían ser analizados, ya que cuentan con una resolución espacial muy alta y una resolución espectral y temporal personalizada en función de los objetivos (Wachendorf et al., 2017; Grüner et al., 2019). De todas maneras, cabe mencionar que a medida que aumenta la resolución espacial, es más difícil escalar el análisis a nivel regional o nacional. Además de esto, un sistema de apoyo a la toma de decisiones debe ser simple y de fácil interpretación para que pueda ser utilizado por diferentes actores.

5. CONCLUSIONES Y PERSPECTIVAS

La degradación de los pastizales tiene impulsores multicausales; sin embargo, la complejidad de este proceso permanece en su mayor parte inexplorada, ya que la mayoría de los estudios se centran en impulsores individuales. A partir de esta tesis, surge un nuevo modelo conceptual que considera impulsores que operan simultáneamente y sus interacciones en diferentes condiciones.

Cabe destacarse que, algunos de los temas mencionados y algunos indicadores de procesos recabados en esta tesis, a diferentes escalas (global y regional), fueron comunes, lo que sugiere que el problema de la degradación podría tener una interpretación común y que puede analizarse con un marco conceptual común. Creemos que el marco conceptual propuesto para analizar degradación del campo natural es una contribución valiosa para los programas de monitoreo y para apoyar las decisiones de manejo, al aclarar los diferentes conceptos involucrados en el proceso (impulsores, indicadores de proceso y consecuencias) y estructuración el análisis de la degradación, permitiendo identificar aspectos clave.

Analizando la altura del tapiz, como variable que se podría asociar a procesos de degradación bajo ciertas condiciones, se observó una variabilidad extrema dentro de cada potrero, para cada fecha de muestreo. Esta variabilidad es con lo que debemos lidiar cuando analizamos la disponibilidad de forraje y, la información satelital, al menos en estas resoluciones espaciales (500 m, 250 m y 30 m píxeles) no pudo representar esa variabilidad de manera adecuada.

En general, no encontramos buenas correlaciones entre las mediciones de la altura del tapiz y los datos MODIS (diarios y compuestos) cuando analizamos todos los potreros considerados juntos o cuando se analizó potrero a potrero. Sin embargo, a nivel diario, la banda del rojo del producto Nbar de MODIS parece ser una variable prometedora ya que se estimaron valores de correlación relativamente buenos en el 41% de los potreros. Cuando se consideraron las imágenes MODIS compuestas, MIR tuvo la mejor performance con el 29% de los potreros con valores de correlación significativos e inferiores a -0.45 (correlación negativa).

Si bien no fue posible detectar la degradación de campo natural usando técnicas de teledetección, identificamos futuras líneas de trabajo que pueden contribuir en este sentido. De acuerdo a los resultados obtenidos, entendemos que información de campo adicional como: densidad o cobertura vegetal, contenido de agua, nivel de clorofila o porcentaje de material seco, carga animal (específicamente la relación lanar-vacuno que interfiere en la estructura de los potreros); necesita ser evaluada, analizada y monitoreada a fin de contar con más elementos que permitan explicar las diferencias encontradas en las respuestas de las variables satelitales en los diferentes potreros.

Entendemos que todavía hay mucho trabajo por hacer para encontrar métodos basados en teledetección que puedan usarse para monitorear la condición "instantánea" del campo natural (altura o biomasa disponible), y esta tesis ha evidenciado algunas de las dificultades y oportunidades relacionadas con esto.

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