UNIVERSIDADE FEDERAL DO PARANÁ

ARMINDO BARTH NETO

IMPACT OF GRAZING MANAGEMENT AND CROP ROTATION ON INTEGRATED CROP-LIVESTOCK SYSTEM: IMPLICATION ON ITALIAN RYEGRASS ESTABLISHED BY SELF-SEEDING

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IMPACT OF GRAZING MANAGEMENT AND CROP ROTATION ON INTEGRATED CROP-LIVESTOCK SYSTEM: IMPLICATION ON ITALIAN RYEGRASS ESTABLISHED BY SELF-SEEDING

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PARECER

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em Agronomia - Produção Vegetal, reuniram-se para realizar a argüição da Tese de DOUTORADO, apresentada pelo candidato **ARMINDO BARTH NETO**, sob o título **"IMPACT OF GRAZING MANAGEMENT AND ROTATION ON INTEGRATED CROP-LIVESTOCK SYSTEMS: IMPLICATION ON ITALIAN RYEGRASS ESTABLISHED BY SELF-SEEDING"**, para obtenção do grau de Doutor em Ciências do Programa de Pós-Graduação em Agronomia - Produção Vegetal do Setor de Ciências Agrárias da Universidade Federal do Paraná.

Após haver analisado o referido trabalho e argüido o candidato são de parecer pela "**APROVAÇÃO**" da Tese.

Curitiba, 25 de Fevereiro de 2015.

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I dedicate this PhD thesis to my grandfather Orestes Bortoleti (*in memoriam*) that gave me the first lessons about the nature, its importance, and especially that we should respect the nature. I would like to thanks also for teaching me that honesty, simplicity and humility are the greatest virtues of a man.

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(Steve Jobs)

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In March 2011, he began his PhD studies in Agronomy at Post-graduate program in Agronomy – Crop production with specialization in Integrated Crop-Livestock Systems at Federal University of Paraná, in Curitiba, Paraná, Brazil.

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RESUMO

Sistemas integrados de produção agropecuária (SIPA) são reconhecidos por sua produção sustentável, tanto agrícola quanto pecuária, devido a melhor utilização dos recursos naturais. Diferentes combinações e proporções de espécies animais e vegetais em SIPA são responsáveis por produzir aproximadamente metade da produção mundial de alimentos. Nas regiões subtropicais do mundo, particularmente na América do Sul, a utilização do azevém anual (*Lolium multiflorum* Lam.) estabelecidos por ressemeadura natural em rotação com milho (*Zea mays* L.) e/ou soja (*Glycine max* L.), são amplamente difundido entre os produtores rurais. Em SIPA a prática de ressemeadura natural são considerados economicamente e ambientalmente mais vantajosos, uma vez que economiza gastos e energia (combustível fóssil). Sobre este arranjo em SIPA, diversas questões ainda não foram respondidas sob a influência das práticas de manejo sobre o estabelecimento do azevém anual proveniente de ressemeadura natural. Por exemplo as plantas de soja e milho tem diferentes estruturas de dosséis, que podem afetar o desenvolvimento inicial das plântulas de azevém anual. Outro ponto é o manejo do pastoreio em SIPA, particularmente o efeito dos diferentes método de pastoreio e intensidades de pastejo que podem afetar o crescimento do pasto. Uma vez que o manejo do pastejo pode restringir a seletividade animal (altas intensidades de pastejo e pastoreio rotativo), afetam negativamente o acúmulo da massa de forragem, densidade de perfilhos reprodutivos e produção de sementes. Entretanto, estudos sobre o entendimento das interações e complementariedades entre as fases lavoura e pastagens em SIPA é pouco abordado na literatura, principalmente com o azevém anual estabelecido por ressemeadura natural. A hipótese deste trabalho é que a rotação das culturas de verão (monocultura de soja ou rotação soja-milho) e diferentes manejos do pasto (método de pastoreio e intensidade de pastejo) afetam diferentemente o desenvolvimento e a resiliência do azevém anual em SIPA no curto e longo prazo. Para comprovar esta hipótese foram preparados três artigos com os seguintes objetivos: i) avaliar os efeitos das práticas de manejo, rotação de culturas, método de pastoreio e oferta de forragem afetam o restabelecimento dos pastos de azevém anual por ressemeadura natural e determinar se os pastos são capazes de restabelecer por mais de um ano sem a adição de sementes no solo. ii) avaliar o impacto da rotação de culturas de verão e o manejo do pasto na massa de forragem no inicio e no final da fase pastejo. iii) Analisar e modelizar a dinâmica do azevém anual em SIPA com uma base de dados histórica do ciclo de vida do pasto e determinar a resiliência sob diferentes práticas de manejo sob uma perspectiva de longo-prazo.

Palavras chave: Sistemas mistos, intensidade de pastejo, método de pastoreio, soja, milho, resiliência.

ABSTRACT

Integrated crop-livestock systems with no-till (ICLS) are recognized to sustained agriculture and livestock production by the efficiently use of natural resources. Different combinations and proportions of animal and plant species in ICLS are responsible for producing about half of the of the word's food. In subtropical regions of the world, mainly in South America, the utilization of Italian ryegrass (*Lolium multiflorum* Lam.) established by self-seed in rotation with maize (*Zea Mays* L.) or soybean (*Glycine max* L. Merril) is widely widespread. In ICLS, the harnessing of self-seeding is economically and environmentally advantageous because is capable to save money and energy (based on fossil fuel). In ICLS many question are unanswered about the Italian ryegrass established by self-seeding in face of different agricultural practices. For example soybean and maize have different canopy structures that can differently affect the pasture establishment phase. The grazing management in ICLS, particularly the effect of different stocking method and different grazing intensity can affect the dynamic of the pasture production. Since manage the pasture restricting the animal selection (i.e. higher grazing intensity and rotational stocking) affects negatively the herbage mass accumulation, the flowering structure and the seed production. However, the understanding of the interactions and of the complementarity between crops and pasture phases is poorly addressed in the literature, mainly in Italian ryegrass established by self-seeding. The hypothesis is that summer crop rotation (soybean monoculture or soybean-maize) and the different grazing management (stocking methods and grazing intensities) affects differently the development and the resilience of Italian ryegrass in ICSL in short and long-term. To prove this hypothesis were prepared three articles with the following objective: i) to evaluate the effects of management practices, crop rotation, stocking method and herbage allowance on the re-establishment of Italian ryegrass pastures by self-seeding and determining if the pastures are able to establish themselves following a year without seed production. ii) to evaluate the impacts of summer crop rotation and grazing management on herbage mass at the beginning and at the end of grazing phase in ICLS. iii) to analyse and modelling the dynamics of Italian ryegrass in ICLS from an experimental database, based on a life-cycle basis to determine the resilience of different cropping systems in a long-term perspective.

Key words: Mixed systems, grazing intensity, stocking method, soybean, maize, resilience.

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1. CHAPTER 1 – INTRODUTION

The modern agriculture, as part of Green Revolution undeniably increased spectacularly of the world agriculture production after the last half of the twentieth century (GRIFFON, 2006). With the increase in food yield increased the use of artificial fertilization, pesticides, irrigation and fossil fuel, this modern practices are now associated with decrease in ecosystem biodiversity and deterioration of soil, water and air quality (STOATE et al., 2001). At the same time that the modern agriculture had attributed as reason of environmental problems, the demand for food, fiber and bioenergy are increasing in the last years and needs to attend two billion more people expected to 2050 (FAO, 2009).

Agriculturalists in the world have confronted in challenge for food production, maybe greater challenge than in Green Revolution, to be more productive and resilient with food security while protect and restore the environment quality (FOLEY et al., 2005; LEMAIRE et al., 2015, *in press*). The main challenge is to change the old paradigm of improving productivity per unit of arable land or person labor to increase productivity for each unit of natural resource (BOMMARCO et al., 2013; LEMAIRE et al., 2014). This concept, to maintain or increase productivity in arable lands and minimizing negative impacts on the environment and ensuring negative feedbacks on agricultural productivity, by integrating the management of ecosystem services delivered by biodiversity is known as ecological intensification (DORÉ et al., 2011; GRIFFON, 2013).

Among arrangements of cropping systems the integrated crop-livestock systems with no-till (ICLS) are recognized to sustained agriculture and livestock production by efficiently use of natural resources (RUSSELLE et al., 2007; TRACY; ZHANG, 2008). ICLS are considered the most promising cropping systems to employ the ecological intensification (FAO, 2010). According to ROTA; SPERANDINI (2011) their benefits are summarized in four general areas: i) agronomy, the preservation and maintenance of the productive capacity of the soil; ii) economic, diversity of food production with security and higher yields at lower cost; iii) ecological, by reducing pests, lower pesticide use and better erosion control; and iv) social, by reducing rural-urban migration with increase new employ opportunities in rural areas.

Different combinations and proportions of animal and plant species in ICLS are responsible for producing about half of the word’s food (HERRERO et al., 2010). In subtropical regions of the world, mainly in South America, the utilization of Italian ryegrass

(*Lolium multiflorum* Lam.) established by self-seed in rotation with maize (*Zea Mays* L.) or soybean (*Glycine max* L. Merril) is widely widespread (CARVALHO et al., 2010).

In ICLS, the harnessing of self-seeding is economically and environmentally advantageous because is capable to save money and energy (based on fossil fuel). The parsimony with seeds and seeding also increase the stocking period, due the seeds starts the emergence at the beginning of the growing season (EVERS; NELSON, 2000).

The majority of research were conducted in North America with the aiming to evaluate the impact of grazing termination date on seed production and seedling establishment in the following growing season (YOUNG, 1996; EVERS; NELSON, 2000; BARTHOLOMEW; WILLIAMS, 2009). The general results of these works showed that as shorter is the grazing termination date decreases reproductive tiller density, seed production and volunteer seedlings, also the seed production is strongly reduced by erratic rainfall (BARTHOLOMEW; WILLIAMS, 2009).

In ICLS many question are unanswered about the reseeding dynamics in face of different agricultural practices. For example the Italian ryegrass established by self-seeding begins the seedling emergence before the crop harvest, beneath of crop canopy (FAVRETO; MEDEIROS, 2004). Soybean and maize have different canopy structures, which can differently affect the pasture establishment phase. Studies that explain the effect of summer crop in tiller density and herbage accumulation of Italian ryegrass during the establishment are virtually unknown in literature.

The grazing management in ICLS, particularly the effect of different stocking method and different grazing intensity can affect the dynamic of the pasture production. Since manage the pasture restricting the animal selection (i.e. higher grazing intensity and rotational stocking) affects negatively the herbage mass accumulation, the flowering structure and the seed production (ATES et al., 2014), that can decrease the resilience of Italian ryegrass in ICLS. BARBOSA et al. (2009) in primary study evaluating the effect of the grazing intensity and stocking method in the first re-establishment of Italian ryegrass by self-seeding found that only the grazing intensity affect the pasture establishment, that was incapable to re-establish managing the pasture with moderate grazing intensity.

Studies in ICLS are normally compartmentalized, focusing on grazing phase to the following phase (i.e. impact of the animal in soil compaction decreasing the crop yield). In ICLS both phases cannot be disconnected, and the management on each phase affect the next one. However, the understanding of the interactions and of the complementarity between crops and pasture phases is poorly addressed in the literature. Mainly, where the summer crop can affect the pasture establishment and the grazing intensity can affect the amount of residual herbage mass, important to cover the aboveground for a desirable no-till.

Until now there have been only a few studies concerning the management strategies effects on resilience of Italian ryegrass (MAIA et al., 2007; BARBOSA et al., 2009), but without the long term perspective. A probable reason for this lack is the difficulty of quantifying the effects of the use of different production systems in long-term protocols because it requires very difficult and costly experiments. Therefore, modelling population dynamics appear as a suitable approach for this purpose, but there is lack of knowledge concerning the resilience of pasture on ICLS, depending of the cropping system and on climate variations.

According the problematic postulated above this thesis presented three chapters with scientific articles that the objectives are presented below:

Chapter 2:

To evaluate the effects of management practices, crop rotation, stocking method and herbage allowance on the re-establishment of Italian ryegrass pastures by self-seeding and (2) to investigate how resilient these systems are, by determining if the pastures are able to establish themselves following a year without seed production.

Chapter 3.

To evaluate the impacts of summer crop rotation and grazing management on herbage mass at the beginning and at the end of grazing phase in ICLS.

Chapter 4.

To analyse and modelling the dynamics of Italian ryegrass in ICLS from an experimental database, based on a life-cycle basis to determine the resilience of different cropping systems in a long-term perspective.

2. CHAPTER 2 - Italian ryegrass establishment by self-seeding in integrated crop–livestock systems: Effects of grazing management and crop rotation strategies[1]

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Italian ryegrass establishment by self-seeding in integrated crop–livestock systems: Effects of grazing management and crop rotation strategies

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ABSTRACT

We evaluated the re-establishment of an Italian ryegrass pasture by self-seeding on a no-till integrated crop–livestock systems (ICLS) in the southern region of Brazil. This work is part of a long-term experimental protocol initiated in 2003. We tested the effects of various management practices, such as summer crop systems (soybean vs. maize–soybean rotation), stocking methods (continuous vs. rotational) and grazing intensities (low vs. moderate), on Italian ryegrass pasture establishment. In addition, we tested resilience of the system by testing pasture's ability to re-establish following a year without seed head production. The experiment consisted in the rotation, on the same area, of Italian ryegrass pasture grazed by sheep during the winter and up to the end of the grass production cycle, and soybean or soybean–maize grain crops rotation cultivated during the summer. The pasture established itself by self-seeding since 2005. Data were collected in 2011 and 2012 stocking season. The soybean summer crop, continuous stocking and low grazing intensity, all positively affected the production of reproductive tillers in 2011. Grazing intensity in 2011 strongly influenced early vegetative tiller densities (before crop harvest) in 2012. However, none of the grazing intensity or the stocking method treatments affected herbage mass at the end of pasture establishment in 2011 or 2012. On the other hand, the soybean summer crop positively affected pasture establishment, both in term of tiller densities and herbage mass at the end of pasture establishment. The removal of all seed heads in 2011 (preventing seed production) resulted in the total failure of pasture establishment in 2012. Overall, Italian ryegrass establishment by self-seeding relies on the annual replacement of the soil seed bank. This experiment demonstrated that under various stocking methods, moderate grazing intensity and maize or soybean summer crop, Italian ryegrass pasture establishment by self-seeding remains successful even when the stocking periods extended up to the end of the grass production cycle. Self-seeding with moderate grazing intensity ensures successful pasture establishment, reduces labour and costs and allows to increase the stocking period and so animal live weight gain over the grazing season.

1. Introduction

Recent research in various regions of the world has indicated that ICLS can enhance sustained crop and livestock production by efficiently using agricultural system resources (Russelle et al., 2007; Liu et al., 2012). In the subtropical South American regions of Brazil, Argentina, Uruguay and Paraguay, soybean (*Glycine max* L. Merril) and maize (*Zea mays* L.) summer crops are widely grown in rotation

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with Italian ryegrass (*Lolium multiflorum* Lam.) winter pastures as integrated no-till systems (Carvalho et al., 2010). Italian ryegrass is traditionally established from one year to the other by self-seeding. This practise reduce pasture production costs and, more important, can substantially extend the grazing period by allowing earlier entry of the animals in the system (Evers and Nelson, 2000). However, in case of mismanagement, pasture establishment can be delayed or fail due to low seedling number and/or vigour (Evers and Nelson, 1994).

The successful establishment of Italian ryegrass by self-seeding depends on the production, year after year, of a sufficient amount of seeds and the emergence of numerous seedlings from the resulting soil seed bank (Bartholomew and Williams, 2009). In no-till systems, Maia et al. (2007) reported that Italian ryegrass seed banks had a low persistence rate, and its viability in the soil is variable. According to Bartholomew and Williams (2009), densities between 885 and 5650 seed heads m^{-2} are required each year to achieve a minimum reseeding rate of 500 established seedlings m^{-2}. Evers and Nelson (2000) reported that self-seeding Italian ryegrass in no-till systems did not have lower forage productivity capacity than conventional systems with mechanical seeding. However, many authors reported that stocking period must be terminated earlier in the spring to ensure the reproductive tillers development, and therefore the re-establishment success (Young et al., 1996; Evers and Nelson, 2000; Bartholomew and Williams, 2009). Nowadays, this technique represents the standard management practice for winter pastures based on Italian ryegrass in subtropical South America. However, by reducing the stocking period this practice is costly in terms of animal production and questions the real benefice of self-seeding for these systems.

Despite the importance of Italian ryegrass as a winter pastures in ICLS, information regarding its establishment and stability under self-seeding are particularly scarce. This is especially true with the widely used soybean and maize annual crops. Several studies reported that early-established Italian ryegrass' seedlings maintained good growth capacity beneath crop canopy (Favreto and Medeiros, 2004; Barth Neto et al., 2012). However, how different grazing management or grazing intensity practices affects the re-establishment of Italian ryegrass pastures by self-seedling is virtually unknown. Grazing intensity, and not only stocking period duration, can strongly affect the demography of the reproductive tillers and consequently the success of pasture establishment in the next stocking season.

In subtropical areas where Italian ryegrass is used for winter pastures in ICLS, the effects of crop rotation, stocking methods or grazing intensities on the subsequent ability of Italian ryegrass to re-establish self-seeding are unknown. The objectives of this study are as follows: (1) to evaluate the effects of management practices, crop rotation, stocking method and herbage allowance on the re-establishment of Italian ryegrass pastures by self-seeding and (2) to investigate how resilient these systems are by determining if the pastures are able to establish themselves following a year without seed production.

2. Materials and methods

This work is part of an long-term experimental protocol of ICLS initiated in 2003 at the experimental farm of the Federal University of Rio Grande do Sul (UFRGS), in the south of Brazil (30°05′ S; 51°39′ W). The ICLS protocol consists in the rotation, on the same area, of an Italian ryegrass pasture grazed by sheep during the winter and a soybean or a soybean–maize grain crops rotation cultivated during the summer. Italian ryegrass pasture establishes itself each year by self-seeding since 2005, which is the common practice in the region for ICLS. The present work investigates the properties of Italian ryegrass establishment during the stocking season of 2011 and 2012.

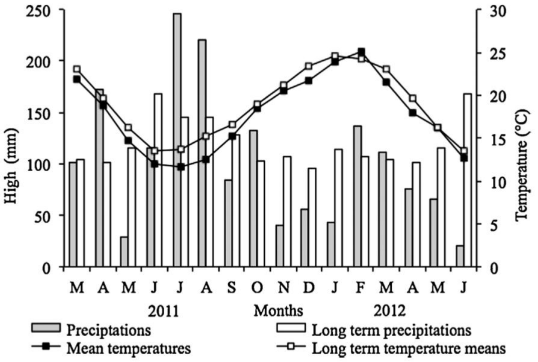

Fig. 1. Monthly precipitations and means temperature observed at the experimental site in 2011 and 2012 vs. long-term climatic means between 1970 and 2000.

2.1. Experimental site

The southern region of Brazil where was conducted the experiment is classified as subtropical humid (Cfa classification, Köppen and Geinger, 1928). It is characterized by a marked seasonality of temperature and a homogeneous repartition of precipitations along the year (Fig. 1, data from the meteorological station located 800 m from the experimental site). However, the study period suffered from an excess of precipitations during the winter 2011 and a deficit of precipitations during the summer 2011–2012. The soil at the experimental site was classified as a Typic Paleudult (USDA, 1999) with 15.2% clay. The chemical soil characteristics for the horizon 0–20 cm are listed as follows: pH = 4.87; SMP index = 5.82; P = 51.78 mg dm^{-3}; K = 106.01 mg dm^{-3}; OM = 1.99%; Al = 0.59 $cmol_c$ dm^{-3}; Ca = 1.95 $cmol_c$ dm^{-3}; Mg = 0.95 $cmol_c$ dm^{-3}; cation exchange capacity = 8.61 $cmol_c$ dm^{-3} and base saturation = 37.04%.

2.2. Experimental design

The experimental site covers a total area of 4.8 ha subdivided into 16 paddocks of similar size. The long-term experimental protocol consists in four replicates of a 2 × 2 balanced factorial design with two stocking methods (continuous and rotational) and two herbage allowances (moderate and high) resulting in 16 paddocks arranged in a randomized complete block design. During the summer, each paddock was divided into two summer crop systems (soybean summer crop and maize–soybean summer crop rotation), in a no-till system, which results in 32 experimental units.

Intake rate of lambs or lactating ewes grazing perennial ryegrass is considered as unrestricted when daily forage allowance reach at least 3 times their potential dry matter intake (Gibb and Treacher, 1976). As a result, herbage allowances treatments were defined as 2.5 times (moderate grazing intensity) and 5 times (low grazing intensity) the potential daily dry matter intake of lambs or lactating ewes according to the NRC (1985). Resulting herbage allowances were 10 kg (moderate grazing intensity) and 20 kg (low grazing intensity) herbage dry matter per 100 kg ha^{-1} animals live weight.

Here, we present dada on Italian ryegrass reproductive tiller density, vegetative tiller density and herbage mass collected in 2011 and 2012. Fig. 2 illustrates the timeline of land use for the paddocks during the study period. In order to test the persistence

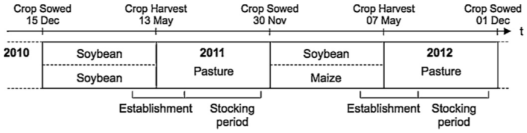

Fig. 2. Timeline of use of each paddock in 2011 and 2012.

capacity of the Italian ryegrass by self-seeding, we delimited, in addition to the long-term protocol, one 5 m × 5 m area in the middle of each experimental unit (two per paddock). During the stocking period in 2011, we regularly mowed these areas at a height of 5 cm after seed heads started to appear. These "control areas" prevented tillers appearances with seed head and so seed production in 2011. In addition, all animal faeces were carefully collected in the control areas on 20/11/2011 to eliminate the potential input of seeds.

2.3. *Management practices*

2.3.1. *Summer crop season*

During summer 2010/2011, the entire area was sown with soybeans and harvested on 13/05/2011. During summer 2011/2012, half of each paddock was sown with soybeans (soybean summer crop treatment) and half with maize (maize–soybean summer crop rotation treatment) on 30/11/2011. Soybean was harvested on 07/05/2012 and maize on 08/05/2012. The maize crop received two application of 75 kg ha^{-1} of nitrogen (urea), on 17/12/2011 and 10/02/2012. Soybean crop did not receive nitrogen fertilization, as seeds were inoculated with *Bradyrhizobium* spp. bacteria before sowing.

2.3.2. *Winter stocking season*

We used Texel and Ile de France cross breed lambs that had an initial weight of 21.9 ± 2.7 kg in 2011. In 2012, we used single-bearing lactating ewes from the same cross breed, with an initial weight of 63.5 ± 11.1 kg and 9.6 ± 2.3 kg for ewes and their lambs. The stocking period extended from 18/06 to 24/10 in 2011 (i.e. 122 days) and from 11/07 to 1/11 in 2012 (i.e. 114 days). In accordance with general practices for Italian ryegrass swards (Balasko et al., 1995), winter pastures received two applications of 75 kg ha^{-1} of nitrogen, the fist one was applied shortly after crop harvest and the second one at the peak of pasture production (beginning of September).

Lambs assigned to the continuous stocking treatment had unrestricted access to the entire paddock. For rotational stocking, we divided the paddocks into successive sub-areas with movable electric fences assigned to maintain a minimum of three animal testers per paddock. Length of the grazing cycle was defined as a function of Italian ryegrass's leaf lifespan. This method ensured that the animals return to any sub-area before the appearance of senescent leaves. On the same experimental site, Pontes et al. (2003) identified a leaf life span for Italian ryegrass of approximately 500 °C d^{-1} in August and 410 °C d^{-1} in September and October. Using these results, we adjusted stoking cycles to 36, 36, 28 and 22 days in 2011 and to 36, 28, 28 and 22 days in 2012. As sheep used each sub-area for a fixed duration (two days), the number of sub-divisions in each paddock depended of the length of the stocking cycle. For both stocking methods, we adjusted the stocking rate to maintain target forage allowance at the end of each rotational stocking cycle. Weighing of the animals was always realized after 12 h fasting.

2.4. *Pasture measurements*

In 2011 and 2012, we assessed established herbage mass by cutting all aboveground material inside three metallic frame of 50 cm × 50 cm randomly positioned inside each experimental unit just before the entry of the animals. During the stocking period of 2011 and the pasture establishment of 2012, we also collected more detailed data on tiller density and herbage accumulation. During the stocking period of 2011, we assessed reproductive tiller density every two weeks by counting the number of reproductive tillers inside three 10 cm × 10 cm metallic frames, per experimental unit. The samples were collected until 15/10/2011 witch corresponds to the end of the production cycle. After this date the pasture browned rapidly. We used a 10 cm × 10 cm metallic frame to allow sampling of the whole experimental area in a single day. We estimated vegetative tiller density during the pasture establishment of 2012 by following the same procedure. During this period (i.e. before the entry of the animals), we also estimated herbage accumulation every two weeks by cutting at ground level all the material present inside the 10 cm × 10 cm metallic frames used to assess vegetative tiller density. In addition, we estimated vegetative tiller density and herbage mass inside of the control areas on the same dates and with the same method as used for the remaining area. However, we collected two rather than three sample replicates. All samples were oven-dried at 60 °C until constant weight.

2.5. *Data analyses*

To account for potential spatial (sample repetitions nested in summer crop systems that were nested in paddocks) and temporal (repeated sampling at different dates) correlations in the data, we used mixed linear models for reproductive tiller density, vegetative tiller density and herbage mass (Zuur et al., 2009). For this analysis, we used the nlme package (Pinheiro et al., 2010) in the R software for statistical computing version 2.12.0 (R Development Core Team, 2010). We selected the structure of these models based on likelihood ratio tests (Restricted Maximum Likelihood for random effect and Maximum Likelihood for fixed effect) and on the Akaike's Information Criterion (AIC). We performed all models based on homogeneous Gaussian distribution as this distribution satisfied residual normality. In all models, the induced correlation at the paddock level was relatively high (>0.3), but was not significant at the summer crop system level. Therefore, we included a compound symmetry autocorrelation structure in all models at the paddock level to account for random effects.

In 2011, we tested the effects of management practices on reproductive tiller density on the last sampling date (15/10/2011). This date corresponded to the end of the reproductive cycle and we effectively observed that a high proportion of seeds were in mature stage. The fixed effects included grazing intensity, stocking method and summer crop system. In 2012, because vegetative tiller density exhibited a two phase dynamic (Fig. 4) and due to the confounding effects of summer crop harvest and nitrogen application, we tested the effects of management practices on vegetative tiller density at two distinct dates. First on the 05/05/2012, before summer crop harvest and nitrogen application, which corresponded to a maximum of vegetative tiller densities (Fig. 4). Second at the end of the establishment period, on the 30/06/2012, just before animals entered the system. On this last analysis, we log-transformed the vegetative tiller density to obtain residual normality.

Regarding herbage mass, we tested the effect of the different management practices on the established herbage mass in 2011 and 2012 (estimated by the 50 cm × 50 cm metallic frame just before the animals enter the experiment). We applied a square-root transformation to correct for residual heterogeneity. In 2012, we also tested the effect of the different treatments on the dynamic of herbage accumulation across the entire pasture establishment period. Fixed effects included day, grazing intensity, stocking method and summer crop system. Day was added as a random effect with an auto-regressive correlation structure

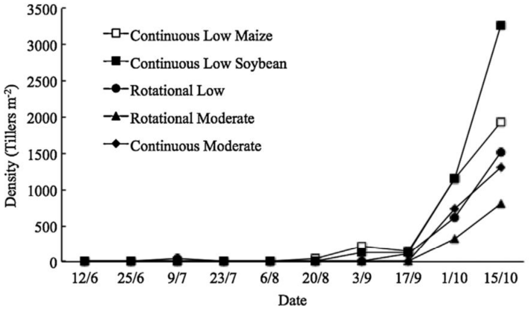

Fig. 3. Evolution of Italian ryegrass reproductive tiller density during the 2011 stocking season under two stocking methods (continuous and rotational), two grazing intensities (low and moderate) and two summer crop systems (soybean and maize–soybean rotation).

order of 1. We applied a cube root transformation to normalize and homogenize the residuals.

3. Results

3.1. Reproductive tiller density

Reproductive tiller density during 2011 stocking period remained close to zero until 17/09/2011 and then increased exponentially (Fig. 3). At the end of the growing season (15/10/2011), mean tiller density ranged between 678 and 3267 tiller m^{-2}, depending on the treatment (Table 1). Densities were significantly higher with continuous stocking and with low grazing intensity than with rotational stocking and with moderate grazing intensity (Table 1 and Fig. 3). The soybean summer crop system only had a significant effect under the continuous stoking × low grazing intensity treatment (Table 1). As a result, we only differentiated the two summer crop systems for that treatment in Fig. 3.

3.2. Italian ryegrass establishment

The establishment of Italian ryegrass in 2012 showed two distinct phases regarding the dynamics of vegetative tiller density and herbage mass (Fig. 4). During a first phase (from March 27th to May 5th, i.e. whereas the summer crop was still in place and before the nitrogen application), vegetative tiller density increased rapidly to a maximum value whereas herbage mass remained low. On a second phase (after May 5th, i.e. after crop harvest), vegetative tiller density tended to stabilize, except in the moderate grazing × soybean summer crop treatment where it continued to increase. On the other hand, herbage mass rapidly increased, with rates varying with treatments.

3.2.1. Vegetative tiller density

During the first phase of 2012 pasture establishment, the maximum values reached by vegetative tiller density were higher for the low grazing than for the moderated grazing intensity treatment ($F_{1,25} = 25.5$, $P < 0.001$, Fig. 4). At the end of the establishment period (i.e. on the 30/06/2012, just before animals entered in the system), the positive effect of the low grazing intensity treatment on vegetative tiller density only remained for the maize–soybean summer crop rotational system (Table 2). Vegetative tiller densities generally reached higher values under soybean summer crop system than under the maize–soybean summer crop rotational system, except on the rotational × low grazing intensity treatment (Table 2).

3.2.2. Herbage mass

In 2011, following a summer crop entirely constituted of soybean, herbage mass of Italian ryegrass reached around 1590 kg ha^{-1} at the end of the pasture establishment period (12/06/2011), before the entry of the animals. At this date, we did not observe any significant effect of the different treatments on herbage mass (Table 3). In 2012, pasture establishment followed a summer crop constituted witch one half of maize and one half of soybean (see Fig. 2). The low grazing intensity treatment ($t_{543} = -5.9$; $P < 0.001$) and the soybean summer crop system ($t_{543} = -2.3$; $P < 0.001$) both positively affected herbage accumulation during pasture establishment (Fig. 4). On the other hand, the stocking method did not have any significant

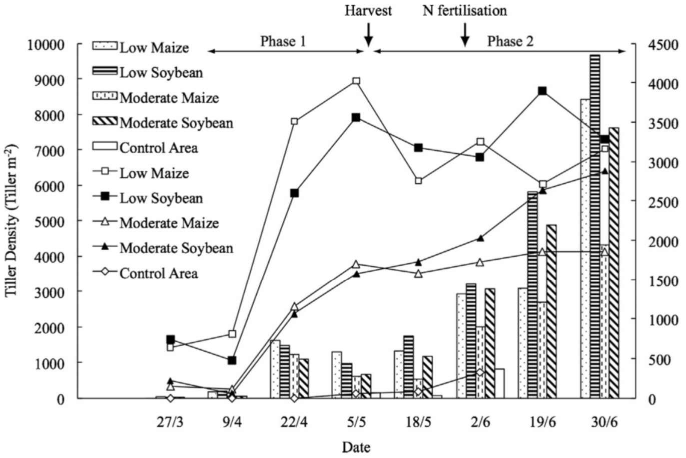

Fig. 4. Evolutions of Italian ryegrass vegetative tiller density and herbage mass during pasture establishment in 2012. Treatments included prior stocking methods (continuous and rotational, not represented here because of its absence of significant effect), prior grazing intensity (low and moderate) and summer crop systems (soybean and maize-soybean rotation). Evolutions of vegetative tillers density and herbage mass in the control areas (where all reproductive tillers were experimentally removed in 2011) are grouped for all treatments.

Table 1

Mean values and treatments effect for Italian ryegrass reproductive tiller density (tiller m^{-2}) at the end of the 2011 reproductive cycle (15/10/2011). Treatments included stocking method (continuous/rotational), grazing intensity (low/moderate) and summer crop system (soybean/maize–soybean rotation).

Summer crop system	Continuous		Rotational		P_M	P_G	P_C	$P_{M\times C}$	$P_{G\times C}$
	Low	Moderate	Low	Moderate					
M–S rotation	1933a	1378b	1433b	944b	0.002	0.006	0.016	0.009	0.001
Soybean	3267a*	1244b	1583b	678c					

M–S rotation: maize–soybean summer crop rotation. P_M = P-value for the stocking method treatment; P_G = P-value for the grazing intensity treatment; P_C = P-value for the summer crop system. Means followed by lowercase letters on the same line differ based on F test contrasts ($P < 0.05$). Soybean means followed by * differ from maize means of identical stocking method and grazing intensity based on F test contrasts ($P < 0.05$).

Table 2

Mean values and treatments effect for Italian ryegrass vegetative tiller density (tiller m^{-2}) at the end of 2012, pasture establishment phase, just before entry of the animals (30/06/2012). Treatments included stocking method (continuous/rotational), grazing intensity (low/moderate) and summer crop system (soybean/maize–soybean rotation).

Summer crop system	Continuous		Rotational		P_M	P_G	P_C	$P_{G\times C}$
	Low	Moderate	Low	Moderate				
M–S rotation	5873b	4000c	8422a	4178c	0.098	0.001	<0.001	0.009
Soybean	7282ab*	6122b*	7425a	6178ab*				

M–S rotation: maize–soybean summer crop rotation. P_M = P-value for the stocking method treatment; P_G = P-value for the grazing intensity treatment; P_C = P-value for the summer crop system. Means followed by lowercase letters on the same line differ based on F test contrasts ($P < 0.05$). Soybean means followed by * differ from maize means of identical stocking method and grazing intensity based on F test contrasts ($P < 0.05$).

Table 3

Mean values and treatments effect for Italian ryegrass established herbage mass (kg ha^{-1}) at the end of 2011 and 2012 pasture establishment, just before entry of the animals. Treatments included stocking method (continuous/rotational), grazing intensity (low/moderate) and summer crop system (soybean/maize–soybean rotation).

Year	Summer crop system	Continuous		Rotational		P_M	P_G	P_C
		Low	Moderate	Low	Moderate			
2011	M–S rotation	1573a	1630a	1457a	1660a	0.50	0.69	0.71
	Soybean	1550a	1480a	1707a	1670a			
2012	M–S rotation	1240a	1210a	1517a	1253a	0.61	0.28	<0.001
	Soybean	1857a*	1810a*	1883a	1680a*			

M–S rotation: maize–soybean summer crop rotation. P_M = P-value for the stocking method treatment; P_G = P-value for the grazing intensity treatment; P_C = P-value for the summer crop system. Means followed by lowercase letters on the same line differ based on F test contrasts ($P < 0.05$). Soybean means followed by * differ from maize means of identical stocking method and grazing intensity based on F test contrasts ($P < 0.05$).

effect ($t_{543} = -0.4$; $P = 0.69$). At the end of the pasture establishment period (08/07/2012), we observed a highly significant effect of the summer crop system on herbage mass, but not of the grazing intensity treatment (Table 3). Herbage mass was around 1810 kg ha^{-1} for soybean summer crop system and 1310 kg ha^{-1} for maize–soybean summer crop rotation system.

3.2.3. *Establishment in the control areas*

The control areas in which we removed all reproductive tillers in 2011 suffered a quasi-absence of plants of Italian ryegrass in the subsequent year (Fig. 4). We could not detect any significant effect of the different treatments for both tiller density ($F_{29,7} = 1.52$, $P = 0.20$) and herbage mass ($F_{30,7} = 1.72$, $P = 0.14$).

4. Discussion

ICLS are farm systems that tend to unite yield, profitability and environmental preservation. Specifically, ICLS allow the occurrence of a positive synergetic effect between crops and pastures and improve the systems production when well managed (Lemaire et al., 2005). In subtropical regions, one of the most common ICLS consists in the rotation of soybean or maize during the summer and self-seeded Italian ryegrass pastures during the winter. However, pasture persistence and the impacts of grazing management on pasture establishment by self-seeding remained poorly documented. Our results show that, even in long-established system, Italian ryegrass pastures cannot re-establish themselves annually by self-seeding if the grazing management (and particularly grazing intensity) results in the consumption of all produced seed heads. However, under moderate grazing intensity and even with the animals allowed grazing until the end of the grass production cycle, the pasture retained its ability to re-establish annually by self-seeding. Previous grazing management and summer crop influenced herbage accumulation dynamic during pasture establishment, whereas previous summer crop was the only factor significantly affecting herbage mass at the date of entry of the animals.

4.1. *Reproductive tiller production*

Our results confirmed the importance of grazing management (grazing intensity and stocking method) on final reproductive tiller production in Italian ryegrass pastures. Higher grazing intensities and rotational stocking reduced final reproductive tiller density. Higher grazing intensities extend the vegetative stage of the pasture (Dumont et al., 2012). Conversely, lower grazing intensities allow herbivores to be more selective and result in more heterogeneous sward structures (Hogan and Phillips, 2011; Da Trindade et al., 2012). Vegetative tillers in weakly grazed areas quickly differentiate themselves in reproductive tillers, which increase seed production (Hodgson, 1990).

The stocking method is also known to affect the sward structure (e.g. Carvalho et al., 2009). Rotational stocking, by imposing high instantaneous grazing pressure, aims to control the spatial and temporal bite allocation of herbivores. In doing so, rotational stocking decreases animal selectivity and increases reproductive tiller consumption. In addition, high instantaneous grazing pressure causes the destruction of most apical meristems, which partially prevents

Table 4
Performance of lambs grazing Italian ryegrass in 2011 and 2012 (sucking lambs). Treatments included stocking method (continuous/rotational) and grazing intensity (low/moderate).

	Variables	Continuous		Rotational		P_{I}	P_{M}
		Low	Moderate	Low	Moderate		
2011	SR	888.3b	1091.3a	833.1b	1345.7a	0.010	0.262
	LWG	152.1a	148.4a	103.1b	76.1b	0.387	0.029
	LWGHA	396.8b	556.0a	336.5b	468.2a	0.005	0.064
2012	SR	921.1b	1243.0a	1016.5b	1485.5a	0.001	0.067
	LWG	239.6a	243.0a	225.5b	193.1b	0.107	0.010
	LWGHA	394.7b	565.0a	461.2b	581.6a	0.029	0.397

Adapted from Savian et al. (Unpublished data).
SR = stocking rate (kg LW ha^{-1}); LWG = live weight gain (g animal^{-1} day^{-1}); LWGHA = live weight gain per area (kg LW ha^{-1}); P_{I} = probability for grazing intensity; P_{M} = probability for stocking method. Means followed by lowercase letters differ by F test ($P < 0.05$).

subsequent reproductive tiller production (Briske and Richards, 1995).

We observed that the soybean summer crop system leaded to higher production of reproductive tillers than the rotational maize–soybean summer crop system under the most favourable conditions (continuous stocking with low grazing intensity) (Fig. 3). This observation can reflects the long-term changes in soil fertility between the two systems as all paddocks were seeded with soybeans in the summer of 2010/2011. Several studies reported long-term positive effect of using legumes to increase nitrogen in the soil and benefits following crop yield (e.g. Krupinsky et al., 2006). However, this effect only appeared on our last sampling date and so need to be treated with caution (Fig. 3).

4.2. Pasture reseeding

Few studies have reported the establishment efficiency of Italian ryegrass by self-seeding (but see Evers and Nelson, 2000; Bartholomew and Williams, 2009; Barth Neto et al., 2012). In this experiment, we simulated very high grazing pressure by removing all seed heads of control areas, resulting in a one-year gap in the seed production. Despite seven consecutive years of seeds production (2003–2010), one year without seed production prevented pasture establishment (Fig. 4). Hence, Italian ryegrass establishment by self-seeding depends on annual soil seed bank replacement, maintained through the production of reproductive tillers.

The persistence of the soil seed bank depends on the balance between seed inputs and outputs (predation, germination or embryo death) with time (Harper, 1977). In no till systems, seeds remain at the soil surface, which exposes them to predation and disturbance and decreases their longevity (Ghérsa and Martínez-Ghérsa, 2000; Chauhan et al., 2012). Ichihara et al. (2009) observed 15% and 97% reductions in Italian ryegrass seed banks over 10 months when seeds were buried at a depth of 5 cm depth and maintained at the soil surface, respectively. In addition, seeds that remain on the soil surface are exposed to high summer temperatures that end their dormancy (Maia et al., 2007). A high germination rate during the first summer would prevent the storage of seeds for germination in subsequent years and contribute to explain the non-persistence of the soil seed bank.

4.3. Pasture establishment

Grazing intensity on the previous year and summer crop both affected the dynamic of pasture establishment. With lower grazing intensities on the previous year, tiller density increased more rapidly and reached greater values during the first phase of establishment (Fig. 4). This probably reflected the higher reproductive tiller density, with heavier tillers, observed under the low grazing intensity treatment. Chastain and Young (1998) also reported that heavier tillers resulted a greater potential for flowering and seed production. This initial advantage positively influenced Italian ryegrass tiller density at the end of the pasture establishment following maize summer crop, but not soybean summer crop. Furthermore, grazing management on the previous year did not result in any significant difference on herbage mass at the end of the pasture establishment (i.e. just before the entry of the animals, Table 3). So grazing management affected the dynamic of pasture establishment, but not final herbage mass. The higher tiller density observed before crop harvest in the low grazing treatment could however have result in a higher competitive abilities of the pasture against weeds.

The summer crop (maize or soybean) affected pasture establishment on a short-term basis. In 2011, when both summer crop systems were sown with soybean, we did not observed any effect of the summer crop system on herbage mass at the end of the pasture establishment (Table 3). In 2012, however, areas sown with maize resulted in significantly lower tiller densities and herbage mass at the end of pasture establishment than areas sown with soybean (Tables 2 and 3). Interestingly, the positive effect of the soybean over the maize summer crop only appeared on the second phase of pasture establishment, after crop was harvested (Fig. 4). Hence, the summer crop probably mostly affected pasture establishment due to short-term physical and chemical effects of plant residuals on the local environment. First, soybean leaves fall early before crop harvest, allowing light to reach the pasture during early establishment. Second, maize harvest resulted in the accumulation of more plant residual on the ground than the soybean harvest, which potentially physically delayed pasture development. Finally, soybean plant residuals are of higher quality than maize ones, with C/N ratio around 25 rather than 62 for maize (Li et al., 2013). Residuals with higher C/N ratio decompose more slowly and induced soil net N immobilization (Muhammad et al., 2011). As a result, soybean summer crop most likely ensured higher availability of soil N for pasture growth.

In the long-term experiment considered here, Italian ryegrass pasture succeeded to re-establish itself by self-seeding since 2005, under both continuous and rotational stocking and moderate and low grazing intensity, and without reduction of the stocking period. Evers and Nelson (2000) and Bartholomew and Williams (2009) reported that, unless a strict reduction of the stocking period at the end of the production cycle, seed head production is drastically reduced and Italian ryegrass pasture fails to re-establish itself by self-seeding. This may has occurred due to a grazing managed practice with too heavy grazing intensity. In our experiment, however, the stocking periods extended up to the end of the grass production cycle without compromising subsequent pasture establishment. The stoking period extended over 122 days in 2011 and 114 days in 2012. Animal production was satisfactory as live weight gain reached 556 kg ha^{-1} or 4.5 kg ha^{-1} day^{-1} in 2011 and 581.6 kg ha^{-1} or 5.1 kg ha^{-1} day^{-1} in 2012 under the moderate grazing intensity treatment (Table 4, Savian et al., unpublished data). This result shows how it is important to succeed in Italian ryegrass establishment by self-seeding without reducing the potential stoking period, as this reduction would be particularly costly.

5. Conclusion

The reliance of Italian ryegrass establishment by self-seeding on the annual replacement of the soil seed bank in no-till integrated crop livestock systems has important management consequences. Grazing management practices need to ensure, mostly by limiting the grazing intensity, sufficient seed heads production to not compromise subsequent pasture establishment. This experiment demonstrated that under various stocking methods (continuous and rotational), grazing intensity (low to moderate) and summer crop (maize and soybean), Italian ryegrass pasture establishment by self-seeding remains successful even when the stocking periods extended up to the end of the grass production cycle. Self-seeding with moderate grazing intensity ensures successful pasture establishment, reduces labour and costs and allows to increase the stocking period and so animal live weight gain over the grazing season. Unfortunately, reduction of the stocking period in such systems remains the common practice in subtropical South American, mostly because of mismanagement by over-stocking.

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3. CHAPTER 3 - Crop rotation and grazing management strategies on herbage mass production at the transition of the crop-pasture phase of integrated crop-livestock systems[2]

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[2] Prepared in accordance with the standards of the European Journal of Agronomy

Crop rotation and grazing management strategies on herbage mass production on transition phase crop-pasture in integrated crop-livestock systems

Abstract

The objective of this work was to evaluate the effects of agricultural practices on Italian ryegrass herbage mass on transition phases between crop-pasture in integrated crop livestock system (ICLS) in Southern Brazil. This work is part of a long-term experiment initiated in 2003. It aimed at assessing the effects of crop rotation (soybean monoculture vs. soybean-maize rotation), stocking method (continuous vs. rotational), grazing intensity (low vs. moderate) on herbage mass at the beginning and end of the grazing period. To better understand the biomass response to the tested variables, we measured tiller density and sward height. The experiment consisted in a rotation of Italian ryegrass, established by self-seeding grazed by sheep during the winter, and sown with either soybean or soybean-maize grain crop rotation during the summer. Data were collected between 2010 and 2012. In 2010 and 2012, the soybean-maize treatments were sown with maize and in 2011 with soybean. Soybean as a previous crop affected positively the herbage mass at the beginning of the grazing phase. Low grazing intensity strongly affected the herbage mass at the end of grazing phase. No effects of ante-previous crop or stocking method were found in herbage mass. For both phases analysed, when the sward height increased, the herbage mass increased as well. Besides, herbage mass and tiller density were not significantly correlated in both phases. Pasture after soybean had a taller canopy than pasture following maize. Rotational stocking affected strongly the sward height at the end of grazing phase in 2010 and in 2012. The grazing intensity had a significant effect across the three years on sward height, with higher sward height in treatments managed with low grazing intensity. In conclusion, Italian ryegrass with soybean as preceding crop and managed with low grazing intensity provided a higher herbage mass accumulation, and as such, was the best crop-livestock management system tested for ICLS to increase herbage mass.

Keywords: Mixed system, crop residue, preceding crop, grazing intensity, stocking method

1. Introduction

Modern agriculture resulted in undeniable yield increases in animal and crop production systems around the world. This advancement was achieved by a high use of inputs (mineral fertilizers and pesticides), and a high specialization of production systems, leading to separate livestock from grain production. However, this combination of intensification and specialization led to serious environmental disservices in industrialized countries, such as degradation of air, soil and water quality and biodiversity loss (Stoate et al., 2001; Milenium Ecossystem Assessments, 2005; Hannah et al., 2013). This, nowadays, is considered to be unacceptable by the society (Lemaire et al., 2014).

Agricultural systems in Brazil are acknowledged as being an example of success in conservation agriculture, with more than 70% of cropland under no-tillage practices (Derpsch et al., 2014). However, in recent years farmers have overlooked crop rotation, which is considered as being one of three pillars of no-till systems. The only investment is on annual cash crops, basically rotating soybean (*Glycine max* L.) - maize (*Zea mays* L.) every year in tropical regions, or soybean-wheat in subtropical regions, in summer and winter respectively. This loss in crop biodiversity increases environmental and economic risks. Integrated Crop-Livestock Systems (ICLSs) involve the rotation or succession of pasture and grain crops in a temporal and spatial scale, resulting in an increase in diversity within an agricultural system. Mixed systems with no-till can be considered more profitable and environmentally friendly than just crop rotation with cover crops (Russelle et al., 2007; Tracy and Zhang, 2008).

In the last decade, research in ICLS concentrated efforts on explaining the grazing animal impacts on the cropping system, mainly on crop yield (Tracy and Zhang, 2008; Lunardi et al., 2008; Franzluebbers and Stuedemann, 2008; Lopes et al., 2009; Carvalho et al., 2010). Those studies showed that the grazing intensity played an important role not only in crop yield, but also in soil proprieties. Lower grazing intensities are considered to be able to keep not only the recommended herbage allowance, but also to provide sufficient plant residue on soil surface to insure the success of no-till systems and ICLS regarding the sustainability of soil proprieties (e.g. soil compaction, nutrient recycling and microbial activity) (Anghinoni et al., 2013). Several publications indicated that the crop phase has also a subsequent effect on grazing phase (e.g. Crusciol et al., 2012; Barth Neto et al., 2014). Crusciol et al. (2012) studied the effects of soybean life-cycle duration in palisade grass (*Urochloa brizantha* Hochst.) production. Results showed that the earlier the soybean cycle is the longer is the grazing season for cattle, without reduction in crop or grass yield. In sub-tropical regions in South America, summer crops used to be rotated with Italian ryegrass (*Lolium multiflorum* Lam.), which is established by self-seeding. Barth Neto et al. (2014) compared Italian ryegrass establishment either after soybean or maize, and found a higher herbage mass production in areas sown with soybean.

ICLSs are considered as dynamic and complex productions systems with many interactions involving both pasture and crop phases. Most studies focused mainly on explaining isolated factors of the pasture phase effects on the grain crop phase (e.g. soil compaction, crop yield, carbon concentration on soil). We assumed that both phases cannot be disconnected, and the management of each phase affects the following one. However, there is limited information in the literature on the interactions and the complementarity between those two phases, especially in the case of systems involving maize or soybean in rotation with self-seeding ryegrass. In this case, pasture starts growing before the cash crop is harvested, and the herbage mass production before the entrance of animals on the pasture and the length of the crop effects on the pasture phase are not sufficiently understood.

Our goal is to investigate the effects of agricultural practices on herbage production in ICLS. The objective of this paper is to focus on herbage mass on transition phases between grains and pasture crops (e.g. from the end of grain crop phase to the beginning of grazing phase; and from the end of grazing phase to the beginning of grain crop phase). We will address the impacts of summer crop rotation (maize-soybean rotation or soybean monoculture) and grazing management (stocking method and grazing intensity) on herbage mass at: I) pasture establishment phase after soybean or maize and II) pasture ending phase preceding soybean or maize. We will use herbage mass as a parameter indicating the effects of crop and livestock management on the pasture crop.

2. Materials and methods

This work is part of a long-term ICLS experiment initiated in 2003 in Brazil. The ICLS protocol consists in the rotation in the same area of two summer crops with no tillage, either a soybean monoculture or a soybean-maize rotation (i.e. mid-November until early-May/mid-June), and each year between cash crops, Italian ryegrass pasture grazed by sheep during the winter (i.e. mid-June/end-July until early-November). Italian ryegrass pasture is established each year by natural reseeding since 2005. During the grazing seasons of 2010 to 2012, we evaluated the effect of agricultural practices on pasture herbage mass accumulation at the establishment phase, prior to grazing, and at the end of the pasture cycle. Those evaluations of herbage mass are considered to be critical links between crops and pasture production.

2.1 Experimental site

The experiment was conducted in Southern Brazil at the experimental station of the Federal University of Rio Grande do Sul, (30°05’ S; 51°39’ W), in a subtropical humid region (Cfa classification) according Köppen and Geinger (1928). It is characterised by a marked seasonality of temperature and evenly spread precipitations along the year (Fig. 1). However, there was an excess of rainfall in the winters of 2010 and 2011 during the study period, and a deficit of rainfall during the 2011-2012 summer. The 2012 spring had temperatures above historic averages. The soil at the experimental site was classified as a Typic Paleudult (USDA, 1999) with 15% clay. Soil chemical characteristics for the surface horizon (0-20 cm), sampled in 2010, are: pH = 4.87; SMP index = 5.82; P = 51.78 mg dm^{-3}; K = 106.01 mg dm^{-3}; OM = 1.99%; Al = 0.59 $cmol_c$ dm^{-3}; Ca = 1.95 $cmol_c$ dm^{-3}; Mg = 0.95 $cmol_c$ dm^{-3}; cation exchange capacity = 8.61 $cmol_c$ dm^{-3} and base saturation = 37.04%.

2.2 Experimental design

The experiment consisted of a 2 by 2 factorial, arranged in a randomized complete block design, with split plots in the winter, with four replicates. During the summer, each paddock was divided in two for sowing either soybean or maize to test the effect of summer crop rotation, which resulted in 32 experimental units, with a total experimental area of 4.8 ha. Treatments resulted from the combinations of (i) two stocking methods (continuous and rotational), (ii) two grazing intensities (low and moderate) in the winter, and (iii) two summer crops (soybean monoculture and maize-soybean rotation). See Barth Neto et al. (2014) for more details on the experimental protocol. For the ryegrass, response variables measured were herbage mass, tiller density and sward height, evaluated at the beginning of grazing phase and after the end of grazing phase for both years.

2.3. Management practices

2.3.1. Summer crop

We worked on three summer crop seasons, where the treatments with crop rotation were sown in a sequence of maize-soybean-maize in 2010 to 2012 respectively and the others treatments with soybean monoculture. Fig. 2 illustrates the timeline of each paddock used during the experimental period. As soybean seeds were inoculated with *Bradyrhizobium* spp. bacteria before sowing, no N fertilizer was applied. Treatments sown with maize received two applications of 75 kg ha^{-1} of N, at the 6th and 9th fully expanded leaf stages (Yamada, 1996).

2.3.2. Winter grazing season

In the treatments with continuous stocking, animals had access to the whole paddock. In rotational stocking, the paddock was sub-divided with electric fence and the animals remained two days in each sub-division. The length of each grazing cycle was defined as a function of the Italian ryegrass leaf lifespan (Pontes et al., 2003). The objective of this method is for the animal to return to the sub-division before leaf senescence begins. As the Italian ryegrass grows slower in the winter and faster in spring, grazing cycles were longer at the beginning than at the end of grazing season. The timeline of land uses during the period studied is presented in Fig. 2. For both stocking methods, the grazing intensity was adjusted according to the target at the end of each rotational cycle. Nitrogen fertilizer was applied at a rate of 150 kg ha^{-1}, split in two applications (in 2010, on 22/08 and 01/10; in 2011 on 25/05 and 01/09; and in 2012 on 01/06 and 30/08). Phosphorus and potassium fertilizer were applied a time per year, just after the crops harvest, with a rate of 60 kg ha^{-1} of P_2O_5 and K_2O, respectively (ROLAS, 2004). Our objective was to replace both nutrients (phosphorus and potassium) in the period of the major extraction of theses nutrients from the agricultural system (grain harvest).

2.4 Measurements

Pasture aboveground biomass was sampled after the establishment phase, just before allocating the animals on the pastures, and again at the end of the stocking period. A 0.25 m² quadrat was allocated randomly in three places per plot and herbage cut at soil level. Samples were dried in forced air oven at 60 °C until reaching constant weight and weighed. To better understand the biomass response to the tested practices, we evaluated tiller density and sward height. Tiller density was measured using three metallic frames of 10×10 cm, and all tillers inside it were counted. Sward height was measured with a sward stick in 75 random points per experimental unit (Barthram, 1985).

2.5 Data Analyses

We used mixed linear models (Zuur et al., 2009) with the nlme package (Pinheiro et al., 2010) in the R software for statistical computing version 2.12.0 (R Development CoreTeam, 2010) for the variables herbage mass, tiller density and sward height. We used models to account the potential spatial (sample repetitions nested in summer crop systems that were nested in plot and in years) correlations in the data. The Akaike's Information Criterion (AIC) and likelihood ratio tests (Restricted Maximum Likelihood for random effect and Maximum Likelihood for fixed effect) were applied to select the structure of the models. To test the effects of management practices on herbage mass, tiller density and sward height on two distinct phases, at the end of establishment phase and at the end of grazing phases and in three separately years, 2010, 2011 and 2012. The model was tested with stocking method (SM), grazing intensity (GI), summer crop system (previous crop (PC) or ante previous crop (APC), according the tested year) as fixed effects and plot (Pl) as a random effect:

$$X_{ijkl} = SM_i + GI_j + PC_k + APC_l + Pl_m +, \varepsilon_{ijklm}$$

where ε_{ijklm} is the error term.

To test the effects of management practices along the years on herbage mass, sward height and tiller density, we tested 2010 and 2012 together because for both years pasture had maize or soybean as a previous crop (and the same ante-previous crop, soybean), whereas in 2011 only soybean was present as a previous crop in both treatments (rotation and monoculture). The models were tested with stocking method (SM), grazing intensity (GI), summer crop system (previous crop (PC) or ante previous crop (APC), according to the tested year) as fixed effects and year (Y) as random effect:

$$X_{ijkl} = SM_i + GI_j + PC_k + APC_l + Y_m + \varepsilon_{ijklm}$$

where ε_{ijklm} is the error term.

Finally, we tested the three years separately to observe cumulative effects on sward height, with stocking method (SM), grazing intensity (GI), summer crop system (previous crop (PC) or ante previous crop (APC), according to the tested year) as fixed effects and plot (Pl) as random effect:

$$X_{ijkl} = SM_i + GI_j + PC_k + APC_l + Y_m + \varepsilon_{ijklm}$$

where ε_{ijklm} is the error term.

We used the lmmfit package (Maj, 2014) to calculate the coefficient of correlation in mixed linear models.

3. Results

3.1. Herbage mass at the beginning of the grazing phase

The herbage mass at the beginning of grazing phase was significantly affected by the previous summer crop (P = <.0001; Table 1). In 2010 and 2012, both years when maize was sowed, pasture established after soybean had higher herbage mass than the pasture preceded by maize (Fig. 3) with an average value of 1626 kg ha^{-1} and 1170 kg ha^{-1} for pasture following soybean and maize respectively. For the treatments with maize as previous crop, the average herbage mass was lower in 2010 than in 2012 (1300 kg ha^{-1} vs. 1562 kg ha^{-1}). There was no significant effect of ante previous crop on herbage mass in 2011, when soybean was sown as a previous crop in all treatments (*P* = 0.7693; Table 1).

3.2. Herbage mass at the end of the grazing phase

The herbage mass at the end of grazing phase was affected by grazing intensity and previous crop (Table 1, *P* <0.0001), but there was no interaction between them. The same effect was found at the end of grazing phase in pasture following soybean comparing with following maize. Pasture subsequent to soybean had higher herbage mass than the after maize (Fig. 3), with an average difference of 391 kg ha^{-1}, with a stronger effect of the summer crop in 2010 (696 kg ha^{-1}) than in 2012 (86 kg ha^{-1}). Treatments with low grazing intensity had higher herbage mass than the pasture with moderate grazing intensity (Fig. 4). In average, pasture under low grazing intensity had 716 kg ha^{-1} greater herbage mass than pasture under moderate grazing intensity.

3.3 Correlation of herbage mass with tiller density and sward height

Herbage mass and tiller density were not significantly correlated in both phases, *i.e.* the beginning of grazing phase and the end of grazing phase (*P* = 0.3286; *P* = 0.7285, respectively; Fig. 5). For both phases, when the sward height increased, herbage mass increased significantly (*P* <0.0001 and *P* = 0.003, respectively; Fig. 6), denoting that sward height explain better herbage mass variability than tiller density.

3.4 Sward height

The previous crop significantly affected the sward height at the beginning of grazing phase and at the end of grazing phase in 2010 and in 2012 (*P*<0.0001, Table 2). In accordance with the results obtained for the herbage mass, pasture following soybean was taller than pasture following maize (Fig. 7). The effect of previous crop was stronger at the beginning of grazing phase than at the end.

The stocking method significantly affected sward height at the end of grazing phase in 2010 and in 2012 (*P*=0.0002 and *P*<0.0001) and no significant effect was observed in 2011 (*P*=0.9594) (Table 2 and Fig. 7). Pasture managed under rotational stocking presented higher values of sward height than pasture managed under continuous stocking.

The grazing intensity significantly affected the sward height at the beginning of grazing phase and at the end of grazing phase (*P*=0.0011 and *P* <0.0001, respectively for the three years analysed together; Table 2). As observed for the herbage mass, pastures managed under low grazing intensity showed higher values of sward height than pastures managed under moderate grazing intensity. The grazing intensity had significant effect on sward height (Table 2, Fig. 8 and Fig. 9). But only in 2010 did not significantly affect sward height at the end of establishment phase and at the end of grazing phase (*P* =0.1788 and *P* =0.1845, respectively). Later on, in 2011 and 2012, the grazing intensity affected sward height in both phases, with an increase in the significance of the effect from 2011 (*P* =0.0288 and *P* =0.0057) to 2012 (*P* =0.0061 and *P* =0.0001). Than is possible to observe an accumulative effect of the grazing intensity in sward height across the years.

4. Discussion

4.1 Effects of the previous crop on herbage mass

At the beginning of grazing phase, pasture grown after soybean crop resulted in higher herbage mass accumulation and taller sward comparing to pasture following maize crop. Maize is able to produce during growing season around of 4.4 Mg ha^{-1} of aboveground crop residue while soybean crop yields around 3.3 Mg ha^{-1} (Mazzilli et al., 2014). The amount of crop residue added to the pasture after maize is harvested represents considerable differences in quantity and quality when compared to soybean. In a study with weeds, Mohler and Teasdale (1993) showed that the higher is the crop residue inputted aboveground, the lower is the weeds emergence and consequently the total weed density. So the higher quantity of maize residue added to pasture could restrict the light interception with more intensity and hinder pasture establishment than pasture following soybean. Despite the difference in quantity of crop residue, the decomposition time is also different in maize from soybean. All maize residues are added on pasture during harvesting. For soybean, the residues are added on pasture in two stages. First when leafs begins to fall during the maturation stage, and secondly during the crop harvest. These two stages could reduce the residual impact of soybean on pasture establishment. For maize, straw is added all at once and at large amounts, which could represent a more important physical barrier, thus reducing dry matter accumulation and sward height. The physical barrier of the crop residues can affect the quickness of herbage mass accumulation and the decrease of sward height on establishment phase.

In addition, the preceding crop could also affect herbage mass through mineral nutrition provided by its residues. During the decomposition process, soil microorganisms immobilize N in the soil, reducing the amount of total N available to the crops. The amount and period of time that N will stay immobilized depends on the C:N ratio of the crop residue, where a large ratio means lower N, therefore lower decomposition rate and longer immobilization period (Trinsoutrot et al., 2000). Maize residue had a C:N ratio of about 78, against 17 in soybean (Mazzilli et al., 2014). Thus, pasture following maize could have lower amount of nitrogen available on soil during the pasture establishment than pasture following soybean, consequently lower herbage mass accumulation with lower height. Moreover, the quality of leaf residue is different than total crop residue. In general the C:N ratio is lower in leaves than in total shoot residue (Soussana and Lemaire, 2014). In the case of soybean, leafs had a C:N ratio around 10:1 (Tavares and Nahas, 2013). Soybean leaves that fall on soil at the beginning of pasture emergence could be decomposed in a few days, allowing an increment of nitrogen concentration on soil favouring the pasture establishment.

The same effect of previous crop at the beginning of grazing phase remained until the end of the grazing phase. Treatments with pasture following soybean had more biomass than those following maize, what is important for no-till systems. According Derpsch et al. (2014), limited in soil cover results in poor performance of no-till (e.g. high water evaporation, reducing production and water use efficiency). Higher sward height was observed at the end of grazing cycle in both years 2010 and 2012. When we analyse only the herbage mass for each year apart, when maize was sown (within soybean-maize rotation, in 2010 and 2012), the effect of previous crop was only observed in final herbage mass in 2010. We attributed this response to the different timing of N fertilization. To avoid the pasture coming into reproductive stage before the entry of animals, N fertilization was delayed in 2010, applied in late August and early October. In 2011 and 2012 the planned timing of fertilization, was followed and N was applied just after grain crop harvesting and at the peak of pasture growth, on early September. The rate of maize residue decomposition could be reduced in 2010 and thus the period while N was immobilized on the soil was increased, limiting the pasture growth.

Better environmental conditions for the pasture growth in areas following soybean crop were expressed in the components of tiller density and sward height. Changes in structure of tiller population, regarding sward height, are consequences of allocation of assimilates in different plant morphological structure according to environmental resources availability, especially light, water and N (Lemaire, 2001). Greater resources availability in areas succeeding soybean crop can increase the supply of N in the soil in short-term, resulting in a high N pool during the pasture establishment, from the beginning of Italian ryegrass emergence, and consequently allowing a larger leaf expansion, with a taller canopy than those treatments succeeding maize.

4.2 Effects of grazing management on herbage mass

The grazing intensity was the main factor affecting herbage mass at the end of grazing phase. Treatments under low grazing intensity had higher herbage mass than treatments under moderate grazing intensity. Changes in grazing intensity affect the sward structure, composition and quantity of herbage mass (Hodgson, 1990). Higher grazing intensities reduce the animal intake, selection and performance, while decrease sward height, leaf area index and herbage mass (Carvalho et al., 2010). Stocking method, continuous or rotational stocking, had not significant effect on herbage mass. Briske et al. (2008) showed that the supposed benefits of rotational over continuous stocking (e.g. control frequency and intensity of defoliation) were often not consistent, resulting in no differences in forage quantity and quality.

In ICLS under no-till, the main challenge is on grazing management, mainly intensity, to maintain sufficient herbage mass to ensure animal performance and to cover the soil at the end of grazing cycle for a proper direct drilling (Carvalho et al., 2010). With respect to the effect of the animals in the amount of biomass left on soil, Denardin and Kochhann (1993) postulated that a minimum of 6.0 Mg ha^{-1} year^{-1} of plant residue is needed for a successful no-tillage planting (e.g. keeping soil covered, crop rotation, increasing water retention in the soil, increasing carbon on soil, avoiding soil degradation and erosion) (Derpsch et al., 2010). Considering that maize and soybean crop residue input aboveground of around 4.4 Mg ha^{-1} and 3.3 Mg ha^{-1}, respectively (Mazzilli et al., 2014) annually, pasture managed with moderate grazing intensity proceeding soybean would not allow a desirable no-till. Nevertheless, (Kunrath et al., 2014) presented an elegant discussion in which stated that even in moderate grazing intensities, sward herbage mass has a different plant tissue flux, allowing a constant production of biomass over almost the whole grazing cycle. Thus, herbage mass at the end of the grazing cycle represent partially the total amount of biomass cycling during the pasture phase and a simple comparison with no-grazed biomass, preceding grain crop sowing, is impossible to be done.

4.3 Effect of grazing management on sward height

Pasture managed at moderate grazing intensity had lower sward height at the beginning of grazing phase than pasture managed at low grazing intensity (Fig. 10). Higher grazing intensities (e.g. lower sward height) could have negative consequences on the seed head production (Evers and Nelson, 2000), thus affecting the ability of natural reestablishment of the pasture for the following years (Bartholomew and Williams, 2009; Barth Neto et al., 2014). In conclusion, managing pasture under moderate grazing intensity could result in the necessity of reseeding in addition to the natural processes of self-seeding.

The stocking method only affected the sward height at the end of the grazing cycle in 2010 and 2012, with higher herbage mass in treatments with rotational stocking than continuous stocking. This result is frequently found in literature in experimentation with grazed pasture (Parsons et al., 1988) and in previous studies at the same experimental site by (Barbosa et al., 2007) and Macari et al. (2011). Rotational stocking aims to control the spatial and temporal bite allocation of herbivores in the sward by manipulating stocking rates and strip size. The impact of grazing in the sward structure is high as animals graze each strip; meanwhile in the remaining areas of the paddock the plants are free to grow. In continuous stocking the animals have unrestricted access to the entire paddock, what allows for more selectivity. This permits the herbivores to return to graze the same tiller or patch more frequently, resulting in plants with lower amount of leaves and with shorter swards comparing to areas managed with rotational stocking (Hodgson, 1990).

4.4 Relationships between tiller density, sward height and herbage mass

Sward height is used as parameter to describe the sward structure, and relate to herbage mass. Classical studies focus on the relationship between sward height and herbage mass, as increases in sward height means increases in herbage mass (Hodgson, 1981, 1985, 1990). Tiller density is very dynamic and extremely related with micro-edaphic-climate conditions (Lemaire, 2001) and grazing management (Matthew et al., 2000). As the herbage mass and tiller density were not sampled at the same time and at the same area, this could explain the lack of relationship between these two variables. Thus, to increase the possibility to describe changes in herbage mass with tiller density we trust that it is important to sample the variables at the same time and at the same place.

5. Conclusion

As we hypostatised, both phases crop and pasture are not disconnected and both affects the herbage mass. The previous crop affects the herbage mass at the beginning and at the end of the grazing phase, with higher herbage mass following soybean than maize. The grazing management affects the herbage mass only at the end of grazing phase, with higher herbage mass under low grazing intensity management than at moderate grazing intensity.

In conclusion Italian ryegrass managed with soybean as previous crop and pasture managed with low grazing intensity provides higher herbage mass accumulation, and maybe the best arrange in ICLS tested, tough our results need to be interpreted with caution. The highlight point ICLS is not to maximize each part of the system, the most important is the balance between parts, favouring the system as a whole. The monoculture is inconsistent in conservationist agriculture, as ICLS, the use of maize in rotation with soybean increases the diversity in agriculture system with benefices for no-till. In the same way, managing pasture under moderate grazing intensity increases the animal production per area and ensures enough residues for zero tillage. Hence, to decide which ICLS arrangement to use, it is important to take in account all trade-offs plays in the system.

Our work presented descriptive results about the effects of managements on herbage mass at the beginning of grazing phase and at the end of grazing phases. We propose that new studies should be done with the objective of explaining in details the cause-effect relationships of previous crop on pasture establishment (e.g. crop residue decomposition, pasture nitrogen nutrition index, pasture canopy light interception,), and grazing intensity management along the year and its impact in the system in a long-term run (e.g. pasture residue decomposition, stocks of carbon on soil, seed production add on soil). In consequence, it will be possible to understand in detail the real impact of agriculture management in pasture-crop transition phase in a long-term perspective, and manage the system in order that the previous phase could favour the following one.

6. References

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Tables and figures

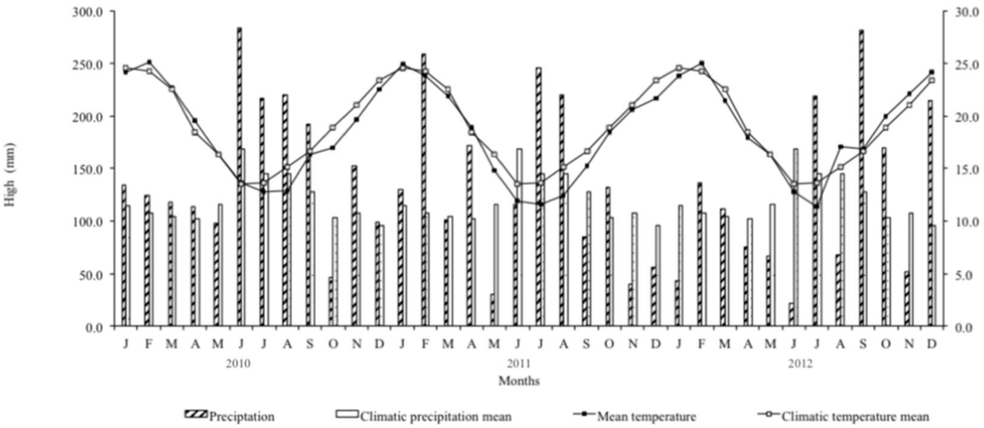

Fig. 1. Precipitation and air temperature during the experimental period (2010-2012) and climatic means 1970-2000.

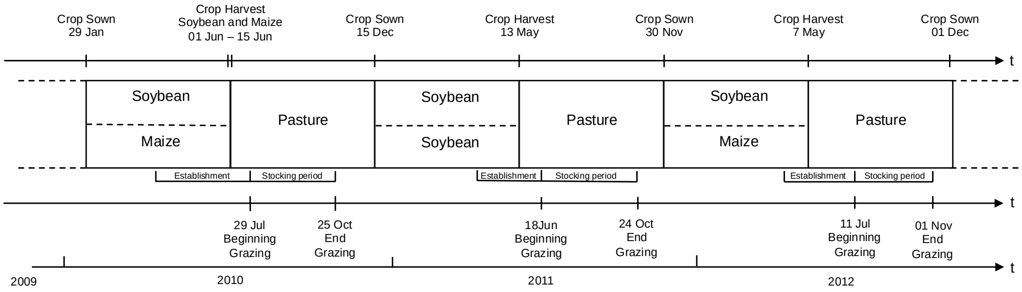

Fig. 2. Timeline representing the use of each paddock in 2010 to 2013.

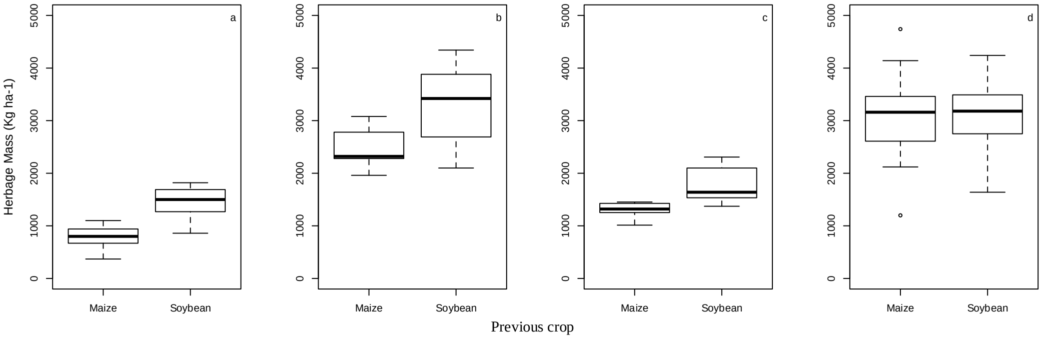

Fig. 3. Herbage mass of Italian ryegrass at the beginning of the grazing phase succeeding soybean or maize, and at the end grazing phase preceding soybean or maize in 2010 and 2012. Treatments represent previous crop (maize and soybean): a) 2010 beginning of grazing phase; b) 2010 end grazing phase; c) 2012 beginning of grazing phase; d) 2012 end grazing phase.

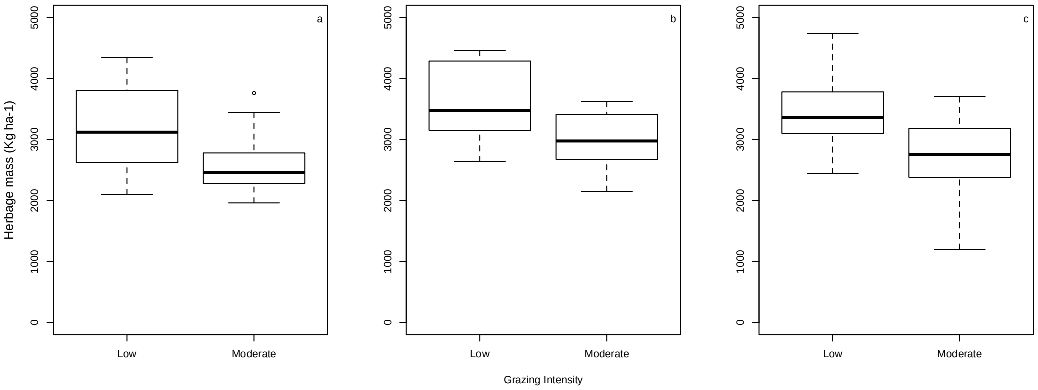

Fig. 4. Herbage mass of Italian ryegrass at the end of the grazing phase preceding soybean or maize in 2010, 2011 and 2012. Treatments represent grazing intensity (low and moderate): a) 2010; b) 2011; c) 2012.

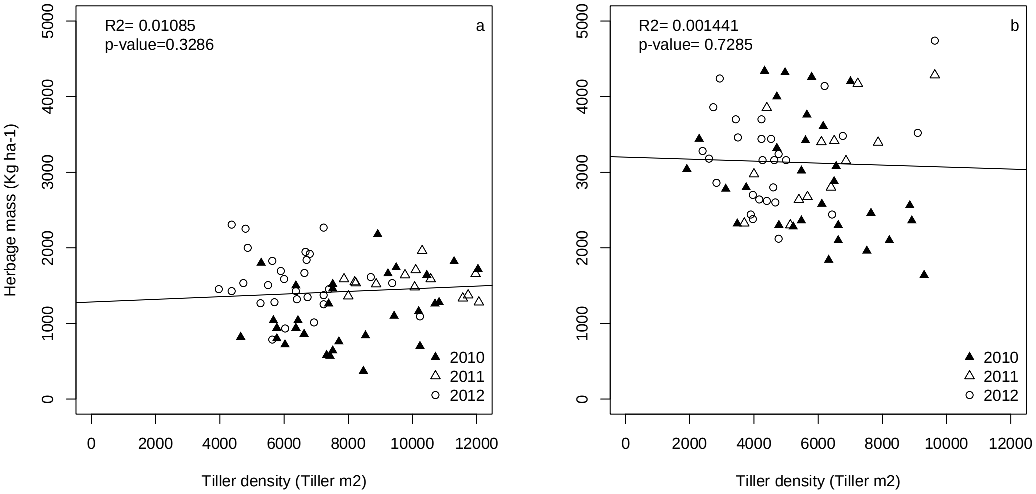

Fig. 5. Relationship between herbage mass and tiller density at beginning of grazing phase (a) succeeding soybean or maize and at the end of grazing phase (b) preceding soybean or maize in 2010, 2011 and 2012.

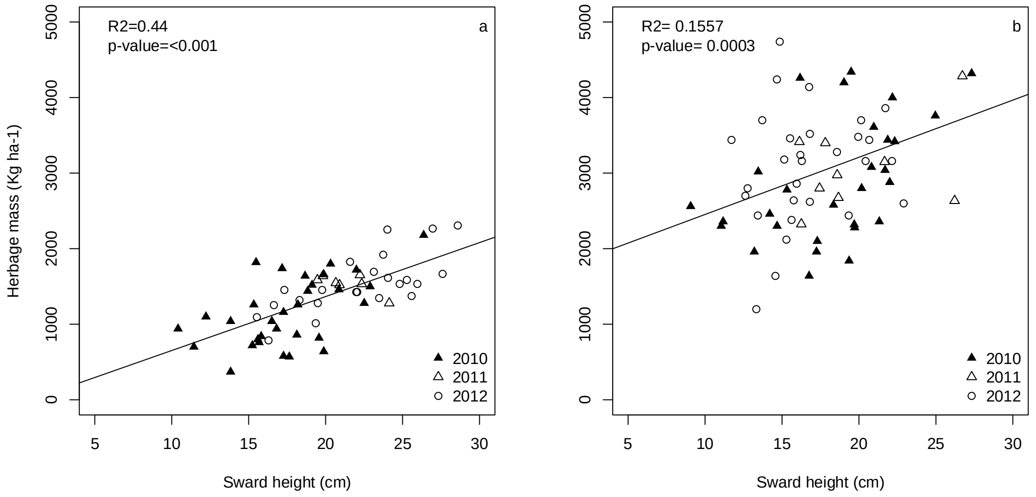

Fig. 6. Relationship between herbage mass and sward height at the beginning of grazing phase (a) succeeding soybean or maize and at the end of grazing phase (b) preceding soybean or maize in 2010, 2011 and 2012.

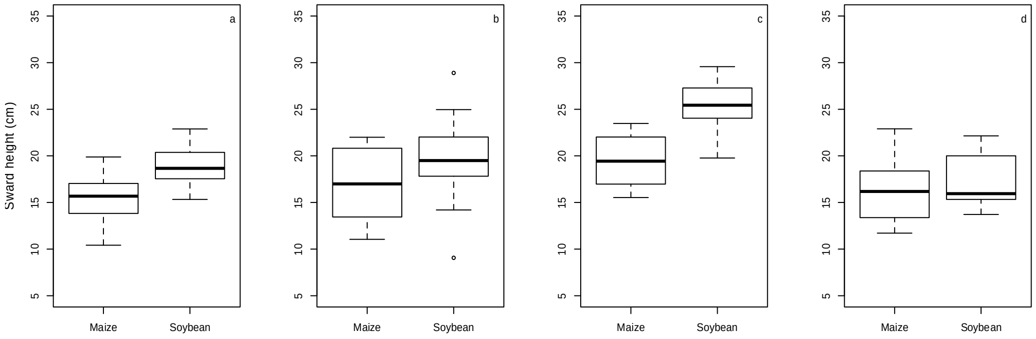

Fig. 7. Sward height of Italian ryegrass at the beginning of grazing phase succeeding soybean or maize, and at the end grazing phase preceding soybean or maize in 2010 and 2012. Treatments represent previous crop (maize and soybean): a) 2010 beginning grazing phase; b) 2010 end grazing phase; c) 2012 beginning grazing phase; d) 2012 end grazing phase.

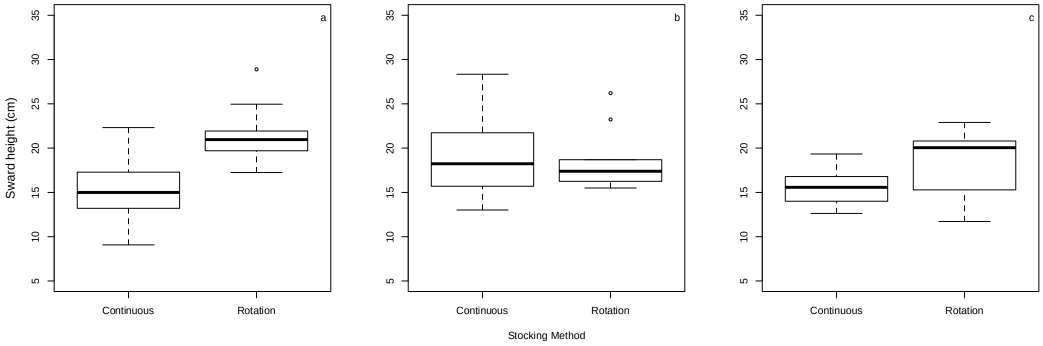

Fig. 8. Sward height of Italian ryegrass at the beginning of grazing phase succeeding soybean or maize and at the end grazing phase preceding soybean or maize in 2010 and 2012. Treatments represent stocking method (continuous and rotational): a) 2010; b) 2011; c) 2012.

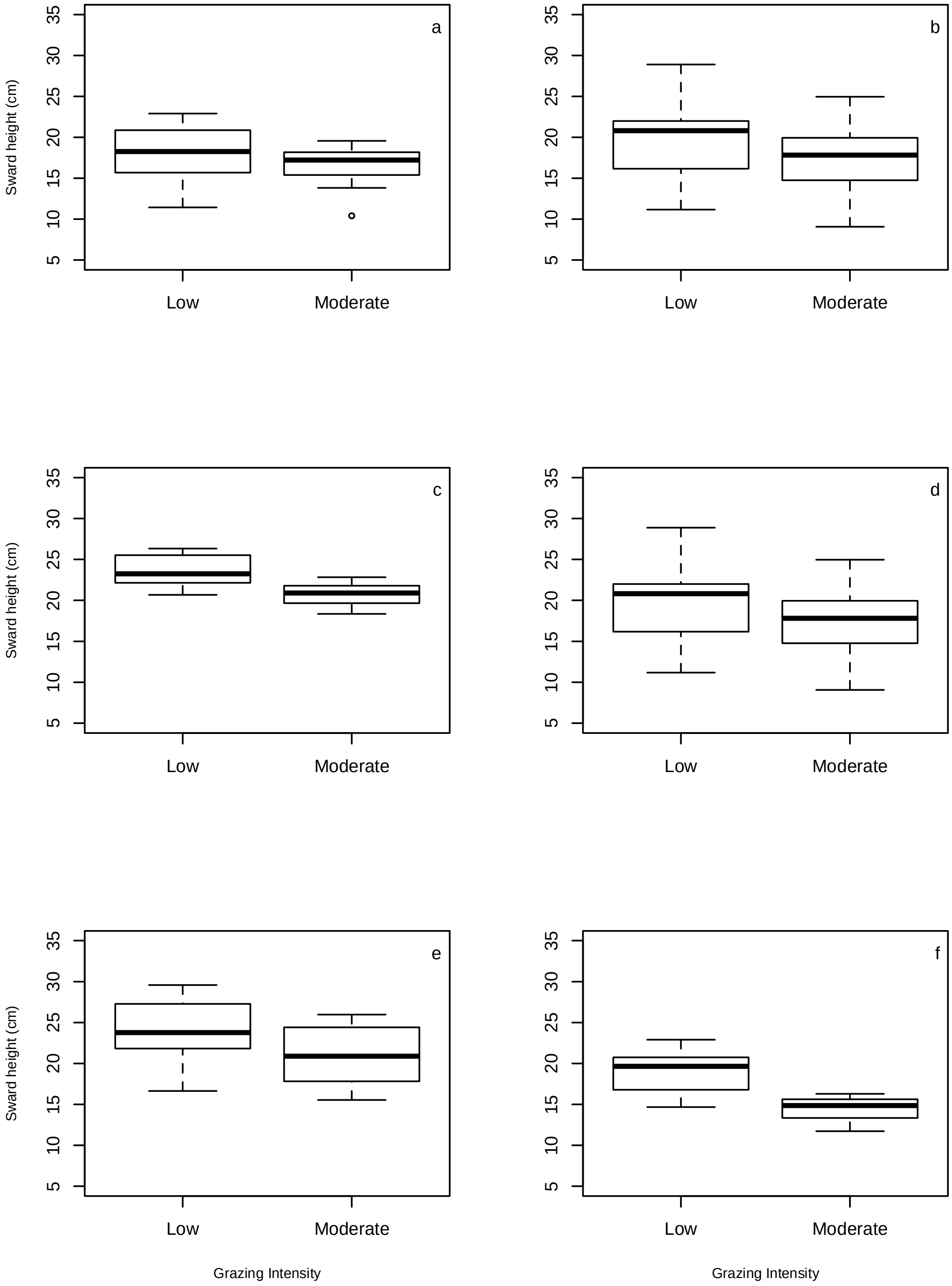

Fig. 9. Sward height of Italian ryegrass at the beginning of grazing phase following soybean or maize, and at the end of the grazing phase preceding soybean or maize, in 2010 and 2012. Treatments represent grazing intensity (low and moderate): a) 2010 beginning grazing phase; b) 2010 end grazing phase; c) 2011 beginning grazing; d) 2011 end grazing phase; e) 2012 beginning grazing; f) 2012 end grazing phase.

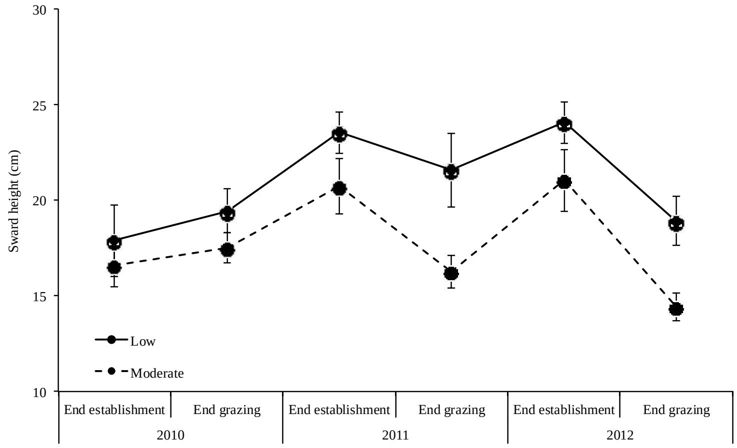

Fig. 10. Effect of grazing intensity in sward height of Italian ryegrass at the beginning of phase, and at the end of grazing phase, in 2010, 2011 and 2012. Treatments represent grazing intensity (low and moderate).

Table 1. Synthesis of the analysis of variance of herbage mass in 2010, 2011, 2012 and 2010 – 2012, at the beginning of grazing phase and at the end of grazing phase. Treatments represents stocking method (continuous and rotational), grazing intensity (low and moderate), previous crop (maize and soybean) and ante previous crop (maize and soybean).

	Beginning grazing phase								End grazing phase							
	2010		2011		2012		2010 - 2012		2010		2011		2012		2010 - 2012	
	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2
Intercept	<.0001***	0.94	<.0001***	0.25	<.0001***	0.8	<.0001***	0.49	<.0001***	0.72	<.0001***	0.37	<.0001***	0.6	<.0001***	0.36
Stocking method	0.1963		0.5001		0.907		0.5018		0.1497		0.078.		0.4996		0.7572	
Grazing intensity	0.115		0.6891		0.5766		0.0814.		0.0025**		0.0068**		0.0369*		<.0001***	
Previous crop	0.0001***				0.0001***		<.0001***		0.0004***				0.6597		<.0001***	
Anti previous crop			0.7693								0.7321					

p-value, probability ($p<0.05$); R^2 coefficient of determination

Table 2. Synthesis of the analysis of variance of sward height in 2010, 2011 2012 and 2010 – 2012 at the beginning of grazing phase and at the end of grazing phase. Treatments represents stocking method (continuous and rotational), grazing intensity (low and moderate), previous crop (maize and soybean) and ante previous crop (maize and soybean).

	Beginning of grazing phase								End grazing phase							
	2010		2011		2012		2010 - 2012		2010		2011		2012		2010 - 2012	
	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2	P-value	R^2
Intercept	<.0001***	0.56	<.0001***	0.43	<.0001***	0.7	<.0001***	0.54	<.0001***	0.66	<.0001***	0.87	<.0001***	0.89	<.0001***	0.55
Stocking method	0.2039		0.0836.		0.0719.		0.715		0.0002***		0.9594		0.0029**		<0.0001***	
Grazing intensity	0.1788		0.0288*		0.0061**		0.0011**		0.1845		0.0057**		0.0001***		<0.0001***	
Previous crop	<.0001***				<.0001***		<0.0001***		0.0376*				0.0156*		0.0284*	
Anti previous crop			0.7693								0.7321					

p-value, probability ($p<0.05$); R^2 coefficient of determination

4. CHAPTER 4 - Modelling the long-term effects of cropping systems on population dynamics of Italian ryegrass on integrated crop-livestock systems[3]

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[3] Prepared in accordance with the standards of the Ecological Modeling

Modelling the long-term effects of cropping systems on population dynamics of Italian ryegrass on integrated crop-livestock systems

Abstract

The aim of this study was to evaluate the effects of cropping systems on the resilience of an integrated crop-livestock systems (ICLS) based on winter grazing on Italian ryegrass established by self-seeding and two main summer crops (maize and soybean). We analysed and modelled the dynamics of Italian ryegrass in ICLS from an experimental dataset. The experiment protocol was a factorial design with four replicates arranged in randomized complete block design, with two stocking methods (continuous vs. rotational) and two grazing intensities (low vs. moderate) during the winter pastured by sheep. During the summer each paddock was divided into two, with similar size, with each part conducted with a different summer crop rotation (soybean monoculture vs. soybean-maize rotation) with no-till. The model was based on a life-cycle basis distinguishing seedling establishment, vegetative, reproductive and seed stages. We hypothesized that the previous crop would affect the establishment phase, while pasture management (stocking method and grazing intensity) would affect tiller and seed production. A stochastic year effect was introduced to account for inter-year variations on each process. After having checked the consistency of the final ryegrass dynamics model, a simulation study was carried out to determine the resilience of different cropping systems. The early vegetative tiller density (i.e. beginning of grazing phase) was positively related to the seedling density and the previous crop had a significant effect, with higher tiller density for treatments with soybean than maize. The late vegetative tiller density (i.e. before peak of flowering) was positively related to the early vegetative tiller density, to grazing intensity and to the stocking method, with positive effect for the treatments with low and continuous stocking. The reproductive tiller density was negatively related to the late vegetative tiller density and significant effect for grazing intensity, with higher spike density for low than moderate grazing intensity. On a long-term perspective, Italian ryegrass establishment by self-seeding was almost two times and a half less resilient under moderate grazing intensity than under low grazing intensity.

Key words: Population model, mixed system, self-seeding, grazing intensity, stocking method, crop rotations.

1. Introduction

Italian ryegrass (*Lolium multiflorum* Lam.) is a winter growing grass widely distributed throughout arable regions of the world. In arable crops, this species is considered as a weed because it significantly reduces in crop yield (Webster and Nichols, 2012), but this species is also used as a short duration grass for forage/livestock systems (Hannaway et al., 1999). In subtropical South American regions, Italian ryegrass is widely used as winter pasture in rotation with soybean (*Glycine max* L. Merril) and maize (*Zea mays* L.) summer crops in integrated crop-livestock systems (ICLS) with no-till (Carvalho et al., 2010). Italian ryegrass is well adapted to ICLS since it has the capacity to establish year after year by self-seeding and produces a high quality forage. This system has the potential to save costs with seeds and planting (Bartholomew and Williams, 2009) and to increase the cattle stocking period by advancing the animals entry thanks to an early pasture establishment starting in the preceding crop than pasture with annual re-sowing (Evers and Nelson, 2000).

The satisfactory establishment of Italian ryegrass requires a minimum of 500 seedlings·m^{-2} established per year (Evers and Nelson, 2000). To ensure this amount of seedlings, the soil seed bank requests to be replenished with new seeds every year. Indeed, the Italian ryegrass soil seed bank in ICLS with no-till is not able to re-establish more than over a year (Barth Neto et al., 2014) because this species does not form any dormant seed bank. Therefore, any practice (e.g. grazing intensity, summer crop management) that would reduce the ability of ryegrass to produce seeds and to replenish the seed bank may threaten the resilience of systems based on Italian ryegrass self-seeding. Modelling the effect of different stocking rate in dual-propose wheat in mixed-system, Moore (2009) showed that reduction of crop yield caused by grazing was proportional to increase in grazing intensity. For instance, the summer crop can hamper the establishment before harvest, by exerting competition for light and water, and after harvest due to residues laying on the soil. Depending on their quantity (i.e. restriction in light interception) and on their quality (i.e. allopathic, nitrogen immobilization or mineralization) when they are on the soil (Chauhan et al., 2012), crop residues decrease early seedling emergence and final seedling density (Mohler and Teasdale, 1993). Later on, the intensity of grazing affects the production of tillers, and especially reproductive tillers, which in turn might affect ryegrass seed production. Not only agriculture practices but also climate would affect the resilience of ICLS. Erratic and insufficient rainfall during the pasture phase have been shown to decrease ryegrass seed production and afterwards seedlings density during the following pasture growing season (Evers and Nelson, 2000).

From a management point of view, farmers are faced with a trade-off between short term production (increasing with grazing intensity) and long-term sustainability where seed production and the self-seeding ability of the pasture decrease with grazing intensity (Ates et al., 2006). Until now there have been only a few studies about the management strategies effects on resilience of Italian ryegrass in ICLS in literature (Maia et al., 2007; Barbosa et al., 2009; Barth Neto et al., 2014), but they did not encompass a long term perspective. A probable reason is that quantifying the effects of management practices in the long-term requires difficult and costly experiments. Therefore, population dynamics modelling appear as a suitable approach for this purpose. Population modelling of Italian ryegrass as a weed is frequent in literature (Benjamin et al., 2010; Parsons et al., 2009), but there is a lack of knowledge concerning the resilience of the pasture on ICLS, depending of the cropping system and on climate variations.

The aim of this study was to evaluate the effects of cropping systems on the resilience of integrated crop-livestock systems based with on Italian ryegrass between two main crops. For that, we analysed and modelled the dynamics of Italian ryegrass in ICLS from an experimental dataset. The model was based on a life-cycle basis distinguishing seedling establishment, vegetative, reproductive and seed stages. We hypothesized that the previous crop would affect the establishment phase, while pasture management (stocking method and grazing intensity) would affect tiller and seed production (Fig. 1). A stochastic year effect was introduced to account for climate effects on each process. After having checked the consistency of the final ryegrass dynamics model, a simulation study was carried out to determine the resilience of different cropping systems.

2. Material and methods

2.1 Experimental site

The model development was based on a four-year dataset (2010 to 2013) from a long-term experiment with ICLS, which started in 2003 in Brazil. The experiment was conducted at the experimental station of the Federal University of Rio Grande do Sul (30°05’ S; 51°39’ W), in a subtropical humid region (Cfa classification) according Köppen and Geiger (1928). It is characterised by a marked seasonality of temperature and evenly spread precipitations along the year, with an average temperature of 19.1 C degrees and annual precipitation average of 1438 mm (data from the meteorological station located 800 m from the experimental site). The soil at the experimental site was classified as a Typic Paleudult (USDA, 1999) with 15% clay and 1.99% of organic matter.

2.2 Experimental design

The experiment protocol is a factorial design with four replicates arranged in randomized complete block design, with two stocking methods (continuous vs. rotational) and two grazing intensities (low vs. moderate) during the winter, which resulted in 16 paddocks, in a total experimental area of 4.8 ha. During the summer each paddock was divided into two, with similar size, with each part conducted with a different summer crop rotation (soybean monoculture vs. soybean-maize rotation) with no-till, which resulted in a total of 32 experimental units. More details on the experiment can be found in Barth Neto et al. (2014).

2.3 Field measurements

Tiller density was measured using three metallic frames with 10×10 cm, and all tillers inside the metallic frame were counted. Here, tiller density was measured distinguishing four stages: i) seedling (i.e. just before crop harvest), ii) early vegetative tiller (i.e. just before the beginning of stocking season), iii) late vegetative tiller (i.e. before peak of flowering in mid-September) and iv) reproductive tiller (at the end of stocking season). Not all variables were measured each year. Seedlings were counted just before the summer crop harvest (01/06/2010 and 07/05/2012 when the previous crop was soybean, 15/06/2010 and 08/05/2012 when the previous crop was maize). Early vegetative tiller density was counted just before the entry of the animals in the system (27/07/2010, 15/06/2011, 13/07/2012, 15/07/2013). Late vegetative tiller density was counted before the peak of seed head emission (22/09/2010, 21/09/2011, 20/09/2012 and 18/09/2013). Reproductive tiller density was measured just before the end of stocking season (15/10/2010, 16/10/2011, 20/10/2012 and 15/10/2013).

2.4 Data analysis for model parameterization

Model parameters were estimated from our field measurements, except the seed production per tiller and the seed bank regeneration (seed survival and ability to produce seedlings) that were taken from Bartholomew and Williams (2009).

To build the model, the objective was to relate each stage of the life cycle to the previous one (Fig. 1), while accounting for the effects of management practices (summer crop rotation, grazing intensity and stocking method). To take into account climatic variability across years, a random year effect was introduced in the model. Each dependent variable X (early vegetative tillers density, late vegetative tillers density and reproductive tiller density) was related to the previous live cycle stage (PS_i, seedlings, early vegetative tillers density, late vegetative tillers density respectively), the stocking method (SM_j), the grazing intensity (GI_k), previous summer crop (SC_l) as fixed effects and year (Y_m) as a random effect, for each model stage:

$X_{ijklm}=PS_i+SM_j+GI_k+SC_l+Y_m+\varepsilon_{ijklm}$

where ε_{ijklm} is the error.

For the "reproductive tiller density" dependent variable we applied a square-root transformation to normalize and homogenize the residuals. For the parameter seed survival and on ability to produce seedlings we used the data from Bartholomew and Williams (2009), where the authors tested the effect of grazing termination date in the Italian ryegrass establishment by self-seeding. We used the data corresponding the best to our low and moderate grazing treatments (H1 and H2 treatments respectively). According to this study, the parameter "seed number per reproductive tiller" was 3.50 and 2.66 (i.e. that correspond mean of the relationship between viable seeds add on soil and seedling density in autumn) viable seeds per reproductive tiller under low and moderate grazing intensities respectively. Similarly, the proportion of seeds in the seedbank producing seedlings in the next growing season was 0.38 and 0.42 under low and moderate grazing intensity. The lower seedling emergence under moderate (compared with low) grazing intensity might result from a reduced seed vigour (e.g. lower seed weight) because of a shorter reproductive phase.

We used the nlme package for these analyses (Pinheiro et al., 2010) in R software for statistical computing version 2.12.0 (R Development CoreTeam, 2010). We selected the structure of these models according the Akaike's Information Criterion (AIC) and likelihood ratio test (Restricted Maximum Likelihood for random effect and Maximum Likelihood for fixed effect).

2.5 Evaluation of the model consistency

The Italian ryegrass model was built from the regression equations determined for each model step. In addition we tested the internal consistency between simulated and observed field data used to build the model. The simulation began with 500 seedlings m^{-2}, amount of seedlings recognized to enabler a correct establishment the Italian ryegrass pasture (Evers and Nelson, 2000) and sown with soybean as previous crop found in both monoculture and crop rotation systems. The year effect was introduced as a stochastic effect following a normal distribution, where the mean and variance were those from analyses in section 2.4. The model was then run thirty years simulating for each of the four cropping systems (two grazing intensities × two stocking methods) tested in our experiment. We used several indicators to compared simulations with observations. The Root Mean Square Error of prediction (RMSEp), the bias (Wallach, 2006), the modelling efficiency, names afterwards R², and the Spearman rank correlation (van de Wiel and Di Bucchianico, 2001) were computed between observed data and simulated ones in each cropping system. Were evaluated the model consistence for the following model life cycle stages: seedling, early vegetative tiller, late vegetative tillers and reproductive tillers. For simulations and analyses of quality predictions we used the R software version 2.12.0 (R Development CoreTeam, 2010) and hidroGof package to calculate the Root Mean Square Deviation (Bigiarini, 2014), spearman package to calculate the Spearman’s rank correlation (Savicky, 2014).

2.6 Analysis of long-term resilience of the systems relying of rye grass self-seeding

We tested the long-term resilience of ICLS by Italian ryegrass self-seeding in the different treatments using the Monte Carlos’s Method (Rubinstein and Kroese, 2008) in R software version 2.12.0 (R Development CoreTeam, 2010). The model of Italian ryegrass was run a thousand times of thirty years simulations. Only the stochastic year effect varied across these simulations. We programmed the model to put the amount of seeds that ensured 500 seedling m^{-2} (minimal seedling density to well establish the Italian ryegrass, Evers and Nelson, 2000). The initial seed number did not affect the simulation after 30 years (preliminary analyses not presented). When initialising with several densities, the model always quickly stabilized at similar densities of seedlings and tillers. For each year when pasture establishment by self-seeding did not guaranty a minimum of 500 seedlings m^{-2}, we simulated a new seeding intervention. At the end of each 30-years simulation we summed the number of times where reseeding by farmers was necessary and we averaged it over the 1000 simulations. Our criterion was that the resilience of a cropping system decreased when the number of reseeding events increased

3. Results

3.1 Effects of management practices on Italian ryegrass dynamics

All the variables related to ryegrass stages could be related to the immediate previous stages and responded to management practices (Table 1 and Fig. 2). First, the early vegetative tiller density was positively related to the seedling density (P<0.0001) and the previous crop had a significant effect (P<0.0035). Tillering was increased in the treatments with soybean as a previous crop, resulting in an average 8326 ± 2080 vegetative tillers m^{-2} while the treatments with maize as previous crop had in average 6637 ± 2116 vegetative tillers m^{-2}. Second, the late vegetative tiller density was positively related to the early vegetative tiller density, to grazing intensity and to the stocking method (P<0.0001, P=0.0004 and P=0.0274, respectively). Late vegetative tiller density was higher under moderate grazing intensity (4129.0 ± 1980 vegetative tillers m^{-2}) than low grazing intensity (3671 ± 1669 vegetative tillers m^{-2}). Late vegetative tiller density was also higher in case of continuous stocking method than in rotational stocking method. Third, the reproductive tiller density was negatively related to the late vegetative tiller density. We found an interaction between late vegetative tiller density and grazing intensity (*P*=0.0001). Low grazing intensity had higher reproductive tiller density (1718 ± 940 reproductive tiller m^{-2}) than moderate grazing intensity (1288 ± 1230 reproductive tiller m^{-2}).

3.2 Evaluation of the model consistency

The simulations of the densities of late vegetative tillers and of reproductive tillers (Table 2 and Fig. 3) correctly matched the observed values with acceptable R^2 (higher than 0.75) and with correct ranking (Spearman correlation coefficients higher than 0.91) of the systems according to their tiller densities. Conversely, the prediction quality was the lowest for the densities of seedling and early vegetative tillers. The mean error of prediction (RMSE) was around 4500 tillers m^{-2} and around 2900 tillers m^{-2} for the first two stages, and around than 1200 tillers m^{-2} and 346 tillers m^{-2} for the last two ones. There was a tendency to an underestimation of seedling densities of 2961 plants m^{-2}, and to an overestimation of reproductive tiller of 184 plants m^{-2}.

3.3 Resilience of the Italian ryegrass established by self-seeding

Considering the Monte Carlo procedure, model steps generally follow the effects founded in statics analyses (Fig. 4), with a grazing management effect on plant densities (grazing intensity and stocking method). The effect of the summer crop rotation was not clearly observed. The year effect was responsible of strong inter-annual variations in plant densities and responsible for most of the variation source in the simulations.

To compare resilience between cropping systems, we used as an indicator the number of pasture new seeding interventions in the 30-years simulations. Therefore, the treatments that required being new seeded fewer times we considered as more resilient than the treatments with more new seeding events. The treatments had different responses about the resilience in ICLS (Table 3). The mean number of reseedings within the 30 years of simulations varies from 2.8 to 7.8 depending on the cropping systems. The different stocking method and previous crop did not affect the resilience of the cropping system. The grazing intensity was the treatment that most affected the pasture resilience. An increase in the grazing intensity decreased the resilience of Italian ryegrass in ICLS. Moderate grazing intensity had new seeded almost two and a half times more than low grazing intensity, with 7.6 and 3.2 respectively.

4. Discussion

4.1 Originality and structure of the model

Despite the importance of Italian ryegrass in grazed systems, the majority of modelling studies considering this species are about weed control (Benjamin et al., 2010; Parsons et al., 2009). In the other hand, the dynamics of pasture species able to establish by self-seeding in arable lands is rarely described in literature. More recently, studies on integrated crop-livestock systems (Moore, 2009; Mcgrath et al., 2014) have gained prominence in international research and studies with modelling in mixed systems increased, mainly with dual-propose wheat (i.e. grain and grazing) but these increases are still modest. This paper is therefore the first attempt, to our knowledge, to model the cropping systems effects on the dynamics of Italian ryegrass in ICLS.

The model was built with a four-year dataset, which confers an important robustness to the equations derived from the data. The summer crop rotation, and more specifically the preceding crop, affected the vegetative tiller density before the stocking season, with higher tiller density after soybean than after maize. All remaining model stages were affected by grazing management (i.e., the grazing intensity on reproductive tiller density). Grazing intensity reduced tiller density, which resulted in a lower seedling density (Smetham and

Dear, 2003; Ates et al., 2006), and this thus susceptible to affect the pasture re-establishment and the resilience of the system. In addition to the grazing management, the variability between years, probably due to weather variations, was responsible of drastic variations in the Italian ryegrass population density, and this factor has been shown to be the most important one for pasture growth and stocking rate (Fang et al., 2014).

4.2 Quality of model simulations

For each life-cycle stage, we evaluated the internal consistency of the model by comparing the simulations with measured data in the field, for each cropping system. In general, the prediction quality was the lowest for the first two stages (i.e. seedling and vegetative tiller), and the quality of simulation increased in two last stages (i.e. late vegetative tillers and reproductive tillers; see Table 2 and Fig. 3). The presence of one or more parameter without a good prediction quality has been frequently found in models with grazing animals based on field data (Wiegand et al., 1989; Köchy et al., 2008; Paruelo et al., 2008), where the sward structure and the environment conditions are not controlled. However we identified two main sources of errors that could explain the low prediction quality of ryegrass early stages. First, the parameter of seed survival and on ability to produce seedlings from Bartholomew and Williams (2009) may have been underestimated because of particular climate conditions in these previously published data (low rainfall in two of the three years which decreased seedling emergence). As advanced in simulations to two last stages, data simulated had more effect from the parameter measured and were adjusted better than the two first steps. Secondly, differently from modelling of plants in free growth (Gonzalez-Andujar and Fernandez-Quintanilla, 2004; Mokhtassi-Bidgoli et al., 2013) that the model is build in general with just two stages of plant growth (i.e. seedling, adults). In our case, models with grazed plats, the herbivores affected strongly the plant population dynamics (Matthew et al.,

2000) and the dynamic of flowering (Dumont et al., 2012), thus was impossible to found a relationship between seedling and adult. The relationship between both stages was possible when we added in the model two intermediary stages (i.e. early vegetative tiller and late vegetative tiller). However to input the to intermediated stages increased data variability and error in the model that could increase the imprecision in model simulated data.

Clearly is important to have quality in all model parameters, mainly in a parameter between crop-pasture transition phases. But in our case the parameters that determines the success in predictions where reproductive tillers, the input and output parameters during the pasture growth, and its had accuracy greater than 95%. This evidence showed that data of seed survival and ability of seed to produce seedling from the same experimental region with closer grazing managements could increase quality of data simulations.

We are aware that to evaluate the quality of model simulations is there absolutely necessary to compare simulations with independent data. Actually, we could not evaluate the model here with independent data due our model was constructed based in a very particular experimental design and there is no precedents in literature. We have the pretention to realize this evaluation in the future with the data that will be collected in the following years.

4.3 Resilience of Italian ryegrass in ICLS

The use of the model was a very relevant tool to compare cropping systems based on their resilience, a very important feature that cannot be experimentally measured. The long-term simulation outputs showed that there is no cropping system without any new seeding over 30 simulated years. Furthermore, pastures with moderate grazing intensity had to be reseeded more that seven times over 30 years, i.e. almost two and a half times more than the ones managed with low grazing intensity (Table 3). The results of resilience is analysed with the viewpoint to ensure the plant growth, that could be establish by self-seeding every year. Is there not a possibility to compare you results with literature concerning pasture resilience (even in other contest).

4.4 Economic evaluation

When we analysed the live weight gain per hectare according to different grazing managements in this experimental site (Barbosa et al., 2007; Macari et al., 2011; Savian et al., 2014) treatments with moderate grazing intensity had 590 kg and low grazing intensity had 413 kg of labs ha^{-1}. In this context of resilience and livestock production farmers have the following scenarios: (1) to manage the pasture with low grazing intensity and to produce less meet per hectare, but to ensure a cropping system more resilient or (2) to manage the pasture with a moderate grazing intensity to produce more meet per hectare but resulting is a less resilient cropping system. In this context we proposed to identify the most economical advantageous option in a long-term ICLS, combining livestock gain per hectare and resilience of the cropping system. In Southern Brazil region costs with seed is in average US$ 38 ha^{-1}, assuming a rate of 20 kg of seeds ha^{-1}, the costs of sowing is estimated in US$ 20 ha^{-1}, and 0.43 of seeding failure (Bartholomew and Williams, 2009). Considering that moderate and low grazing intensity needs to be need seed 7.62 and 3.22 times in thirty years respectively. Treatments with moderate grazing intensity had annual costs with new seeding estimated in US$ 88.41 ha^{-1} against US$ 37.41 ha^{-1} in low grazing intensity. Analysing the lamb meat production, assuming 0.44 of carcass yield (Carvalho et al., 2007) and the price of carcass sell around US$ 4.50 per kg. The annual coasts to buy lambs are around US$ 2,128.46 and US$ 1,307.12 for moderate and low grazing intensity, respectively. Treatments with moderate grazing intensity had US$ 2,970.70 ha^{-1} and low grazing intensity with US$ 1,922.92 of gross income with lamb production. Discounting the both costs of annual new seeding and to buy lambs from the rent of meat production, the moderate grazing intensity saved US$ 753.84 ha^{-1}

and low grazing intensity saved US$ 578.40 ha^{-1} in average of thirty years of a thousand simulations. With a relatively simple economic analyses comparing costs with new seeding and the rent with lambs meet production, even the treatment with moderate grazing had less resilient than low grazing intensity, but the increase in meat production seems to be more economically advantageous.

However, not just economic results need to be taking into account to decide which grazing intensity is the most sustainable. In literature are not rare found problems with soil degradation (i.e. decrease of soil organic matter) (O'Mara, 2012) and increase of methane emission by the ruminants per hectare (Savian et al., 2014) with higher grazing intensity. Moreover managed the pasture with greater animal feed restriction, the animals cannot reach the desirable carcass weight and carcass fat thickness for slaughter at the end of grazing season (Lopes et al., 2008). Thus to decide what grazing intensity needs to be adopted it is necessary the farmers to take in account the positive and the negative points of this decision analysing the system as a whole.

5. Conclusion

Is possible to modelling the Italian ryegrass live cycle established by self-seeding in ICLS. The resilience of Italian ryegrass establishment by self-seeding with a long-term perspective, the choice to manage the pasture with moderate grazing intensity was almost two times and a half times less resilient than low grazing intensity. Even of that to manage the pasture with moderate grazing intensity allow an increase of stock weight gain per hectare over grazing season.

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Tables and figures

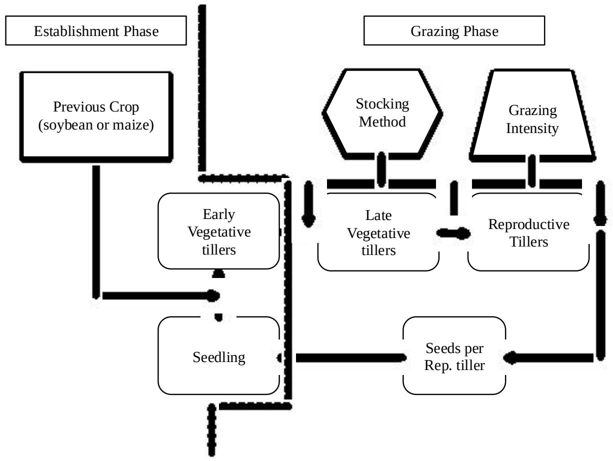

Fig. 1. Life cycle diagram used to modelling Italian ryegrass in integrated crop-livestock system.

Table 1. Results of multiple regressions between each model step with the effects of previous crop (maize and soybean), grazing intensity (low and moderate) and stocking method (continuous and rotational).

		Early vegetative tiller	Late vegetative tiller	Reproductive tiller
Grazing intensity				
	Low	ns	1610.1**	3156.2***
	Moderate	ns	738.5**	-183.7***
Previous crop				
	Maize	4017.6**	ns	ns
	Soybean	1270.3**	ns	ns
Stocking Method				
	Continuous	ns	1164.5*	ns
	Rotational	ns	-445.5*	ns
Previous model stage				
	Seedling	0.483***	nt	nt
	Early vegetative tiller	nt	0.292***	nt
	Late vegetative tiller	nt	nt	$-1.95\ 10^{-5}$†
	Late vegetative tiller × low grazing intensity	nt	nt	$-1.95\ 10^{-5}$**
	Late vegetative tiller × moderate grazing intensity	nt	nt	$-3.3\ 10^{-5}$**
Year	(standard-error of the random effect)	0± 1202.7	0± 1301.0	0± 227.2
R²		0.50	0.65	0.77

Notes: ns, not significant; †0,05 < P < 0.1*P < 0.05; **P < 0.01; ***P < 0.001. nt: not tested.

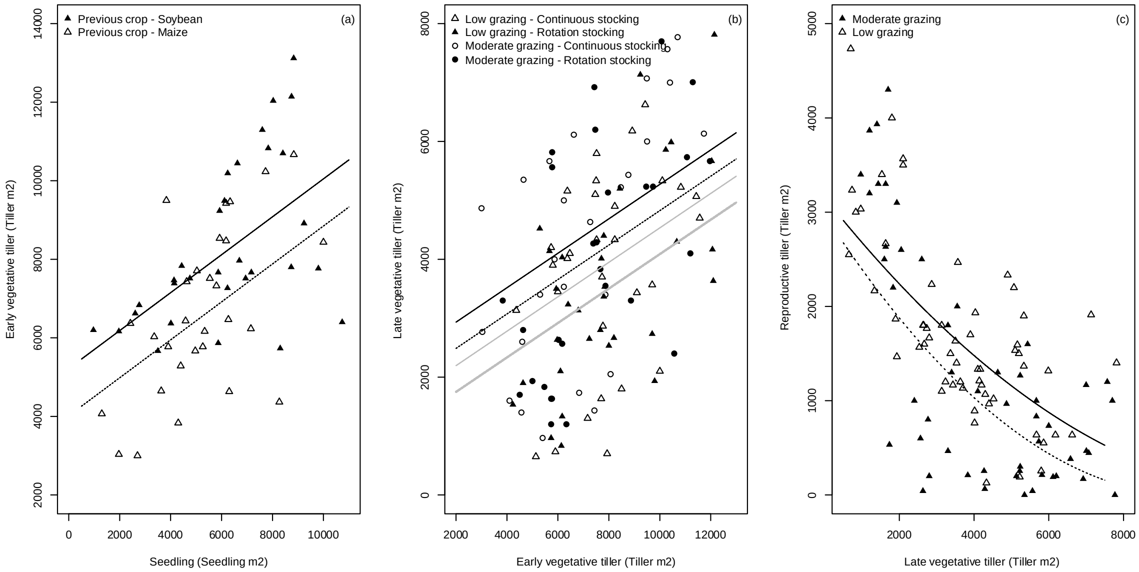

Fig. 2. Relationships between successive Italian ryegrass stages to predict (a) early vegetative tiller density, (b) late vegetative tiller density and (c) reproductive tiller density. Regression lines are the results of linear mixed models.

Table 2. Tests of internal consistence of the model of Italian ryegrass established by self-seeding in ICLS

Model stages	Bias	RMSE*	Spearman	Spearman p-value	R^2
Seedling^1	-2960.6	4589.1	0.57	0.15	0.51
Early Vegetative Tiller^1	-2278.9	2901.8	0.76	0.0049	0.053
Late Vegetative Tiller^2	-752.6	1079.2	0.91	<0.0001	0.78
Reproductive Tiller^2	-184.4	346.1	0.97	<0.0001	0.91

^{1}data from 2010 and 2012; ^{2}data from 2010 – 2013
*Root mean square error

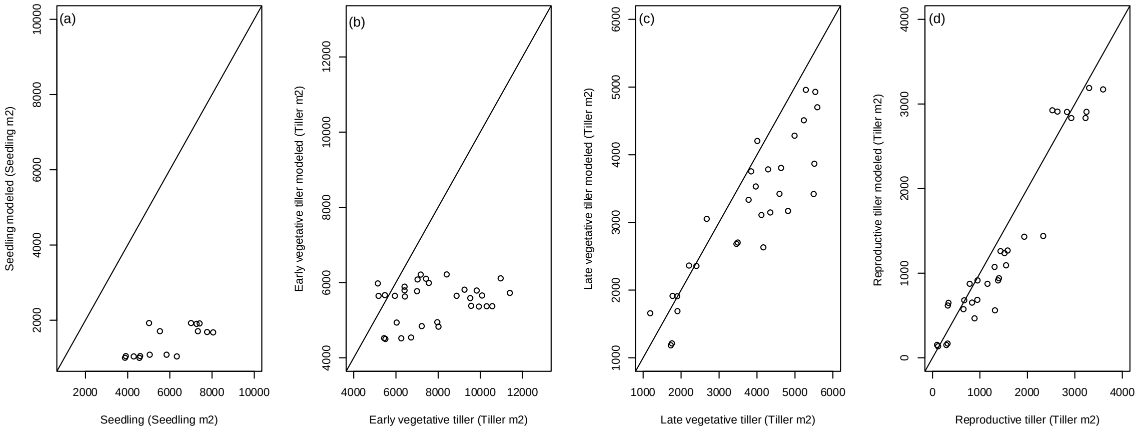

Fig. 3. Evaluation of the internal consistency of the model of Italian ryegrass in integrated crop-livestock system. Comparison between observations and simulations (with year random effect). (a) Seedling density; (b) Early vegetative tiller density; (c) Late vegetative tiller density; (d) Reproductive tiller density.

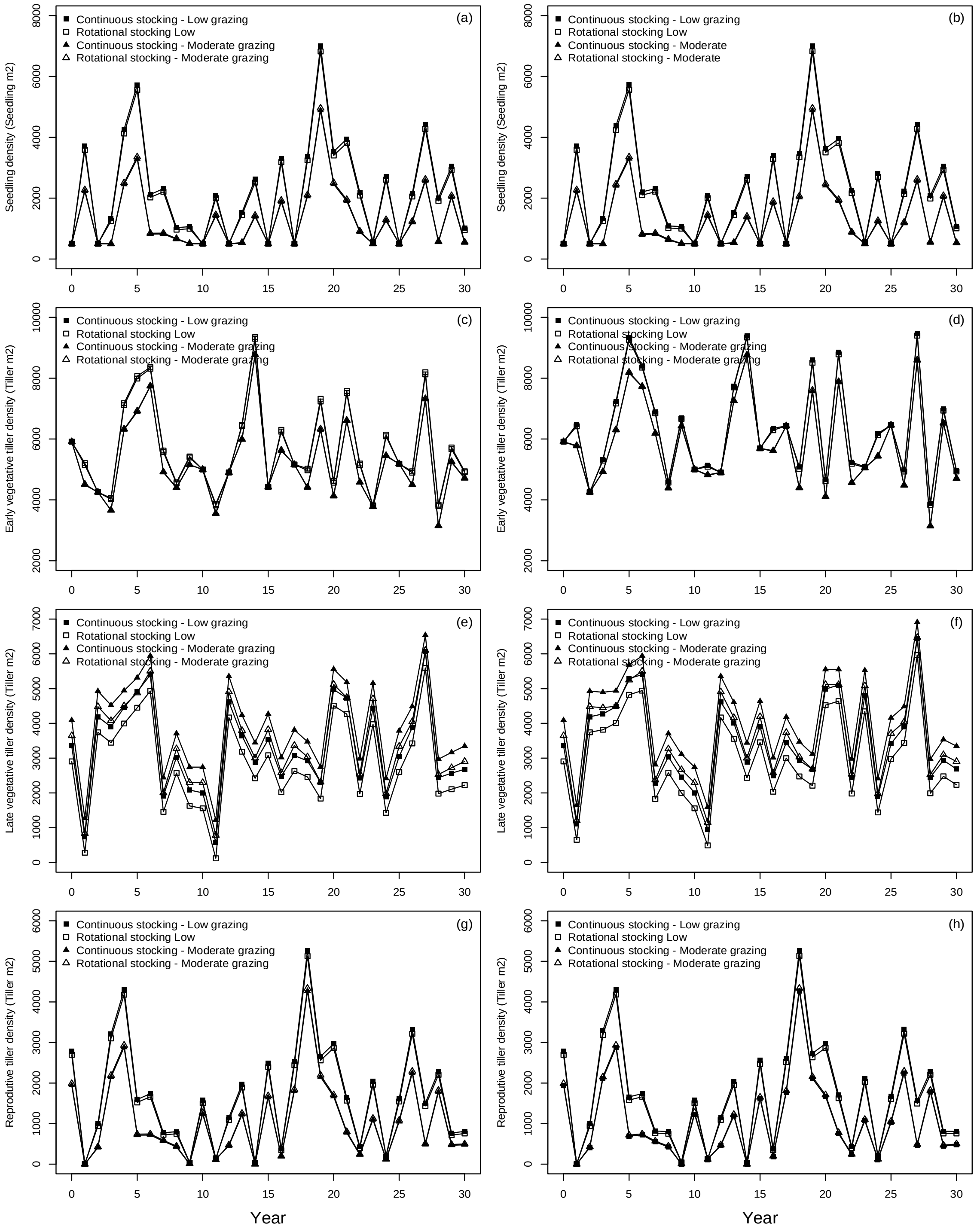

Fig. 4. Modelling Italian ryegrass establishment in integrated crop-livestock systems. Data from equation of regression analysed with year as random effect. (a) Seedling density with soybean-maize crop rotation; (b) Seedling density with soybean monoculture; (c) Early vegetative tiller density with soybean-maize crop rotation; (d) Early vegetative tiller density with soybean monoculture; (e) Late vegetative tiller density with soybean-maize crop rotation; (f) Late vegetative tiller density with soybean monoculture; (g) Reproductive tiller

density with soybean-maize crop rotation; (h) Reproductive tiller density with soybean monoculture.

Table 3. Simulation of long-term estimative of new seeding in Italian ryegrass established by self-seeding according grazing intensity, stocking method and summer crop rotation.

Grazing intensity	Stocking Method	Crop rotation	Number of reseedings during 30 years *
Low	Continuous	Monoculture	2.85 ± 1.6
		Rotation	3.07 ± 1.8
	Rotational	Monoculture	3.36 ±1.8
		Rotation	3.63 ±1.8
Moderate	Continuous	Monoculture	7.79 ± 2.4
		Rotation	7.69 ± 2.4
	Rotational	Monoculture	7.55 ± 2.4
		Rotation	7.48 ± 2.4

*Mean and the standard deviation of a thousand simulations (means of values saved from 30 years of simulations).

5. FINAL CONCLUSIONS

The international scientific community in recent years has recognized the integrated crop-livestock systems (ICLS) as the way forward ecological intensification. ICLS can promote food production with quantity and quality, while conserving the environment. These are attributes considered pivotal for agricultural systems facing the global future food demand, which must conciliate production and sustainability. The results presented in this thesis agree in this direction, even working in a much more narrow context. ICLS using Italian ryegrass established by self-seeding in winter and maize-soybean crop rotation in summer are capable to bring a higher level of diversification to intensive cash-crop rotations. Grain and livestock can be produced on the same land with no major conflicts. On the contrary, pasture and crops such as those used in this long-term experiment can be managed with certain harmony, planning synergistic effects between crops and pasture rotations. Therefore, we consider this kind of ICLS as an important alternative to increase production and diversification in sub-tropical regions in Brazil and around the world.

Moreover, as illustrated by many studies before, it is important to keep in mind that grazing management (grazing intensity in particular) is the key point determining ICLS success or failure. In order to promote the majority of benefits expected in ICLS grazing intensity would be lower than normally observed.

Specifically for this subtropical system that uses Italian ryegrass, next steps would focus on studies clarifying details of causal effects of previous crop on pasture growth dynamics (e.g., crop residue decomposition, forage nitrogen nutrition index, forage canopy light interception,). Additionally, studies should focus on long-term impacts of grazing intensity at the whole system level (e.g., pasture residue decomposition, soil carbon stocks, soil seed bank dynamics) in order to understand process at higher levels of organization. Then, it would be possible to advance knowledge in order to better understand the impact of agricultural practices on Italian ryegrass, promote modelling precision and manage these systems so as to favour both pasture and crop phases.

In perspective, we need to advance in the knowledge of the food production limiting factors operating in current cropping systems. Moreover, crop research needs to incorporate a new approach to integrate ecological process that sustains natural ecosystems (i.e. forests savannas and rangelands) on commercial systems, mimicking natural processes and nutrient fluxes. ICLS seems a reliable way for this target. This approach would drive experimental proposals of how to better use trophic resources and, the most important, how to increase natural resources use efficiency. For that approach it is fundamental to analyze the system as a whole (i.e., holistic perspective), and not from a compartmentalized standpoint (i.e., crop phase disconnected from grazing phase). This approach demands dramatic changes in crop science current concepts, where simplification and standardization of management practices are prevalent rules. The consequential challenge is the complexity of more diverse mixed crop-livestock systems, where sources of variability are enormous and some causal effects are virtually impossible to study at systemic level. Therefore, investments in good experimental designs, high level statistics oriented to production system analysis, and principally long-term modeling are crucial to foster science in this research area. So that crop science would propose solutions to global food security that could assure the sustainability of future generations.

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