UNIVERSIDADE FEDERAL DO PARANÁ

LEONARDO SILVESTRI SZYMCZAK

PASTORAL MANAGEMENT STRATEGIES BASED ON ECOLOGICAL PROCESSES FOR SUSTAINABLE INTENSIFICATION

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PASTORAL MANAGEMENT STRATEGIES BASED ON ECOLOGICAL PROCESSES FOR SUSTAINABLE INTENSIFICATION

Tese apresentada ao curso de Pós-Graduação em Agronomia, Setor de Ciências Agrárias, Universidade Federal do Paraná, como requesito parcial à otentção do título de Doutor em Ciências.

Orientador: Prof. Dr. Anibal de Moraes
Coorientador: Prof. Dr. Paulo C. de Faccio Carvalho
Coorientador: Prof. Dr. Charles-Henri Moulin

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Curitiba, 09 de Agosto de 2018.

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RESUMO

A intensificação sustentável da produção atual e futura de alimentos demanda estratégias condizentes com os princípios e conceitos ecológicos na promoção da produção, eficiência e resiliência agrícola. Aliado a isso, a agricultura deve ser orientada à favorecer a redução das condições socioeconômicas indesejáveis, impactos econômicos e ambientais externos negativos promovidos pelas mudanças climáticas. A hipótese da tese está orientada em responder a quatro principais questões: I) Existe uma estrutura de dossel de *Schedonorus arundinaceus* que maximize a taxa de ingestão instantânea de ovinos?; II) Se a hipótese anterior for confirmada, existe um ponto convergente ótimo entre a taxa de ingestão instantânea de ovelhas e a taxa instantânea de acúmulo de forragem de *Schedonorus arundinaceus*?; III) Os sistemas integrados de produção agropecuária podem contribuir para a promoção da resiliência no contexto econômico e de fluxo de nutrientes?; IV) Se confirmado, a intensidade de pastejo é um fator importante para o aumento da resiliência? A tese está organizada em três capítulos no formato de artigos científicos. Cada capítulo inclui um estudo de diferentes processos ecológicos e/ou econômicos em diferentes escalas espaciais e temporais, conduzidos em experimentos separados. O objetivo foi identificar estratégias de manejo de pastagens baseadas no aumento da eficiência dos processos ecológicos da interface planta-animal e avaliar de que forma elas podem contribuir para a promoção da sustentabilidade em sistemas agrícolas por meio da resiliência global. No primeiro estudo foi possível entender a dinâmica do processo de ingestão de forragem no nível de bocado, na perspectiva da otimização da colheita de forragem pelos animais. Verificou-se que a altura do dossel de 22,30 cm de *S. arundinaceus* maximiza a taxa de ingestão instantânea de ovinos. No segundo estudo, verificou-se que nos períodos do outono e primavera há taxas elevadas de acúmulo de forragem, com a maximização da taxa de acúmulo instantâneo de forragem na altura do dossel entre 19 e 25 cm. No terceiro capítulo, foi observado que os sistemas agrícolas que adotam a diversificação com animais em pastejo são importantes promotores de resiliência agrícola sob o contexto econômico e de fluxo de nutrientes. As intensidades de pastejo não tiveram efeito no aumento da resiliência.

Palavras chave: Comportamento ingestivo de ruminantes, *Schedonorus arundinaceus,* Festuca, Manejo de pastagens, Sistemas integrados de produção agropecuária, Resiliência, Sustentabilidade.

ABSTRACT

Sustainable intensification of current and future food production demands strategies consistent with ecological principles and concepts in promoting agricultural production, efficiency and resilience. Allied to this, agriculture must be oriented to favor the reduction of undesirable socioeconomic conditions, negative external economic and environmental impacts promoted by climate change. The hypothesis of the thesis are oriented to answer four main questions: I) Is there a sward structure of *Schedonorus arundinaceus* that maximizes the short-term intake rate of sheep?; II) If the previous hypothesis is confirmed, is there an optimum convergent point between short-term intake rate and instantaneous herbage accumulation rate of *Schedonorus arundinaceus*?; III) Can integrated crop-livestock systems contribute to the promotion of resilience in the economic and nutrient flow context?; and IV) If confirmed, can grazing intensities contribute to increased resilience? The thesis is organized in three chapters in scientific articles format. Each chapter includes a study of different ecological and/or economic processes at different spatial and temporal scales, performed in separate experiments. The objective was to identify pasture management strategies based on increasing the efficiency of the ecological processes of the plant-animal interface and to evaluate if they can contribute to the promotion of sustainability in agricultural systems through global resilience. In the first study, the dynamics in the herbage intake process at the bite level were described, from the perspective of optimization of animal herbage harvest. The results demonstrated that the sward surface height of 22.30 cm of *S. arundinaceus* maximizes the short-term intake rate of sheep. In the second study, it was shown that there are high herbage accumulation rates in the autumn and spring periods, with the instantaneous herbage accumulation rate being maximized at sward surface heights between 19 and 25 cm. The third chapter describes how agricultural systems that adopt diversification with grazing animals are important promoters of agricultural resilience under the nutrient flow and economic context. The grazing intensity had no effect on increasing resilience in the crop-livestock systems described.

Key words: Ingestive behaviour of ruminants, *Schedonorus arundinaceus,* Tall Fescue; Pasture Management, Integrated crop-livestock system, Resilience, Sustainability.

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1. INTRODUCTION

According to FAO (2014) the current and future production safe food must be in accordance with the principles of sustainable agriculture in a manner that is environmentally, economically and socially responsible over time. This requires proper management of agricultural systems in food and other products production, in relation to the available ecological resources, while improving or maintaining ecosystem services measured in a specified area and over a given period of time (GUTON et al., 2016; STRUIK and KUYPER, 2017).

The integrated crop–livestock systems (ICLS) are an alternative aligned with the aspirations of sustainable agriculture (BONAUDO et al. 2014; LEMAIRE et al., 2014; FRANZLUEBBERS et al., 2014; GARRET et al., 2017). The ICLS are planned systems involving temporal and spatial interactions at different scales with animal and crop exploitation within the same area, simultaneously or disjointedly and in rotation or succession. ICLS aim to achieve synergism and emergent properties as a result of soil–plant–animal–atmosphere interactions (MORAES et al., 2014).

Thus, the design and management of ICLS should be concentrated in the application ecological concepts and principles (GLIESSMAN, 1998; TITTONELL, 2014; LEVAIN et al., 2015) to act on the functions of ecosystems (BONAUDO et al., 2014), thereby increasing efficiency (KEATING et al., 2010; ALTIERI et al., 2012), resilience (ALTIERI et al., 2015; BRISKE et al., 2017), and productivity (TILMAN et al., 1996; CARVALHO et al., 2013) into agriculture.

This can be achieved by practices that promote biodiversity (TSCHARNTKE et al., 2012; DURU et al., 2015; FAUCON et al., 2017), soil carbon and nitrogen stock, soil conservation, mitigation of greenhouse gas emissions (MARTINS et al., 2017; SÁ et al., 2017; STAHL et al., 2017; SAVIAN et al., 2018), water conservation (TANG et al., 2014; KUNRATH et al., 2015), landscape heterogeneity (SABATIER et al., 2013), integrated pest and disease management (BARZMAN et al., 2015), and stocking rate of livestock (BRISKE, 1993; VON WEHEDEN et al., 2012, MUTHONI et al., 2014; MEZZALIRA et al., 2017), etc.

Therefore, it is fundamental to understand the functioning of processes such as nutrient cycling, predator/prey interactions, competition, symbiosis, successional changes and social systems involved in agroecosystems, for the determination of management targets to promote sustainable ecologically-based intensification of agriculture (ALTIERI AND NICHOLLS, 2005; TOMICH et al., 2011).

This thesis is organized in three chapters in the form of scientific articles. Each chapter includes a study of different ecological and/or economic processes at different spatial and temporal scales, performed in separate experiments. The processes involved in each chapter are summarized in a single conceptual model proposed for the thesis.

The main objective of the conceptual model was to facilitate the understanding of the studied processes and identify the importance of each variable between chapters.

The first chapter consists of understanding of the interactions between the sward structure and the processes of herbage harvesting of sheep. In addition, the short-term intake rate of sheep was assessed for the formulation of pasture management targets were interpreted in this chapter.

The second chapter is composed of herbage mass accumulation modeling for the estimation of the instantaneous herbage accumulation rate as a function of the herbage mass. This study links the results of the first chapter, under the perspective of optimizing the efficiency of the process of herbage growth and the herbage intake by the animals.

The third chapter consists of the understanding of ecological and social processes involved in the interactions between soil, livestock, crop components and external environment, under the context of integrated systems. The objective of this study was to interpret the effect of different grazing intensities in the economic and flow of nitrogen and phosphorus dynamics, to promote resilience[1]. The grazing intensities in this study represent the level of interaction between the pasture and the animals studied in the first two chapters.

The first and second chapters are studies that evaluate plant, animal, and climate interactions in small spatial-temporal scales. In the third, the study evaluates the productive system within the context of large scales of space and time.

Hypotheses

- Is there a sward structure of *Schedonorus arundinaceus* that maximizes the short-term intake rate of sheep?

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[1] Resilience is understood in this thesis as the ability of a system to absorb an amount of disturbance, in nutrient flow and economic context and under time effect, without changing to a different state.

- If the previous hypothesis is confirmed, is there an optimal convergent point between short-term intake rate and instantaneous herbage accumulation rate of *Schedonorus arundinaceus*?
- Can integrated agricultural production systems contribute to the promotion of resilience in the economic and nutrient flow context?
- If confirmed, can grazing intensities contribute to increased resilience?

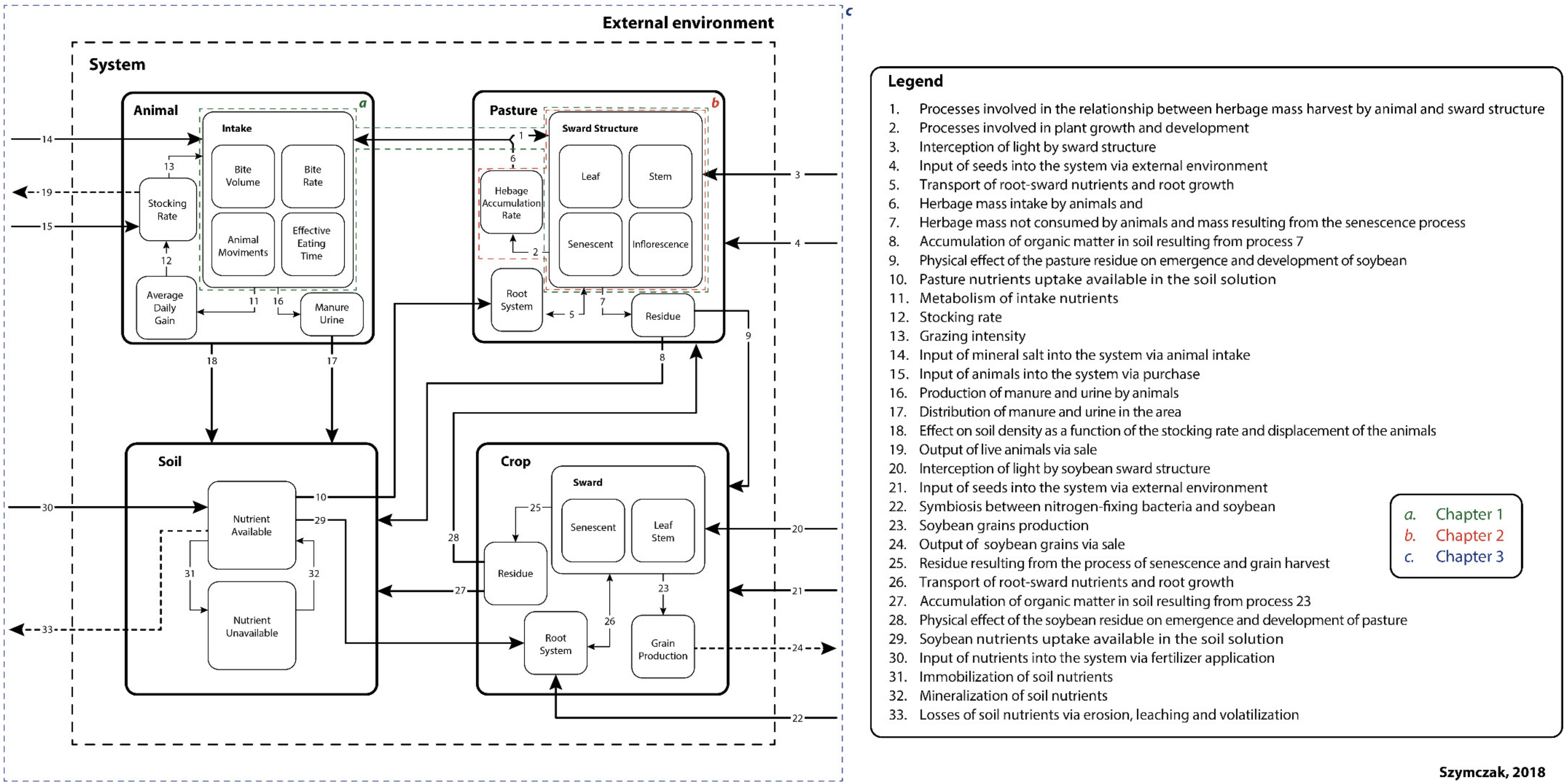
Objectives

The thesis aims to identify pasture management strategies based on a more efficient use ecological processes of the plant-animal interface and to evaluate if they can contribute to the promotion of sustainability in agricultural systems through resilience.

Specific objectives

- To evaluate short-term intake rate of sheep as a function of different structures of *Schedonorus arundinaceus*;
- To model the herbage mass accumulation of *Schedonorus arundinaceus* throughout the seasons, based on the Gompertz curve model;
- To estimate the instantaneous herbage accumulation rate of *Schedonorus arundinaceus* as a function of the herbage mass throughout the seasons;
- To develop a model of nutrient flow in an integrated crop-livestock system under different grazing intensities;
- To calculate resilience of nitrogen and phosphorus flow using Ecological Network Analysis in an integrated crop-livestock system under different grazing intensities;
- To develop and calculate the economic resilience index of an integrated crop-livestock system under different grazing intensities;
- To evaluate the correspondence between flow and economic resilience an integrated crop-livestock system under different grazing intensities.

2. CONCEPTUAL MODEL



Legend

1. Processes involved in the relationship between herbage mass harvest by animal and sward structure
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Figure 1. Conceptual model of the thesis with the representations of the processes involved between the compartments of the system (Soil, Crop, Pasture/Plant Cover and Animal) and External Environment in the studies. The green, orange and blue dashed lines delimit the variables studied in Chapters 1, 2 and 3, respectively.

3. CHAPTER 1

How can *Schedonorus arundinaceus* [Schreb.] Dumort sward structure affect the grazing process of sheep?[2]

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[2] Prepared in accordance with the standards of the Applied Animal Behaviour Science

How can *Schedonorus arundinaceus* [Schreb.] Dumort sward structure affect the grazing process of sheep?

Key words: *Festuca arundinacea* Schreb., tall fescue, intake rate, pasture management, sward surface height.

ABSTRACT

The study of factors influencing animal intake can provide a better understanding of the dynamics of the pasture ecosystem and provide a basis for the management of livestock in a more efficient way. This study aimed to evaluate different sward surface heights (SSH) of Tall Fescue (*Schedonorus arundinaceus*) (14, 17, 20, 23 and 26 cm) in the process of short-term intake rate (STIR) of sheep. The experiment was carried out at the experimental farm of the Federal University of Paraná, located in Pinhais, Paraná, Brazil. Twenty grazing tests were performed between June 24 and July 12, 2016 (morning and afternoon). The STIR was measured by weighing the sheep a pre- and post-grazing for each tests, corrected for insensible weight losses. The bite rate, total jaw movement rate and effective eating time were measured with behavior recorders. The sward measurements included the SSH pre- and post-grazing, herbage mass and the pre- grazing vertical distribution of morphological components. There was a significant difference for the structural variables (total and stratified) of the pasture between the treatments, which affected the ingestive behaviour of sheep. The SSH of Tall Fescue corresponding to the maximum short-term herbage intake rate was 22.3 cm, being influenced by the bite mass and the effective eating time. I conclude that the animals prefer a specific sward structure, which thus optimizes herbage intake.

1. Introduction

In recent years alternative management of agriculture systems have been sought that support the principles of eco-efficiency (Keating et al., 2013; Herrero et al., 2015; Rouquette, 2015). Carvalho et al. (2009) and Laca et al. (2009) presented a perspective on precision livestock management, which is based on productive efficiency with environmental responsibility. A way to achieve these goals is the understanding and mimicry of natural ecological processes (Bonaudo et al., 2014).

For millions of years the herbivores and forage plants have been in a co-evolutionary battle. Among several foraging strategies, the animals developed a "mouth" that optimizes the herbage intake, in order to meet the requirements in quantity and daily quality of food in less time, to perform other daily activities. On the other hand, forage plants have developed morphological structures that restrict grazing, favoring the development, growth and perpetuation of the species (Massey and Hartley, 2006; Shipley, 2007; Mendoza and Palmqvist, 2008; Strömberg, 2011).

The intake rate represents the consumption of forage per unit of time and is considered as a component of the ingestive behaviour of grazing animals. In this way being a variable determined by the bite mass, the bite rate and the grazing time. In this context, the bite can be considered as the first scale of the grazing process (Allden and Whittaker, 1970; Laca et al., 1992; Laca and Ortega, 1996; Prache and Delegarde, 2011) and therefore, under direct influence of the sward structure.

Structural characteristics of the forage sward can stimulate, inhibit or limit the ingestive behaviour of the animals (Gross et al., 1993; Decruyenaere et al., 2009; Amaral et al., 2012). These structural variables include leaf size and shape, cuticle thickness, stem physical properties, proportion of senescent material, proportion and quantity of leaf blades, which are dependent on the species, growth habit, height, morphogenic characteristics, life cycle and longevity of the forage plant (Hodgson, 1990; Amaral et al., 2012; Fonseca et al., 2012, Mezzalira et al., 2013; 2014; Guzzati et al., 2017). Thus, under a context of competition strategy at the plant-animal interface, the animals adapt to the different changes found in the pasture at the time of grazing, promoting behavioral changes, such as change in the pattern of displacement in the area, in food selection, alteration between the ratio of mass acquired and rate of harvest by animals and mandibular and non-mandibular movement (Bailey et al., 1996; Griffiths et al., 2003; Gonçalves et al., 2009; Fonseca et al., 2013).

The ingestive behavior of the animals has great relevance, because it determines the daily nutrient intake and animal performance, as well as the location and the intensity of its impact on the vegetation, providing a better understanding of the dynamics of the pasture ecosystem and giving the basis for more efficient management of animals and forage plants (Hodgson, 1990; Prache and Delegarde, 2011; Carvalho, 2013).

In this article we test the hypothesis that there is a balance between plants and animals, in that there is an optimal structure for the grazing animals, expressed in sward surface height (SSH) and components of the sward promote changes in short-term intake rate of sheep.

The objective of this study was to evaluate different sward structures of a temperate perennial forage species (*S. arundinaceus* [Schreb.] Dumort cv. Aurora), represented by different SSH, in the process of short-term intake rate (STIR) of sheep, from a perspective of optimization of pasture management.

2. Materials and Methods

All procedures involving animals were approved by the Commission for Ethics in the Use of Animals of the Sector of Agricultural Sciences of the Federal University of Paraná (07/2016).

2.1 Experimental Site

The experiment was carried out on the Canguiri experimental farm of the Federal University of Paraná - UFPR located in Pinhais city, Paraná state, Brazil (25°26'30"S and 49°7'30"W). The experiment was established in a 3.000 m^2 experimental area of *Schedonorus arundinaceus* [Schreb.] Dumort cv. INIA Aurora (nomenclature suggested by Soreng et al. (2001), previously named *Festuca arundinacea* Schreb. and Tall Fescue as common name) sown in June 2015 by the conventional method of soil preparation, with a seeding density of 55 kg ha^{-1}.

Nitrogen, phosphorus and potassium were applied uniformly in the experimental area. Before the sowing, 540 kg ha^{-1} of P_2O_5 was applied and after sowing (between 3 and 5 leaves) 200 kg ha^{-1} of N and 60 kg ha^{-1} of K_2O were applied. In March 2016, 180 kg of N ha^{-1} and 40 kg ha^{-1} of K_2O were applied. All fertilizations were based on the soil chemical analysis done before the sowing of Tall

Fescue (depth 0.00 – 0.20 m). The soil test results were as follows: 4.55% of organic matter ([C organic x 1.74]/10), pH = 5.70 ($CaCl_2$), exchangeable aluminum = 0.00 ($cmol_c$ dm^{-3}), K = 0.11 (cmolc dm^{-3}), Ca = 5.00 (cmolc dm^{-3}), Mg = 3.10 (cmolc dm^{-3}), V(%) = 71 e P = 2,90 (mg dm^{-3}).

The experimental area had been managed under continuous grazing since September 2015, with sward height maintained between 10 and 15 cm.

2.2 Treatments and experimental design

Five pre-grazing SSH (14, 17, 20, 23, 26 cm) were evaluated, with a randomized complete block design with four replicates. The heights were achieved by allowing regrowth and development of the plants from an initial residue height of 7 cm. The time of the day (morning and afternoon) was used as a blocking criterion. Twenty grazing tests of 45 ± 1 min were performed between June 24 and July 12, 2016, with two tests in the morning (between 8:30 and 9:30) and two in the afternoon (between 15:30 and 16:30).

2.3 Sward measurements

To determine the pre- and post-grazing SSH, a sward stick was used to make 150-point evaluations (≈ 1 point m^{-2}) within each sample unit (Barthram, 1985). A total of three forage samples of 0.25 m^2 each per experimental plot were harvested at pre- and post-grazing, to obtain the total herbage mass (HM), leaf lamina mass (LLM), pseudo-stems + sheaths mass (PSM), senescent mass (SM) and other species mass (OSM), through morphological and botanical separation.

The herbage mass was quantified in strata of the forage sward by collecting samples from 0.02 m^2 per experimental plot and stratifying them from the top of the plants to ground level in every vertical 0.03 m strata. These samples were separated into leaf lamina and pseudo-stem + sheath and subsequently the herbage bulk density was calculated by dividing the dry mass by the volume of the sampled cube in each stratum (0.0006 m^3). The number of green leaves in each strata were also counted. All samples were dried in a forced air oven at 65 °C until reaching constant weight for mass measurements.

2.4 Animal measurements

Six ewes, 50% White Dorper and 50% Suffolk, were used with an average weight of 61.9 ± 5.5 kg and two years of age. Three test animals were used to determine the rate of instantaneous intake.

All animals were previously acclimated to the experimental procedure and maintained in an area similar and adjacent to the experimental paddocks.

Before the grazing tests, the animals were equipped with diapers for collecting feces and urine and with IGER (Institute of Grassland and Environmental Research - Ultra Sound advice, London, UK) Behaviour Recorders (Rutter et al., 1997) which record mandibular movements (masticatory and manipulative) used to determine the effective eating time [total time spent separating, manipulating and chewing the pieces without lifting the head; (grazing = consumption + search)]. The data were analyzed with the Graze software (Rutter et al., 2000) and used to calculate bite mass (BM), bite rate (BR), time per bite (TB), total jaw movement rate (TJMR) and effective eating time (ET).

After the 45-minute test period of grazing, the animals were allocated to an adjacent area of 9 m^2 under open air condition, without access to water and food for 45 minutes, to estimate insensitive weight losses (H2O evaporation and CO2 and CH4) (Gibb,1998).

STIR was estimated by the double-weighing technique (Penning and Hooper, 1985). A digital balance (MGR-3000 Junior, Toledo, Canoas, Brazil) with a precision of 10 g was used to determine herbage intake. Formula (1) was used for the calculation of STIR:

$$\text{STIR} = d\, X \left\{ \left[\frac{(W2-W1)}{(t2-t1)} \right] + \left[\frac{(W3-W4)}{(t4-t3)} \right] \right\} X \left[\frac{(t2-t1)}{ET} \right] \quad (1)$$

where *d* is the proportion of dry mass in the herbage; *W1* and *W2* are pre- and post-grazing animal's weight respectively; *t1* and *t2* are pre- and post-grazing time; *W3* and *W4* are animal's weight pre- and post-insensible weight losses; *t3* and *t4* are pre- and post-insensible loss time and *ET* is effective eating time.

Bite mass was calculated by dividing the STIR during the grazing test by the total number of bites. Time per bite was calculated by dividing the total number of bites and ET. Total jaw movement rate was calculated by dividing the total number of jaw movements by the ET during the grazing test.

For the correction of the herbage mass intake during the grazing test, the proportion of herbage mass consumed by the animals was determined by the continuous bite monitoring method (Agreil and Meuret, 2004; Bonnet et al., 2011; Bonnet et al., 2015), after each grazing test. The green herbage mass was weighed after the grazing simulation and then dried in a forced air oven at 55 ° C until reaching constant weight.

2.5 Statistical analysis

The paddocks were considered as an experimental unit and the animals as sampling units of each paddock. The data set were analyzed using the R software (R Development Core Team, 2016). Data were submitted to analysis of variance (ANOVA) and when The F-test for treatment differences was significant ($p < 0.05$), the treatment means were compared using the Tukey test, at a significance level of 5%.

The grazing variables (STIR, BM, BT, TB, TJMR and ET) were analyzed using a quadratic model ($y_{ij} = a + bx + cx^2 + error_{ij}$). The correlation coefficient (R) was used as a measure of dependence between the variables.

3. Results

The observed SSH, pre- and post-grazing, increased linearly with expected SSH (treatments). There was no significant difference ($p < 0.01$) between pre- and post-grazing SSH in each treatment with each grazing test period, so the average values between pre- and post-grazing were used for forage variables. The pre-grazing observed SSH were very similar to the expected SSH (Table 1).

There was a significant effect for HM ($p < 0.01$), LLM ($p < 0.01$) and OSM ($p < 0.05$) (Table 1). For HM, there was a difference ($p < 0.01$) between the SSH of 26 cm and the two lowest SSH (14 and 17 cm). The highest LLM was obtained at SSH of 26 cm, followed by SSH of 23 and 20 cm, which differed from the SSH of 14 cm (Table 1). There was a linear relationship between the SSH and the LLM and HM. There was no significant effect of the SSH on the PSM ($p > 0.05$) and SM ($p > 0.05$), so the increase of HM is related to the increase of LLM.

A significant interaction was found between SSH and strata in the leaf lamina bulk density ($p < 0.01$), herbage total bulk density ($p < 0.05$) and number of leaves ($p < 0.01$). For the pseudo-stem + sheath bulk density, there was a significant effect only between strata ($p < 0.01$).

The highest leaf lamina bulk density was verified in strata 3-6 cm for SSH of 14, 6-9 cm for SSH of 17, 20 and 23 cm and 9-18 cm for SSH of 26. As there was an increase in the SSH pre-grazing, there was also a linear increase in the leaf lamina bulk density (Table 2).

The pseudo-stem + sheath bulk density was higher in the first strata, decreasing in the upper strata (Table 2).

The highest herbage total bulk density was verified in the strata 0-6 cm for 14 and 20 SSH, 0-9 cm for 17 SSH, 0-3 for 23 SSH and 0-18 cm in the SSH of 26 (Table 2). With the increase of the SSH pre-grazing, there was also an increase in herbage total bulk density in the upper strata (Table 2).

The highest number of leaves was verified in the strata 3-9 cm to 14 SSH, 6-12 cm for 17 and 20 SSH, 6-18 cm for 23 SSH and 9-18 cm for the SSH of 26, consequently having a reduction of leaf number in the upper and lower strata (Table 3). During the grazing tests, the presence of other species was verified, with a larger mass of these at SSH of 26 and a smaller at SSH of 14 ($p < 0.05$). The proportional mass of other species in all treatments was less than 2.85% (Table 1). The species found were *T. repens* (seedling stage), *V. sativa* (seedling stage), *P. tomentosa* (vegetative stage), *O. corniculata* (vegetative stage), *A. verlotorum* (vegetative stage) e *C. cardunculus* (vegetative stage).

No effect was observed on the BR ($p = 0.27$), TJMR ($p = 0.30$) and TB ($p = 0.22$) as a function of SSH (Figure 1, A, B and C respectively). There was a significant effect ($p < 0.01$) between ET and the different SSH of the Tall Fescue. There was a better adjustment of the quadratic model between ET and SSH in relation to the linear model, with an increase of ET up to 22.2 cm (Figure 1, D). There was a significant effect ($p < 0.01$) of SSH of Tall Fescue on the STIR ($p < 0.001$) and BM ($p < 0.01$). There was a better adjustment of the quadratic model between the STIR and the SSH, thus increasing up to 22.3 cm ($y = 5.61$ g MS min^{-1}), with the STIR decreasing at greater SSH (Fig. 2 A). The model that was best suited for MB as a function of SSH, was also quadratic, with increasing BM up to 22.8 cm (Fig. 2 B). A high correlation of 0.97 ($p < 0.01$) was also observed between STIR and BM variables (Fig. 3).

4. Discussion

The reduction of pre-grazing SSH by the animals, for each paddock during the grazing test, as measured by the post-grazing SSH, did not exceed 5% (Table 1). This indicated that similar structures were available to the animals from the beginning to the end of the grazing tests.

According to Ungar et al. (1991), Laca et al (1994), and Hirata et al. (2010), the STIR in homogeneous swards can be explained mainly by BM (Fig. 3). Similar results to the present study were observed by Mezzalira et al., (2014) and Mezzalira et al., (2017) evaluating the STIR in *Cynodon* sp. and *Avena strigosa*.

BM is dependent on the bite volume and herbage bulk density of the forage (Black and Kenney, 1984; Laca et al., 1992; Hirata et al., 2010). Thus, in lesser SSH there is a restriction in the formation of BM due to the low amount of leaves and in higher SSH the volume of the bite is restricted by the presence of pseudo-stem + sheath in the grazing horizons. In other words, SSH affects the bite depth (Black and Kenney, 1984; Burlinson et al., 1991; Benvenutti et al, 2008; Amaral et al., 2012; Fonseca et al., 2013). According to Illius et al. (1995) these conditions are also dependent on the animal motivation.

As the SSH increased in this study, there was probably an increase in the depth of the bite, as the free horizon depth of the pseudo-stems + sheath (grazing horizon) was 5, 8, 11, 11, and 11 cm for the SSH of 14, 17, 20, 23 and 26 cm, respectively (Table 3). There was an increase in the leaf lamina bulk density in the grazing horizon, according to the SSH increase (Table 2), providing an increase in the BM, with maximum values at 22.8 cm SSH (Fig. 2). This SSH was quite similar to the maximum STIR (Fig. 2 and 3).

The decrease in STIR at heights above 22.3 cm may be associated with increased sward bulk density (Table 2), which may seem counter-intuitive, but there are several possible explanations for this response of decreasing STIR at SSH above 22.3 cm. In the case of sheep, the animals are less able to increase the area of the bite (size of the jaw), moving their heads in the forage capture (Baumont et al., 2004; Hirata et al., 2010).

According to Illius et al. (1995), the high herbage bulk density (SSH of 26 cm), that is, increase in leaf lamina bulk density and number of leaves in the swards (Tables 2 and 3), promote less mass harvesting through the bites, since they require greater strength by the animal due to the greater physical resistance of the material to be cut. According to the same authors, species *Festuca ovina*, *Anthoxanthumod oratum* and *Agrostis tenuis* require greater forces in the process of forage capture, compared with other species of lower leaf lamina bulk density, thus promoting the preference of the animals for other species during the grazing process, in the case of mixed pastures.

In addition, at a SSH of 26 cm there may have been a greater need for interaction time with the sward in the bite formation, such as the positioning of the head and the choice of the place of the bite, causing the animals to search for smaller structures that optimize the consumption (Bremm et al., 2012; Mezzalira et al., 2014). According to Black and Kenney (1984), sheep tend to seek pasture structures that maximize the speed of ingestion. The additional time may be associated to three-dimensional aspects of the sward, such as increases in angulation, positioning and larger number of leaves (Table 3), and the height of the plant itself (Sonohat et al., 2002; Evers et al., 2007; Verdenal et al., 2008; Vos et al., 2009; Barillot et al., 2011). According to Baumont et al. (2004), the strategy of exploitation by the animals in horizons of the sward corresponds to a strategy of maximization of the quality of the diet and the STIR.

The results obtained for ET indicate that the animals had a preference for a specific structure, and that preferred structure consequently optimizes the intake rate, i.e., the ET maximum was 22.2 cm (Fig. 1 D). According to Pearson et al. (1994), preference is a term that describes the individual's herbage consumption in the absence of any restrictions on availability and accessibility. Utsumi et al. (2009) cite the importance of the structure of Tall Fescue in affecting the continuity in the grazing and permanence of the animals in the patch, thus verifying that the animals tend to prefer smaller and dense sward structures that promote lower mass depletions in the horizon during grazing.

Therefore, structures between SSH 20 and 23 cm would be within the best distribution and amount of mass in the canopy (Tables 2, 3), and the structures of SSH 14, 17 and 26 cm possibly promoted an increasing of the displacement and the search, shorter time of feeding station by the animals, resulting in lower ET and consequently lower STIR, results that are in agreement with the theory of optimal foraging (Schoener et al., 1971, Pyke et al., 1977). Different results regarding BR and TJMR were verified by Fonseca et al. (2013) and Mezzalira et al. (2014). They found an increase in the rate, which can be attributed mainly to the size of the animal, since those two studies were carried out with cattle. According to Illuis et al. (1995) animals of larger size are less constrained by the physical properties of the pasture structure. Black and Kenney (1984) did not observe changes in the rate of jaw movements of sheep in different structures of *Pennisetum clandestinum* and *Lolium perenne*. For the variable TB the results in the study were similar to the study of Mezzalira et al. (2014) and Hirata et al. (2010).

It was verified that the SSH of the Tall Fescue corresponding to the maximum STIR of sheep was 22.3 cm. That SSH can be adopted as a pre-grazing height for intermittent systems.

Chapman and Clark (1984), aiming to optimize animal consumption, suggest that the management of *L. perenne* and Tall Fescue (Hume and Brock, 1997) should be maintained between 1000 and 2500 kg DM ha^{-1}, which brackets the mass of the optimal SSH obtained in this work.

Conclusion

The sward surface height of Tall Fescue corresponding to the maximum short-term herbage intake rate was 22.3 cm, being affected by the bite mass and the effective eating time, suggesting that the animals have a preference for a specific forage sward structure.

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Tables and Figures

Table 1. Observed sward surface heights pre- and post-grazing (SSH, cm), total herbage mass (HM, kg DM ha^{-1}), leaf lamina mass (LLM, kg DM ha^{-1}), pseudo-stems + sheaths mass (PSM, kg DM ha^{-1}), senescent mass (SM, kg DM ha^{-1}) and others species mass (OSM, kg DM ha^{-1}) as function of expected swards surface heights (SSHe, cm) of *Schedonorus arundinaceus* [Schreb.] Dumort (Tall Fescue).

	SSHe (cm)					p
	14	17	20	23	26	
SSH pre-[1]	14.19±0.19^{eA}	17.32±0.20^{dA}	19.72±0.27^{cA}	22.78±0.28^{bA}	25.91±0.26^{aA}	0.000
SSH post-[1]	14.06±0.18^{eA}	17.05±0.19^{dA}	19.62±0.28^{cA}	22.75±0.25^{bA}	25.90±0.23^{aA}	0.000
HM	1825.42^{b}	1955.99^{b}	2175.88^{ab}	2157.80^{ab}	2510.98^{a}	0.000
LLM	1046.30^{c}	1257.64^{bc}	1387.29^{b}	1333.13^{b}	1659.18^{a}	0.000
PSM	454.19	419.97	441.89	443.53	510.00	0.785
SM	377.34	278.37	346.69	381.13	341.80	0.743
OSM	16.66^{b}	48.05^{ab}	37.36^{ab}	31.30^{ab}	70.65^{a}	0.020

[1] Means± Standard error;

$^{a-e}$Means within a row with different superscripts differ *($P < 0.05$)* by the Tukey's test.

^{A}Means within a column with different superscripts differ *($P < 0.05$)* by the Tukey's test.

Table 2 Leaf lamina bulk density (LBD), Pseudo-stems + sheaths bulk density (PSBD) and Total herbage bulk density (THBD) by sward strata as function of swards surface heights (SSH) of *Schedonorus arundinaceus* [Schreb.] Dumort (Tall Fescue).

Strata	Swards surface heights (cm)				
(cm)	14	17	20	23	26
LBD (g DM m^{-3})[1]					
33-36			0.08^{aG}	0.16^{aG}	1.41^{aD}
30-33			0.87^{aG}	1.60^{aG}	3.49^{aD}
27-30			2.86^{bG}	4.38^{abFG}	14.54^{aCD}
24-27		0.93^{bF}	7.45^{bG}	11.32^{abEFG}	32.86^{aCD}
21-24		4.15^{cF}	17.27^{bcFG}	36.70^{abDEF}	60.81^{aBC}
18-21		14.17^{cDF}	37.13^{bcEF}	55.66^{bCD}	91.45^{aAB}
15-18	7.72^{dC}	41.32^{cDEF}	58.85^{bcDE}	82.39^{abBC}	113.06^{aA}
12-15	20.61^{cC}	73.35^{bBCD}	86.41^{bCD}	104.07^{abAB}	131.56^{aA}
9-12	44.32^{bC}	104.74^{aABC}	116.27^{aAB}	105.20^{aAB}	121.35^{aA}
6-9	95.82^{bAB}	156.43^{aA}	123.71^{abA}	127.65^{abA}	106.83^{abAB}
3-6	126.18^{aA}	111.97^{aAB}	90.74^{abBC}	58.35^{bcCD}	39.37^{cDE}
0-3	84.93^{aB}	59.12^{abCDE}	48.61^{bE}	43.60^{bDE}	29.63^{bCD}
PSBD (g DM m^{-3})[2]					
12-15				0.00^{C}	0.274^{C}
9-12				0.633^{C}	10.60^{C}
6-9	0.68^{B}	23.87^{C}	10.28^{C}	24.03^{C}	46.95^{B}
3-6	44.72^{B}	75.83^{B}	60.47^{B}	83.48^{B}	62.00^{B}
0-3	135.19^{A}	165.65^{A}	127.05^{A}	185.01^{A}	114.83^{A}
THBD (g DM m^{-3})[3]					
33-36			0.08^{aH}	0.16^{aF}	1.41^{aE}
30-33			0.87^{aH}	1.60^{aF}	3.49^{aE}
27-30			2.86^{bH}	4.38^{abEF}	14.54^{aDE}
24-27		0.93^{bC}	$7.45b^{GH}$	11.32^{abEF}	32.86^{aDE}
21-24		4.15^{cC}	17.27^{bcGH}	36.70^{abDEF}	60.81^{aCD}
18-21		14.17^{cCD}	37.13^{bcFG}	55.66^{bCDe}	91.45^{aBC}

15-18	7.72^{dD}	41.32^{cCD}	58.85^{bcEF}	82.39^{abCD}	113.06^{aABC}
12-15	20.61^{cCD}	73.35^{bBC}	86.41^{bDE}	104.07^{abBC}	131.84^{aAB}
9-12	44.32^{bCD}	104.74^{aB}	116.27^{aCD}	105.83^{aBC}	131.96^{aAB}
6-9	96.51^{bBC}	180.30^{aA}	133.99^{abBC}	151.69^{abB}	153.79^{abA}
3-6	170.91^{aAB}	187.81^{aA}	151.22^{abAB}	141.83^{abB}	101.38^{bABC}
0-3	220.13^{aA}	224.78^{aA}	175.67^{aA}	228.62^{aA}	144.46^{aAB}

^{1}p significance level: SSH $p < 0.001$; Strata $p < 0.001$; SSH *x* Strata $p < 0.01$.

^{2}p significance level: SSH $p = 0.46$; Strata $p < 0.001$; SSH *x* Strata $p < 0.44$.

^{3}p significance level: SSH $p < 0.001$; Strata $p < 0.001$; SSH *x* Strata $p < 0.05$.

$^{a\text{-}d}$Means within a row with different superscripts differ *($p < 0.05$)* by the Tukey's test.

$^{A\text{-}G}$Means within a column with different superscripts differ *($p < 0.05$)* by the Tukey's test.

Table 3. Numbers of leaf lamina by sward strata as a function of sward surface heights (SSH) of *Schedonorus arundinaceus* [Schreb.] Dumort (Tall Fescue).

Strata	SSH (cm)[1]				
(cm)[1]	14	17	20	23	26
33-36			0.25^{aG}	0.37^{aD}	1.75^{aE}
30-33			2.00^{bFG}	2.50^{abD}	5.50^{aE}
27-30			5.00^{bFG}	7.00^{abD}	17.25^{aE}
24-27		1.25^{bE}	10.37^{bFG}	14.62^{bD}	31.75^{aDE}
21-24		6.25^{cE}	22.15^{bcEF}	33.00^{bCD}	61.87^{aCD}
18-21		17.50^{cDE}	40.87^{bcE}	50.87^{bBC}	83.25^{aBC}
15-18	9.62^{cD}	40.75^{bcCD}	64.25^{abD}	81.12^{aAB}	95.87^{aABC}
12-15	25.50^{cCD}	73.75^{bB}	87.12^{bBC}	100.00^{abA}	128.62^{aA}
9-12	51.37^{bBC}	111.87^{aA}	108.00^{aAB}	107.00^{aA}	101.00^{aAB}
6-9	100.75^{abA}	127.50^{aA}	115.50^{abA}	112.87^{abA}	80.00^{bBC}
3-6	113.12^{aA}	70.12^{bBC}	69.50^{bCD}	56.62^{bBC}	36.62^{bDE}
0-3	81.50^{aAB}	41.62^{bCD}	41.12^{bE}	34.25^{bCD}	23.37^{bDE}

[1] p significance level: SSH $p < 0.001$; Strata $p < 0.001$; SSH x Strata $p < 0.001$.

$^{a\text{-}c}$Means within a row with different superscripts differ ($p < 0.05$) by the Tukey's test

$^{A\text{-}F}$Means within a column with different superscripts differ ($p < 0.05$) by the Tukey's test

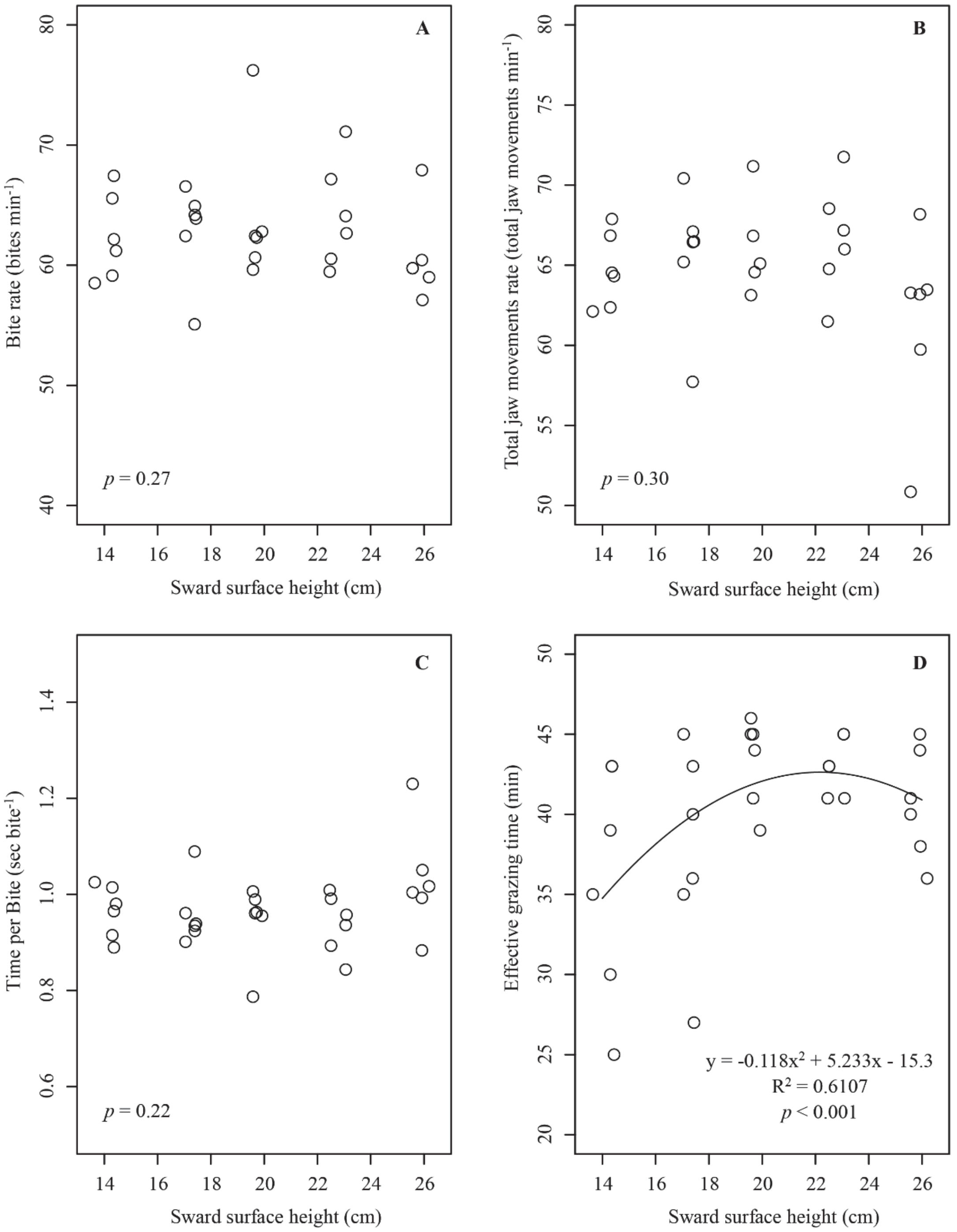

Fig. 1. Bite rate (BR; A), total jaw movements rate (TJMR; B), time per bite (TB; C) and effective grazing time (ET; D) of sheep as function of different *Schedonorus arundinaceus* [Schreb.] Dumort. (Tall Fescue) sward surface heights (SSH).

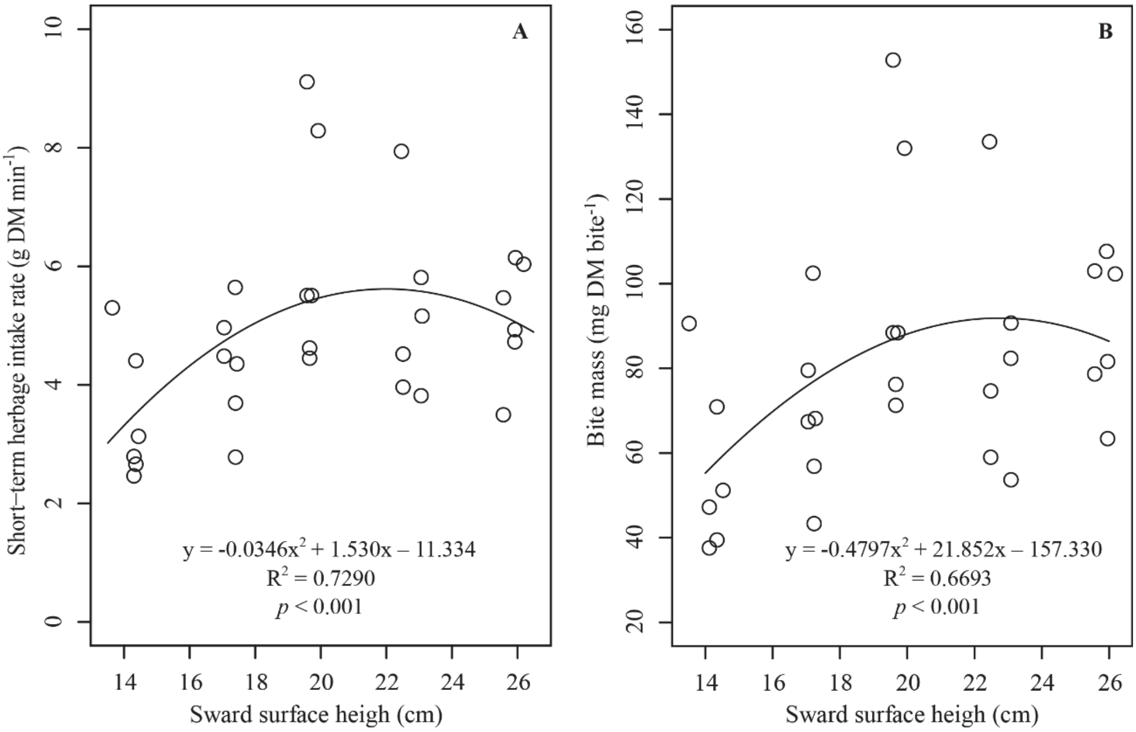

Fig. 2. Short-term herbage intake rate (STIR; A) and bite mass (BM; B) of sheep as function of different *Schedonorus arundinaceus* [Schreb.] Dumort. (Tall Fescue) sward surface heights (SSH). Maximum STIR = 22.3 cm.

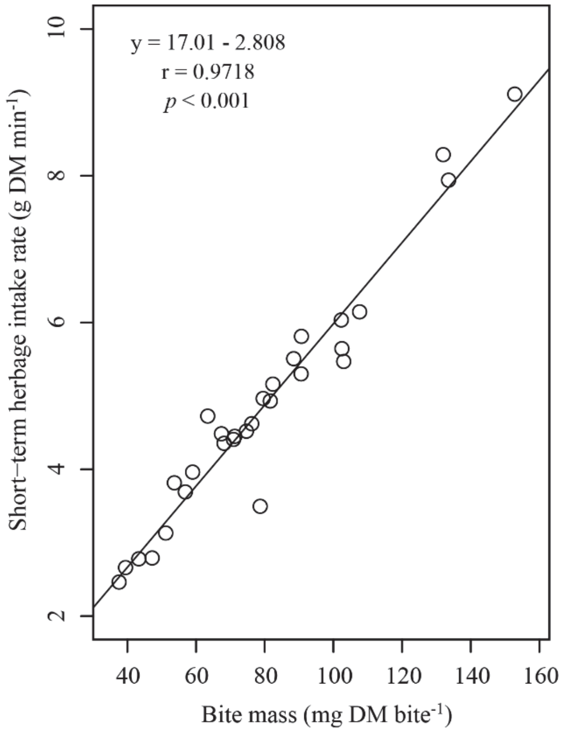

Fig. 3. Relationship between short-term herbage intake rate (STIR) and bite mass (BM) of sheep as function of different *Schedonorus arundinaceus* [Schreb.] Dumort. (Tall Fescue) swards surface heights (SSH).

4. CHAPTER 2

Is there a "double entendre" in the efficient pasture management?[3]

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

Is there a “double entendre” in the efficient pasture management?

ABSTRACT

The pasture management dilemma is oriented towards sustainable intensification and stability of yield between the ideal compensation of the amount of leaves removed during grazing and the amount left in the residual, in order to support soil-plant carbon balance and animal harvest rates. This study aimed to evaluate the optimal point from both plant and animal perspectives, through the adjustment of instantaneous herbage accumulation rate by the Gompertz curve and short-term intake rate of sheep using as the species *Schedonorus arundinaceus* (Tall Fescue) as an experimental model. Were measured the weekly herbage accumulation during seven growth periods (October 2015, November 2015, December 2015, March 2016, April 2016, August 2016 and September 2016) with the initiation dates in a randomized complete block design with four repetitions. Total herbage mass, leaf lamina mass, pseudo-stems + sheaths mass, senescent mass and sward surface height were collected. The results demonstrated that the pre-grazing sward surface height of 22.30 cm of Tall Fescue promotes the maximization of the short-term intake rate of sheep and the instantaneous herbage accumulation rate in the spring and autumn periods. Therefore, we find a convergent point in the plant-animal interface that provides increases in productive efficiency in agricultural systems.

Keyword: Grazing management, efficiency of production, sustainability, *Festuca arundinacea* Schreb, Tall Fescue.

1. Introduction

The pasture management dilemma is oriented towards sustainable intensification (Gunton et al., 2016) and stability of yield (Conway, 1987) between the ideal compensation of the amount of leaves removed during grazing and the amount of residual, in order to support soil-plant carbon balance and animal harvest rates (Hodgson and Da Silva, 2000; Pearson et al., 2011).

Thus, the way in which pasture is managed has a direct influence on the maintenance of productivity, profitability, biodiversity and mitigation of greenhouse gases in pastoral systems (Zhang et al., 2015) and desertification (Feng et al., 2015).

Plant growth and development can be represented by a sigmoid curve (Yin et al., 2003; Thornley and France, 2005). In pasture management, the curve can adequately illustrate herbage production as a function of time, as a consequence of the management adopted (Barker et al., 2010), where the dynamics of carbon (Brougham, 1955; Richards and Caldwell, 1985; Pearson et al., 2011) and nitrogen (Lemaire et al., 2007), morphogenesis, tillering, height, architecture (Birch et al., 2003; Evers et al., 2007a; Evers et al., 2007b; Verdenal et al., 2008; Barillot et al., 2014) and nutritional value for animals (Nave et al., 2013) are implicit.

For a long time, many authors have been discussing the best criteria for pasture management from a plant perspective. Pearson et al. (1988) indicate as a point of reference the criterion 95% of light interception (LI) by the sward and critical leaf area index (LAI) as the moment of interruption of regrowth for temperate species. Da Silva and Nascimento Jr (2007) suggest the criterion of 95% LI for C4 grasses. Lemaire and Agnusdei (2000) add the importance of considering the LAI criteria and morphogenic processes.

The plant variables mentioned above describe the processes of growth of the primary component under the influence of grazing animals, which are very important in predicting pasture efficiency and long-term sustainability under grazing (Lemaire et al., 2009).

Carvalho (2013) presented a perspective for pasture management, where by the criterion is based on the spatio-temporal scales of the plant-animal interface, represented by pasture sward surface height. From this perspective, several studies have demonstrated that there is an optimal forage structure for the maximization of the short-term intake rate (STIR) of grazing ruminants (view Fonseca et al., 2012; Amaral et al., 2013; Mezzalira et al., 2014; Silva et al., 2017). Therefore, this process can be understood as a way to promote greater harvest efficiency, as a function of time, by the animal.

Defining management strategies consistent with increased efficiency in agriculture processes is of paramount importance (Keating et al., 2010; Struik and Kuyper, 2017). Thus the main question of the work is oriented if is there a common point in pasture management that maximizes the efficiency for both the primary and secondary components of pasture-based livestock production?

In this study we consider that the plant growth is under the effect of time as modulator of growth and plant development processes; however, for the animal the maximum intake rate can be considered as static in time.

The purpose of this study was to evaluate the optimal point for grazing management from the plant and animal perspective, through the adjustment of instantaneous herbage accumulation rate by the Gompertz curve, proposed by Barker et al. (2010), and the short-term intake rate, proposed by Carvalho (2013), using the species *Schedonorus arundinaceus* [Schreb.] Dumort (Tall Fescue) as the model system.

2. Material and Methods

2.1 Experimental Site

Two experiments were conducted at the Canguiri experimental farm of the Federal University of Paraná, located in Pinhais city, Paraná, Brazil (25°26'30"S and 49°7'30"W).

The experimental area of *Schedonorus arundinaceus* [Schreb.] Dumort cv. INIA Aurora (nomenclature suggested by Soreng et al. (2001), previously named *Festuca arundinacea* Schreb. and Tall Fescue as common name) was seeded at 55 kg ha^{-1} density in June 2015 using the conventional tillage method to prepare the seedbed.

Nitrogen, phosphorus and potassium were applied to the experimental area. Phosphorus was applied before sowing at 540 kg P_2O_5 ha^{-1}. When seedlings were at the 3 to 5 leaf stage, 200 kg ha^{-1} of N and 60 kg ha^{-1} of K_2O were applied. All fertilizations were carried out according to the soil analysis. Soil chemical analysis results of the experimental area before sowing of Tall Fescue (depth 0.00 – 0.20 m) were: 4.55% of organic matter ([C organic x 1.74]/10), pH = 5.70 ($CaCl_2$), exchangeable aluminum = 0.00 ($cmol_c$ dm^{-3}), K = 0.11 (cmolc dm^{-3}), Ca = 5.00 (cmolc dm^{-3}), Mg = 3.10 (cmolc dm^{-3}), V(%) = 71 e P = 2,90 (mg dm^{-3}).

The experimental area was managed under continuous stocking beginning in September 2015 with the sward surface height maintained between 10 and 15 cm.

2.2 Treatments, experimental design and measurements

Herbage accumulation was measured during seven growth periods, with initiation dates in mid-October 2015, mid-November 2015, mid-December 2015, mid-March 2016, mid-April 2016, mid-August 2016 and a mid-September 2016. At the beginning of each growth period, the forage was clipped to a 5-cm stubble height and allowed to grow unharvested for the remainder of the growing season. The initiation dates were replicated four times in a randomized complete block design. Individual plots (experimental units) were 1 m^2.

Thirty days before the initiation date of each growth period, N was applied at 90 kg ha^{-1}, to avoid growth restriction due to lack of N (Nelson, 2000), and before the beginning of each growth periods the area was isolated to prevent animal grazing.

Sward surface height (SSH) was monitored each week using the sward stick, recording 6 points per experimental plot (Barthram, 1985). Herbage mass was randomly collected from a 0.25 m^2 area within each experimental unit on a weekly basis. The forage samples were collected at the soil level and afterwards morphological separation was performed to obtain the total herbage mass (HM), leaf lamina mass (LLM), pseudo-stems + sheaths mass (PSM) and senescent mass (SM). All samples were dried in a forced air oven at 65 °C until reaching constant weight.

For the calculation of thermal time (TT), expressed in cumulative degree-days (°Cd), we used equation 1. The maximum daily air temperatures during the experiment did not exceed 35 degrees, so the coefficient for the upper threshold temperature was considered zero (Moreno et al., 2014). In this study, 4°C was used as the T_b (Errecart et al., 2012).

$$TT = \sum(T_\mu - T_b) \qquad (1)$$

where T_μ represents the mean daily air temperature (the average of minimum and maximum temperatures).

2.3 Statistical analysis

HM, LLM, PSM and SM (means of the four experimental units sampled per initiation date) were fitted to thermal-time accumulation using the Gompertz (equation 2, figure 2) with software R (R Development Core Team, 2016). Four parameters of the model were estimated (equation 4) through software R, according to Barker et al., (2010):

$$H = H_\Delta e^{ae^{bt}} + H_{min} \qquad (2)$$

where H is the herbage mass, H_Δ is the maximum (asymptotic) herbage mass, H_{min} is the lower asymptote for herbage mass, t is the time in thermal time accumulated and a and b were parameters that determined the shape and curvature of the Gompertz curve, respectively.

The calculation of the instantaneous herbage accumulation rate (HAR$_i$) was obtained by the equation 3:

$$HAR_i = \frac{dH}{dt} = bH_{\Delta}e^{ae^{bt}}\ln\left(\frac{1}{e^{ae^{bt}}}\right) \qquad (3)$$

The logistic model of Gompertz is characterized by an asymmetric curve, property increases the biological value to the forage accumulation model, because it is more sensitive to changes in initial growth rates and suppression of growth (Barker et al., 2010)

3. Results

There was adjustment of the Gompertz model for HM, LLM, PSM and SM, in all periods, except for those beginning in March and April for the last variable (Fig. 2 and Table 1).

The coefficients of curvature (*b*) of the Gompertz model for HM, LLM, PSM and SM varied during the periods of growth. For HM, the highest values of the coefficient *b* occurred in the periods beginning in October-2015 (0.0039), November-2015 (0.0036) and September-2016 (0.0036) and the lowest were in the periods beginning in March-2016 (0.0025) and April-2016 (0.0025) (Table 1).

For LLM, the highest values of coefficient *b* occurred in the periods beginning in October-2015 (0.0060), November-2015 (0.0052) December-2016 (0.0063) and September-2016 (0.0055) and the lowest in the periods beginning in March-2016 (0.0023) and April-2016 (0.0019) (Table 1).

For PSM, the highest values for coefficient *b* occur in the periods beginning in August-2016 (0.0080) and September-2016 (0.0049) and lower beginning in December-2015 (0.0012) and April-2015 (0.0026) (Table 1).

For SM, the highest values for the *b* coefficient were in the period beginning in December-2015 (0.0062) and the lowest values beginning in October-2015 (0.0011) (Table 1).

$HAR_{i\text{-}max}$ of HM varied between 4.76 and 1.60 kg DM ha^{-1} $°C^{-1}$ and $HAR_{i\text{-}max}$ of LLM varied between 4.05 and 1.20 kg DM ha^{-1} $°C^{-1}$, in the periods beginning in October-2015 and April-2016 respectively. For the $HAR_{i\text{-}max}$ of PSM there was variation between 0.75 and 0.38 kg DM ha^{-1} $°C^{-1}$, in the periods beginning in October-2015 and September-2016, respectively (Table 1). For the $HAR_{i\text{-}max}$ of SM the variation was 1.84 and 1.30 kg DM ha^{-1} $°C^{-1}$, in the periods beginning in September-2016 and August-2016, respectively (Table 1).

The highest optimum total herbage mass at $HAR_{i\text{-}max}$ for HM were in the periods beginning in August-2016, September-2016, April-2016 and October-2015, with values of 2889, 2848, 2160 and 2068 kg DM ha^{-1}, respectively. This HM corresponds to SSH of 23.93, 23.75, 25.26 and 22.53 cm (Table 1).

For LLM the highest values of optimum total herbage mass at $HAR_{i\text{-}max}$ were in the periods beginning in September-2016, August-2016 and April-2016 and October-2015, with the values of 2523, 2445, 1323 and 1311 kg DM ha^{-1}, respectively. Values that correspond to SSH of 21.30, 20.70, 25.51 and 14.07 cm (Table 1).

For the PSM, the highest values of optimum total herbage mass at $HAR_{i\text{-}max}$ were in the periods beginning in September-2016 and April-2016, with 3689 and 3046 kg DM ha^{-1} and SSH of 28.75 and 31.89 cm, respectively (Table 1).

The highest values of optimum total herbage mass at $HAR_{i\text{-}max}$ for SM were observed in the periods beginning in August-2016, September-2016 and October-2015, with SSH of 32.42, 30.28 and 40.99 cm, respectively (Table 1).

4. Discussion

4.1 Pasture growth

The $HAR_{i\text{-}max}$ variation observed between growth periods may be related to differences in mean temperatures (figure 1) during the conduct of the experiment. According to Sun et al.

(2014) the optimal growth temperature of Tall Fescue is between 15 and 20 °C. Under these conditions photosynthesis is maximized largely by the high activity of Rubisco, reflecting the higher assimilation rate of CO_2 (Sage and Kubien, 2007). Thus, in the periods beginning in October-2015, April-2016, August-2016 and September-2016, there were average temperatures of 20.56, 15.50, 16.99 and 18.50°C promoted increase of $HAR_{i\text{-}max}$ and coefficient *b* values for HM and LLM. During the periods of November-2015, December-2015 and March-2016 there was an increase in the frequency of daily maximum temperatures above 30 °C.

Similar results were verified by Nave et al. (2013), evaluating growth and accumulation of herbage in a pasture with mixture of Tall Fescue and *Poa pratensis* L. in Columbus, OH, USA, were $HAR_{i\text{-}max}$ varied with season, probably based on climatic differences (rainfall and temperature varied with the season of the year in that study)

The coefficient *b* in the Gompertz model has the function of adjusting the slope of the curve in the exponential phase, thus, higher coefficient values represent higher herbage accumulation rate. In the case of the leaves the increase in coefficient *b*, provided by the optimum temperature in relation to lower temperatures, is related to the increase in the rate of leaf elongation, consequently decreasing the phyllochron (Pearson and Penning, 1988; Thomas and Stoddart, 1995).

Data for the periods beginning in January-2016, February-2016, May-2016, June-2016 and July-2016 were not presented in this study, as it was not possible to estimate with confidence the $HAR_{i\text{-}max}$. We attribute this to the effect of temperature, since in the summer months (January and February) maximum temperatures were frequently above 30 °C and in winter (May to July) there were minimum temperatures below 5 °C (Figure 1), which affected the growth and development of Tall Fescue (Bélanger, et al., 1994; Atkinson and Porter, 1996; Yin and Struik, 2009).

In the early stages of regrowth (after the cut), the accumulation of leaves occurs first, representing a large part of the total accumulation of the pasture. With the increase in LAI, there is an increase in the interception of light, and as a result, there is an increase in the pseudo-stem accumulation rates, mainly in response to the effect caused by the alteration of the light quality within the sward (Aphalo et al., 1999; Gommers et al., 2013) (Figure 2).

There was no adjustment of the Gompertz curve for SM in the periods beginning in March-2016 and April-2016, since it is probably related to low senescence rates when the plants grow under the effect of the lower temperature (Thomas and Stoddart, 1995). The effect of higher temperatures on SM can also be seen in the period beginning in December-2015, with higher values for coefficient *b* and optimum SM at $\text{HAR}_{i\text{-}max}$ was lower than the other months (Table 1).

The decrease of the growth rate is related to the advance of the development of the plants (above the critical LAI), due to the increase of the senescent material rate, age of the leaves, and shading of the lower leaves, thus reducing the photosynthetic efficiency (Gastal and Lemaire, 2002; Li et al., 2013; Li et al., 2014; Pedreira et al., 2015).

The H_{min} values, in the periods beginning in October-2015, November-2015 and December-2015, was probably lower than in 2016 because the tall fescue had just been established in June 2015 as the stand established, the H_{min} increased (more tillers, bigger tillers, etc), so the H_{min} naturally increased.

4.2 Implications for pasture management

The results obtained in this work suggest that the SSH referring to the optimum total herbage mass at $\text{HAR}_{i\text{-}max}$ for HM and LLM are convergent with SSH at $\text{STIR}_{\text{-}max}$ of sheep (Table 1, Fig. 2 and Chapter 1). For the periods beginning in October-2015, March-2016, April-2016, August-2016 and September-2016, the SSH at $\text{HAR}_{i\text{-}max}$ of HM were 22.53, 19.97, 25.26, 23.93, 23.75 cm, values close to those found at SSH at STIR_{-max}, i.e., 22.30 cm. The SSH at $\mathrm{HAR}_{i\text{-}max}$ of LLM were close to SSH at STIR_{-max} in the periods beginning in April-2016, August-2016 and September-2016, i.e., 25.51, 20.70 and 21.30 cm, respectively.

This means that the net accumulation rate of forage during regrowth (after cut) reaches the maximum at a SSH very similar to the SSH that provides maximum harvest efficiency for sheep.

This relationship in the plant-animal interface can be explained by the significant increase of leaves in the sward (Fig. 2 and Table 1), promoting increases in plant growth potential and harvesting by the animals, since in this SSH the animals tend to consume only leaves.

Our results are contrary to the postulates by Briske and Heitschmidt (1991), where they argued that the optimization processes of interception and light conversion to biomass production and harvesting efficiency by animals cannot be maximized at the same time. The authors denominated this process as the fundamental ecological dilemma.

Using pre-grazing SSH of 22.30 cm (Chapter 1) as a management criterion in intermittent systems, there may be optimization of efficiency in use of light and nitrogen, tillering rate, carbon balance, and leaf appearance rate. This also may promote less instantaneous senescent material and an increase in the vegetative period of the forage in relation to the higher SSH (Nelson, 2000; Gastal and Lemaire, 2002; Evers et al., 2007a,). For animals in this pre-SSH, high intake of high quality and good digestibility forage occurs, providing increases in feed conversion efficiency and reductions in methane enteric emissions by average daily gain of sheep (Savian, 2017; Savian et al., 2018), all of which are criteria that should be prioritized in pasture management strategies.

Our results demonstrated that the convergence between optimal SSH for plant growth and harvesting by sheep occurs only under optimal growth conditions of Tall Fescue, i.e., periods beginning in October-2015, March-2016, August-2016 and September-2016. In the periods beginning in November-2015 and December-2015, $HAR_{i\text{-}max}$ occured at lower SSH, which would probably reduce the efficiency of the herbage net production and increase the amount of senescent material (figure 2), consequently decreasing herbage production.

For animals, the change in $STIR_{\text{-}max}$ over time is more related to a drastic change in sward structure. Guzatti et al. (2017) demonstrated that the $STIR_{\text{-}max}$ of animals can be kept constant throughout the vegetative stage of the forage, with a decrease in the $STIR_{\text{-}max}$ in the reproductive stage, caused mainly by the decreasing leaf/stem ratio.

Thus, in the non-optimal periods of plant growth, the production of the system probably will be more affected by the lower stocking rate, due to lower herbage production, than due to the individual performance of the animals.

However, an important issue to be considered in pasture management is the grazing intensity adopted. Pearson et al. (1988) discuss growth processes, based on the growth curve, under different intensities of sward depletion. The authors suggest that more lenient defoliation provides a maximization of pasture productive potential, thus maintaining higher photosynthetic rates.

According to Carvalho (2013) the depletion criterion in the “Rotatinuous stocking”, occurs when there is a 40% decrease from the pre-SSH, thus promoting the maintenance of the $STIR_{\text{-}max}$ of the animals during grazing on the paddock (view Fonseca et al., 2012; Mezzalira et al., 2014).

Savian (2017) applied this concept in an experiment, comparing “Rotatinuous stocking” with traditional rotational stocking (greater sward depletion and less lenient) of sheep grazing *Lolium multiflorum*. Greater herbage production and greater individual performance of the animals were documented in “Rotatinuous stocking”.

Management strategies that prioritize the lower intensity of sward depletion promote less stress on plant regrowth, since there is greater leaf area remaining after grazing, which in turn is extremely important in the carbon balance process of regrowth (Figure 2). Using this strategy, the instantaneous growth rate will be maintained in the exponential phase of the curve, thus promoting a higher frequency of grazing.

Our results suggest that the adoption of the criterion based on the intake behaviour of the animals has great importance from the perspective of increasing the efficiency of the ecological processes of the plant-animal interface. However, more studies will be needed to understand the influence of the heterogeneity of the pasture caused by successive cycles of grazing animals in the HAR_i.

5. Conclusion

The pre-grazing sward surface height of 22.30 cm in pastures of Tall Fescue promotes the maximization of the short-term intake rate of sheep and the instantaneous herbage accumulation rate during the spring and autumn periods. Therefore, this study suggests that there is a convergent point in the plant-animal interface that provides increases in productive efficiency in agricultural systems.

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Tables and Figures

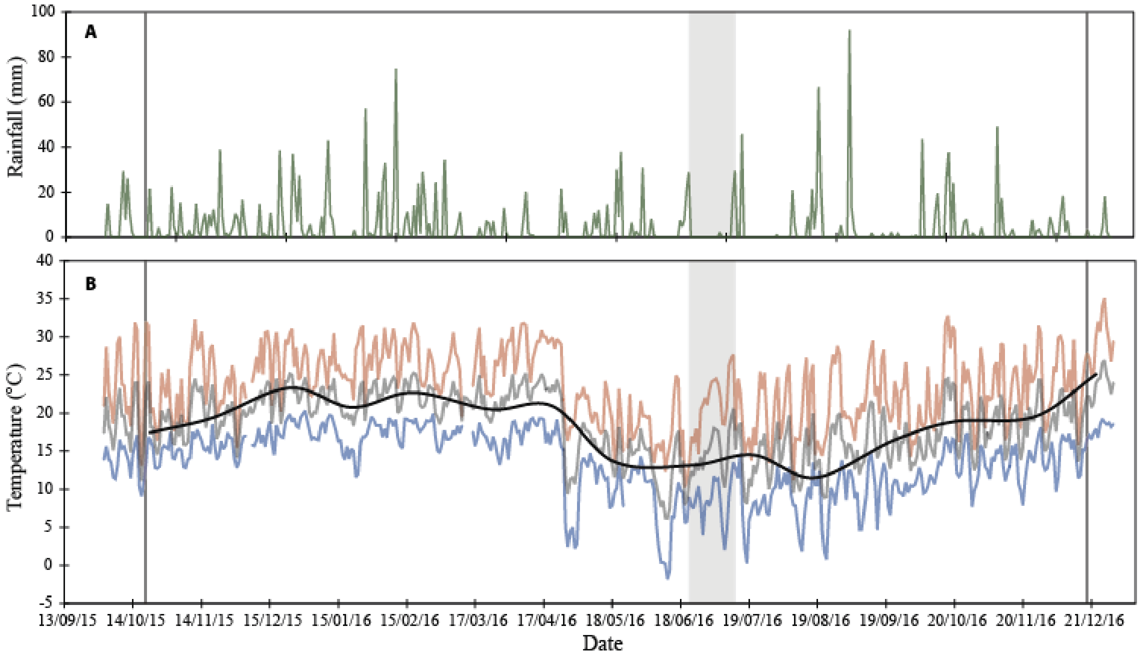

Fig. 1. Rainfall (A) and temperature (B) during the experiments. Black lines at the two corners of the graphs indicate the start and end date of experiment 1 and the gray range represents the evaluation period of experiment 2. Blue, black and orange lines represent the minimum, average and maximum daily temperatures, respectively.

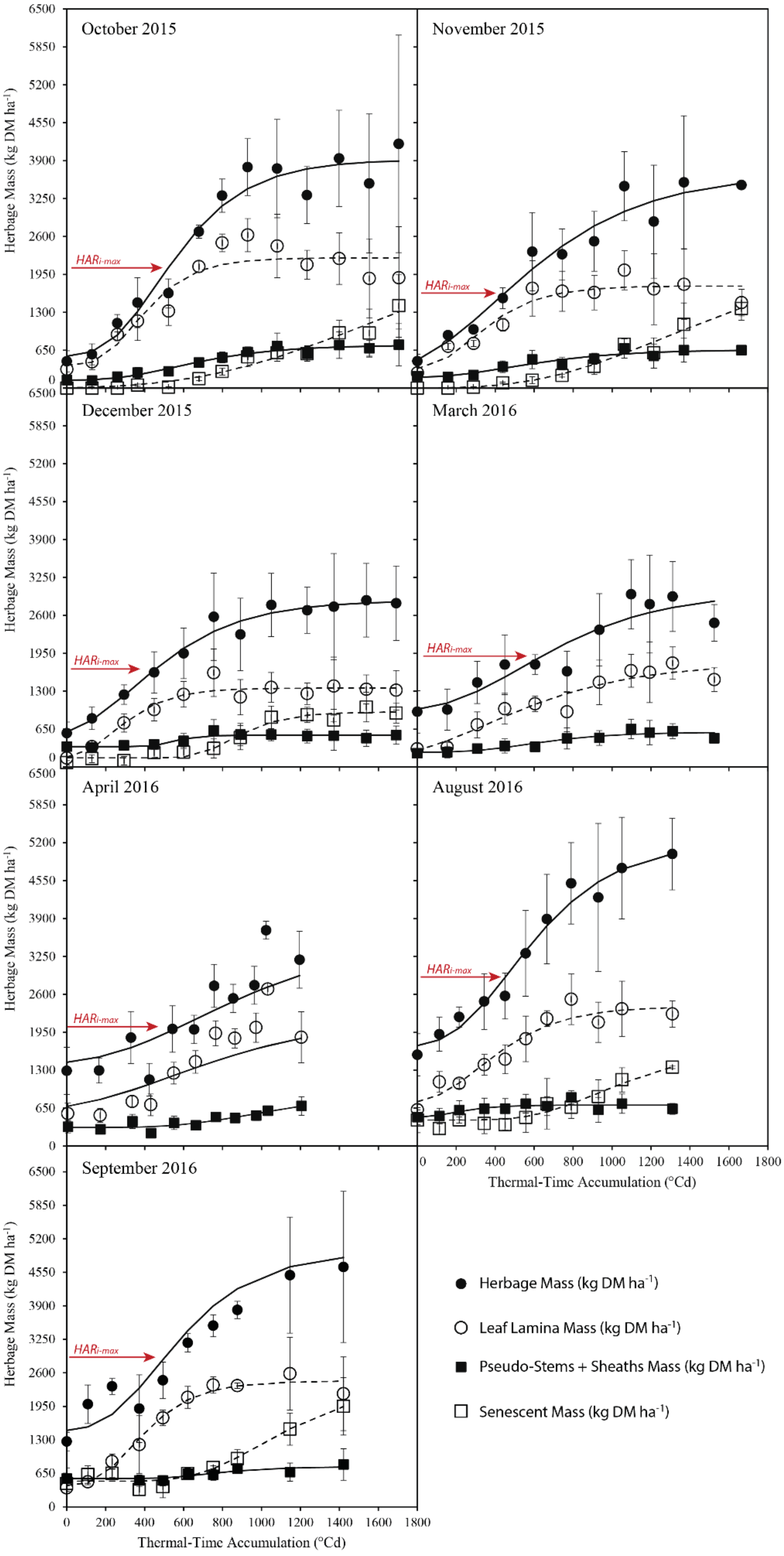
October 2015
November 2015
December 2015
March 2016
April 2016
August 2016
September 2016
HARi-max
Herbage Mass (kg DM ha^{-1})
6500
5850
5200
4550
3900
3250
2600
1950
1300
650
0
Thermal-Time Accumulation (°Cd)
0
200
400
600
800
1000
1200
1400
1600
1800
● Herbage Mass (kg DM ha^{-1})
○ Leaf Lamina Mass (kg DM ha^{-1})
■ Pseudo-Stems + Sheaths Mass (kg DM ha^{-1})
□ Senescent Mass (kg DM ha^{-1})

Fig. 2. Average above ground herbage mass (kg DM ha^{-1}), leaf lamina mass (kg DM ha^{-1}), pseudo-stems + sheath mass (kg DM ha^{-1}) and senescent mass (kg DM ha^{-1}) of *Schedonorus arundinaceus,* for seven initiation dates with fitted Gompertz curves. The bars represent the standard error of the mean for each week. The equations for each curve are presented in table 1.

Table 1. Gompertz equations of herbage mass (H) curves and their coefficients of determination (R^2), equations of the instantaneous herbage accumulation rate (HAR_i), values of the maximum instantaneous herbage accumulation rate ($HAR_{i\text{-}max}$), optimum total herbage mass at $HAR_{i\text{-}max}$, and sward surface height (SSH) at $HAR_{i\text{-}max}$, for all periods evaluated. HM, LLM, PSM and SM represents the total herbage mass, leaf lamina mass (kg DM ha^{-1}), pseudo-stems + sheaths mass (kg DM ha^{-1}) and senescent mass (kg DM ha^{-1}), respectively, of *Schedonorus arundinaceus*.

	Equation H	R^2	Equation HAR_i	$HAR_{i\text{-}max}$‡	Optimal Total Herbage Mass at $HAR_{i\text{-}max}$†	SSH at $HAR_{i\text{-}max}$⁑
	October					
HM	$y=3379e^{6.14e0.0039x}+541$	0.77	$y=0.0039(3379e^{6.14e0.0039x})\ln(1/e^{6.14e0.0039x})$	4.76	2068.19	22.53
LLM	$y=1844e^{7.74e0.0060x}+390.6$	0.72	$y=0.0060(1844e^{7.74e0.0060x})\ln(1/e^{7.74e0.0060x})$	4.05	1311.06	14.07
PSM	$y=601.7e^{6.48e0.0034x}+136.3$	0.72	$y=0.0034(601.7e^{6.48e0.0034x})\ln(1/e^{6.48e0.0034x})$	0.75	2740.98	22.53
SM	$y=3196e^{5.96e0.0011x}+0$	0.82	$y=0.0011(3196e^{5.96e0.0011x})\ln(1/e^{5.96e0.0011x})$	1.31	3873.48	40.99
	November					
HM	$y=3453e^{2.61e-0.0036x}+230.7$	0.78	$y=0.0036(3453e^{2.61e0.0036x})\ln(1/e^{2.61e0.0036x})$	4.28	1482.42	18.00
LLM	$y=1437e^{4.34e0.0052x}+315.9$	0.68	$y=0.0052(1437e^{4.34e0.0052x})\ln(1/e^{4.34e0.0052x})$	2.79	1152.26	12.99
PSM	$y=481.5e^{4.24e0.0031x}+177$	0.66	$y=0.0031(481.5e^{4.24e0.0031x})\ln(1/e^{4.24e0.0031x})$	0.55	1601.67	17.33
SM	$y=2374e^{7.14e0.0015x}-1.83$	0.88	$y=0.0015(2374e^{7.147e0.0015x})\ln(1/e^{7.147e0.0015x})$	1.34	3349.77	35.08
	December					
HM	$y=2359e^{3.13e0.0033x}+498.3$	0.73	$y=0.0033(2359e^{3.13e0.0033x})\ln(1/e^{3.13e0.0033x})$	2.84	1663.19	18.23
LLM	$y=1195e^{4.56e0.0063x}+161$	0.71	$y=0.0063(1195e^{4.56e0.0063x})\ln(1/e^{4.56e0.0063x})$	2.64	1224.00	13.99
PSM	$y=198.9e^{691.2e0.012x}+349.9$	0.35	$y=0.0012(198.9e^{691.2e0.012x})\ln(1/e^{691.2e0.012x})$	0.64	2037.67	22.19
SM	$y=787.2e^{174.2e0.0062x}+161.6$	0.83	$y=0.0062(787.2e^{174.2e0.0062x})\ln(1/e^{174.2e0.0062x})$	1.69	2504.74	27.35
	March					
HM	$y=2059e^{3.85e0.0025x}+948.5$	0.63	$y=0.0025(2059e^{3.85e0.0025x})\ln(1/e^{3.85e0.0025x})$	1.88	1838.22	19.97
LLM	$y=1678e^{2.31e0.0023x}+114.9$	0.73	$y=0.0023(1678e^{2.31e0.0023x})\ln(1/e^{2.31e0.0023x})$	1.44	1297.61	16.68
PSM	$y=341.2e^{8.78e0.0039x}+258.3$	0.54	$y=0.0039(341.2e^{8.78e0.0039x})\ln(1/e^{8.78e0.0039x})$	0.48	1838.22	19.97
SM	-	-	-	-	-	-
	April					
HM	$y=2160e^{3.87e0.0025x}+1392$	0.76	$y=0.0044(2160e^{18.5e0.0044x})\ln(1/e^{18.5e0.0044x})$	1.60	2160.83	25.26
LLM	$y=1637e^{2.87e0.019x}+571.4$	0.84	$y=0.0062(1637e^{31.5e0.0062x})\ln(1/e^{31.5e0.0062x})$	1.20	1322.78	25.51

PSM	$y=608.4e^{11.75e0.0026x}+309.5$	0.63	$y=0.0026(608.4e^{11.75e0.0026x})\ln(1/e^{11.75e0.0026x})$	0.58	3046.38	31.89
SM	-	-	-	-	-	-
	August					
TM	$y=3524e^{4.87e0.0033x}+1696$	0.78	$y=0.0033(3524e^{4.87e0.0033x})\ln(1/e^{4.87e0.0033x})$	4.31	2889.18	23.93
LLM	$y=1676e^{3,87e0.0042x}+727.2$	0.79	$y=0.0042(1676e^{3,87e0.0042x})\ln(1/e^{3,87e0.0042x})$	2.62	2445.19	20.70
PSM	$y=213.2e^{4.08e0.0080x}+489.7$	0.20	$y=0.0080(213.2e^{4.08e0.0080x})\ln(1/e^{4.08e0.0080x})$	0.60	2022.73	17.27
SM	$y=1254e^{16.25e0.003x}+445$	0.71	$y=0.003(1254e^{16.25e0.003x})\ln(1/e^{16.25e0.003x})$	1.30	4741.47	32.42
	September					
TM	$y=3387e^{5.51e0.0036x}+1493$	0.75	$y=0.0036(3387e^{5.51e0.0036x})\ln(1/e^{5.51e0.0036x})$	4.51	2848.02	23.75
LLM	$y=1887e^{6.36e0.0055x}+379.2$	0.83	$y=0.0055(1887e^{6.36e0.0055x})\ln(1/e^{6.36e0.0055x})$	3.78	2522.85	21.30
PSM	$y=212.3e^{33.37e0.0049x}+508.4$	0.21	$y=0.0049(212.3e^{33.37e0.0049x})\ln(1/e^{33.37e0.0049x})$	0.38	3688.89	28.75
SM	$y=463.1e^{20.49e0.0030x}+463.1$	0.81	$y=0.0030(463.1e^{20.49e0.0030x})\ln(1/e^{20.49e0.0030x})$	1.84	4001.36	30.28

‡ $HAR_{i\text{-}max}$ in kg DM ha^{-1} °C^{-1}

† Optimum Total Herbage Mass at $HAR_{i\text{-}max}$ in kg DM ha^{-1}

⁑ SSH at $HAR_{i\text{-}max}$ in cm

5. CHAPTER 3

Resilience in an integrated crop–livestock system under different grazing intensities[4]

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[4] Prepared in accordance with the standards of the Agriculture Ecosystem & Environment

General resilience in an integrated crop–livestock system under different grazing intensities

ABSTRACT

Sustainable intensification of current and future food production demands strategies consistent with ecological principles and concepts in promoting agricultural production, efficiency and resilience. Allied to this, agriculture should be oriented to favor the reduction of undesirable socioeconomic conditions, negative external economic and environmental impacts promoted by climate change. The objective of this study was to assess different agricultural systems based on a traditional integrated crop-livestock system (ICLS) in the southern region of Brazil and a specialized soybean system under the aspect of economic and ecological resilience over a five-year period under the influence of different sources of environmental variation. The study was based on a long-term ICLS trial that has been carried out since 2001, composed of soybean production during summer and grazing in the winter of a mixed pasture of black oat and italian ryegrass, maintained under no-tillage management. Treatments consisted of four sward heights (grazing intensities) 10, 20, 30 and 40 cm (ICLS) plus a control (no-grazing/crop system – NG/CS), in 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017. The experiment was carried out using a randomized complete block design with three replicates. The ecological network analysis was applied to each treatment and year, for the assessment of the resilience of nitrogen (N-R_{flow}) and phosphorus (P-R_{flow}) flows. In an input-output model, we compared the economic resilience ($R_{US\$}$) of the systems facing the same climatic hazards, price volatility and management options, through the 1 – coefficient of variation (CV) of the gross value added (GVA) per hectare and of its components. We show that integrated systems are more economically resilient than specialized cropping systems. If we show that grazing management options could explain differences between ICLS (10 to 40 cm), globally, considering the GVA, there is no difference between ICLS. From the network flows, we find the same conclusion (integrated system more resilient than specialized, no difference between ICLS). The conclusions are the same, considering P or N flows. R_{flow} (N or P) is a good proxy to assess the general resilience of an agroecosystem.

Keywords: Nitrogen flows, Phosphorus flows, Economic analysis, Sustainability, Ecological network analysis

1. Introduction

According to FAO (2014) the production of current and future safe food must be in accordance with the principles of sustainable agriculture in a manner that is environmentally, economically and socially responsible over time. The development of an agriculture focused on sustainable intensification is based on the application of ecological concepts and principles, favoring the diversity and heterogeneity of the landscape, to be productive, efficient and resilient, combined with the reduction of undesirable socioeconomic conditions, economic and environmental impacts promoted by climate changes (Bonaudo et al., 2014; Altieri et al., 2015). In this context, resilience in agriculture is an important factor regarding future prospects, such as food supply for a growing population, instability and climate change, scarce raw materials and economic instability (Altieri et al., 2015; Li, 2011; Fair et al., 2017; Chaudhary et al., 2018).

The concept and application of the term resilience has been widely discussed in the literature. According to Mori (2011), ecological resilience is the most adequate concept and presents better application in the aspect of ecosystem management. Angeler and Allen (2016) discussed definitions and concepts related to resilience and suggested the definition of ecological resilience proposed by Holling (1973) as “a measure of the amount of change needed to change an ecosystem from one set of processes and structures to a different set of processes and structures”, i.e., the ability of a system to absorb an amount of disturbance without changing to a different state. Increasing resilience means promoting ecological adaptation mechanisms in terrestrial ecosystems, in other words, a relationship of interdependence with climatic and management aspects of productive systems (Morecroft et al., 2012; Altieri et al., 2015; Seidl et al., 2016; Briske et al., 2017). It is directly related to the increase of diversity and complexity, coupled with the adoption of agroecological practices, thus promoting a greater participation of compartments in the outflows and ecosystem services (Briske et al., 2008; Heller and Zavaleta, 2009; Duru et al., 2015; Stark et al., 2016). Integrated crop-livestock systems (ICLS) according to Stark et al. (2018) appear as effective production systems to promote the improvement of resilience. This is, in large part, due to the use of practices that improve physical, chemical and biological quality of the soil, nutrient recycling, increased diversity of functional groups of plants, diversity of the production system, regulation of pests and diseases, among others (Morecroft et al., 2012; Altieri et al., 2015; Rapidel et al., 2015; Garrett et al., 2017; Migliorini and Wezel, 2017). In this way, understanding the dynamics of resilience is fundamental to achieving sustainable human interactions with their ecosystems of support (Mori, 2011; Angeler and Allen, 2016,).

Stark et al. (2018) used Ecological Network Analysis (ENA) to assess the interest of crop-livestock integration at the farm level. ENA is a methodology oriented to analyze the ecological interactions within the ecosystems, used to identify holistic properties through the network of flows (Fath et al., 2007). They assessed the resilience through the concept of ascendancy proposed by Ulanowicz et al. (2009), modeling the nitrogen fluxes in agroecosystems of humid tropics, from the annual operation of farms. They suggested that resilience studies in agricultural systems should address, for a better understanding, the interannual effect of environmental factors, peculiarly to test the theoretical indicator of resilience calculated at a given time from the network analysis. Angeler and Allen (2016) and

Seidl et al. (2016) argued about the importance of using multiple approaches to resilience measures (within the ecological and socioeconomic context) in the studies, because it is thus possible to have a broader understanding of the general resilience of ecosystems.

The first hypothesis of this study is that agricultural systems that seek to increase the diversity of production, will promote greater general resilience over time compared with more specialized systems. The second hypothesis is that, for a system combining a given range of productions, the management practices have an impact on the resilience. The objective was to assess different agricultural production systems based on the traditional ICLS of the southern region of Brazil and soybean monoculture under the aspect of resilience in the economic and agronomic context, in five years under the influence of different sources of environmental variations.

2. Materials and methods

2.1 Area Study

This study used data from a long-term ICLS trial that has been carried out since 2001 in Rio Grande do Sul state, Southern Brazil (28°56’14.00”S, 54°20’45.61”W). The soil is a clayey oxisol (Rhodic Hapludox, Soil Survey Staff, 1999), with 540, 270 and 190 g kg^{-1} of clay, silt and sand, respectively. The region has a subtropical humid climate (Cfa) according to Köppen’s classification. From 2009 to 2018, the average maximum monthly temperatures were between 16 °C and 33 °C and the average minimum monthly temperatures were between 6 °C and 21 °C (Fig. 1). Average temperatures presented the same pattern over time. For the monthly rainfall, there were more important variations between the years. In the summer/autumn of 2011/2012, there was a marked decrease in the amount of monthly rainfall compared to the historical monthly average of the region. In the first half of 2011, 2015 and 2016 and in the second half of 2009, 2012, 2014 and 2015 there were periods in which the rainfall was above normal.

For the economic conditions, there were large variations in the sale prices of the products (soybean grains and live animals) and in the purchase prices of the inputs (fertilizers, seeds, herbicide and live animals) for the period between 2009 and 2017 (Fig. 1).

The variables described above were considered as sources of variation of the external environment, both climatic and economic, influencing the performance of the studied system.

2.2 Treatments and Experimental Design

The experimental area was managed under no-tillage soybean (*Glycine max*) production in the summer and black oat (*Avena strigosa*) cover crop in the winter since 1993. From May 2001 on, the no-tillage ICLS was adopted, with soybean production during summer and grazing of mixed black oat and italian ryegrass (*Lolium multiflorum*) pasture during winter.

The experiment was carried out using a randomized complete block design with three replicates with experimental units ranging from 0.8 to 3.2 ha. Treatments consisted of four sward heights (or grazing intensities) 10 (ICLS10), 20 (ICLS20), 30 (ICLS30) and 40 cm (ICLS40); plus a control non-grazed treatment (no grazing/crop system – NG/CS) representing the soybean monocropping – winter cover crop system.

In this study the production years of 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017, were evaluated. In the 2009/2010, 90 kg ha^{-1} of N were applied in winter pasture phase and 60 kg ha^{-1} of P_2O_5 and K_2O in the soybean. In 2011/2012, 90 kg ha^{-1} of N were applied in winter pasture and 60 kg ha^{-1} of P_2O_5 and K_2O in the soybean, however, in the period between November and June there was a drought that affected soybean production. In 2014/2015, 140, 60 and 90 kg ha^{-1} of N, P_2O_5 and K_2O were applied, respectively, in the pasture winter phase. In 2015/2016, only 90 kg of N were applied in the winter pasture phase. In

2016/2017, 115.5, 60 and 90 kg ha^{-1} of N, P_2O_5 and K_2O were applied, respectively, in winter pasture phase (Fig. 1). The fertilizers used were in the form of urea, triple superphosphate and potassium chloride, the first one applied in cover at two moments (30 and 60 days after sowing) and the last two together with sowing of the soybean or black oat.

Basic experimental protocol was carried out uniformly every year. Black oat was seeded in May at a 45 kg ha^{-1} seeding rate, in rows spaced 17 cm apart, and Italian ryegrass was established by natural reseeding. In November the area was desiccated (glyphosate + chlorimuron-ethyl or saflufenacil) and between November and December soybean was seeded in rows spaced 45 cm apart at a 45 seeds m^{-2} density. Soybean seed inoculation with rhizobium and agronomic management was performed according to the technical recommendations for the crop, and the soybean harvest occurred in April.

The stocking period occurred between July and November of each year and grazing began when herbage mass reached 1500 kg ha^{-1} of DM. The experimetnal animals were cross-bred Angus x Hereford x Nelore castrated steers with approximately 10 months of age and average initial body weight of 210 kg. Each grazed paddock received three tester animals and a variable number of 'put-and-take' animals (Mott and Lucas, 1952) in order to periodically adjust the stocking rate and maintain the sward heights as close as possible to the target.

2.3 Measurements

The monitoring of sward heights was done every 15 days, evaluating 100 points per paddock using a sward stick (Barthram, 1985). For the determination of the total herbage accumulation, we performed the evaluation of the daily herbage accumulation rate and the determination of the herbage mass at the beginning of the stocking period. The latter was estimated in each paddock by the double sampling technique (Wilm et al., 1944). For this purpose, five samples of 0.25 m^2 were determined by clipping above litter level at random locations and oven dried at 50 °C until reaching constant weight. For the correction of the herbage mass at paddock level, a calibration equation was generated by the linear regression between the herbage mass of the samples and the sward height measured at five points per sample. This equation was then applied to the average paddock sward height to determine the initial herbage mass. Herbage accumulation rates were determined every 28 days using three exclosure cages per experimental unit (Klingman et al., 1943). Total herbage accumulation was calculated by the product between the daily herbage accumulation rates of all the periods and the number of days in the corresponding period, added to the initial herbage mass at the beginning of the stocking period.

For the evaluation of animal performance, steers were weighed at the beginning and at the end of the stocking period after 12-hour feed and water restriction. Average daily gain was calculated by the division between the total live weight gain of the tester animals and the number of days in the stocking period. To evaluate the productive outputs of the system, we calculated the live animal production (LAP - kg ha^{-1} $year^{-1}$) as the sum of the live weights of the testers and the 'put-and-take' animals of each paddock at the end of the stocking period.

At the end of the stocking period, pasture litter was sampled using the same methodology described for the herbage mass determination. All pasture assessments were also performed to NG treatment. Soybean grain yield (SGY - kg ha^{-1} $year^{-1}$) was determined at R8 stage (harvest maturity), by sampling five random points of 4.5 m^2 per paddock. The samples were threshed, cleaned, weighed and the grain moisture was determined and adjusted to 13%.

2.4 System conceptualization

A conceptual model of the systems was developed with the purpose of determining all compartments and the biomass and mineral flows between them and with the external environment (Fath et al., 2007; Rufino et al., 2009). For the ICLS, the model was composed of five compartments, Soil, Annual Winter Pasture, Summer Crop, Air and Animal. For NG, model was composed of four compartments Soil, Winter Cover, Summer Crop and Air. The Air compartment corresponds to the source for atmospheric N uptake by bacteria in the process of symbiosis via biological N-fixation flow (Fig. 2).

The inflows (from the environment) correspond to the flows of mineral fertilizers and seeds towards the soil compartment; and the flows of purchased live animals and mineral salt towards the animal compartment. The productive outflows (for the environment) correspond to animal products (live animal production) and crop products (soybean grain yield). The non-productive outflows (for the environment) correspond to flows as potential sources of system pollution and / or losses (emissions from animal wastes and mineral fertilizers such as leaching and volatilization), soil nutrient unavailability and flows that participate in the processes of organic accumulation and mineralization. In this study we did not distinguish the flow of losses and the accumulation of nutrients in the soil, because we understand that this is a process of complex nature, difficult to quantify and involves the dynamics of nutrients in the soil, under biotic and abiotic effects (Jarvis et al., 1996, Oenema, 2006; Lemaire et al., 2014) and of each production system tested.

The assessed models were not considered at steady state and therefore an inflow was added to the system (from the environment) to characterize the supply of minerals “stored” in the soil. In this way, the soil compartment within the system is composed of the elements readily available for the uptake flow towards the compartments winter pasture and summer crop.

From this generic model, all network flows, corresponding to the five treatments, three repetitions and five years, i.e. 75 networks, were quantified, using data from the experiment, data from scientific literature and calculations performed in spreadsheets

The uptake flows of the Summer crop compartment were calculated by the difference between estimated values of the biological nitrogen fixation (Hungria et al., 2005) and soybean total nutrient requirement (Malavolta et al., 1997; Hungria et al., 2005) as a function of soybean grain yield. Residues and senescent flows from Summer crop compartment to the Soil compartment were considered as the total amount of above ground soybean biomass, calculated by harvest index (Spaeth et al., 1983; Assmann et al., 2014).

The senescence flow of winter pasture was calculated as the difference between herbage mass, pasture residue and herbage intake by the animals (Souza Filho, 2017). The flow of mineral salt was calculated as the difference between the outflow and inflows of animal, herbage intake and animal excreta flows. The latter was calculated as the difference between the amount of nutrient exported by the animals and the flow of herbage intake by the animals.

The non-productive outflows are the result of the sum of losses by volatilization when applying fertilizers or depositing excreta and from leaching or storage of elements in the soil, in soil organic matter. In 2015/2016 there was no inflow of phosphate fertilizer (Fig. 1), thus resulting in the negative balance of the system. This means that the flow of phosphorus uptake in the Winter pasture and Summer crop compartments is a result of the use of the stock of the nutrient in the soil.

2.5 Data analysis

2.5.1 Resilience assessment through an input-output perspective

Two indicators are used for crop and livestock production: the soybean yield (SGY) for crop system and the live animal production (LAP) for the livestock system.

In an input-output perspective, we compare the economic resilience ($R_{US\$}$) of the systems facing the same climatic hazards, price volatility and management options, through the variability of the Gross Value Added (GVA) per hectare and of its components. GVA is the difference between the Gross Production Value (GPV) and the Intermediate Consumption Value (ICV). GPV was calculated by multiplying the quantity of product units (kg of soybean grain or kg of live steers) by the average price of one product unit. The price paid to the farmers in Rio Grande do Sul state, in May for soybean (CONAB, 2018d) and in November for live steers (CEPEA 2018a) are considered.

ICV was calculated as the sum of the costs of seeds (CONAB, 2018c), fertilizers (CONAB, 2018a), herbicide (CONAB, 2018b), steers (CEPEA, 2018a), mineral salt and veterinary products, for each year evaluated (Fig. 1).

The cost of each intermediate consumption component was the result of the multiplication between the amount of that component used in the experiment and the average value of the product paid by the farmers in the state of Rio Grande do Sul, Brazil. The mineral salt costs were obtained by multiplying the P flow via mineral salt and the value of the average price of the kg of nutrient of the triple superphosphate provided by CONAB (2018a). Costs with veterinary products were calculated as the product between the number of animals and the average cost per animal provided by CEPEA (2018b). No data are available to appreciate the quantity of energy used to carry out the cropping operations. As they are the same for all treatments for a given year, the comparison of the cost values was not biased; we systematically made the same under-estimation of cost values, for a given year. Nevertheless, between years, the energy cost could vary, due to the price volatility and the differences of operation between years. In that way, the inter-annual variation of ICV was underestimated. All values were obtained in Brazilian national currency (R$) referring to domestic market prices for each year studied, and subsequently converted to constant R$ prices, using the General Price Index (average of the cities of Brazil and all items, of the Getúlio Vargas Foundation). To obtain the dollar values (US$), the average long-term conversion was made using the current exchange rates between R$ and US$ (BACEN, 2018).

$R_{US\$}$ is calculated from $R_{US\$} = 1 - CV$, with CV, the coefficient of variation being the ratio between the standard deviation and the average of the variable GVA for the five years of the treatments. $R_{US\$}$ can range from -∞ to 1. Values close to 1 represent that the systems have high capacity to absorb the impacts of external economic factors.

2.5.2 Resilience assessment through an ascendency perspective

The resilience of a system is its adaptive capacity to face hazards or disturbances (Darnhofer et al., 2010). The ascendency should be a dimension of the resilience of a system. It can be assimilated with the effective activity of a system and can be defined as the capacity of a system to grow and develop depending on its capacity to exercise efficient activity uses, while simultaneously keeping a reserve of flexible pathways to adapt uncertainties (Ulanowicz et al., 2009). The ascendency is calculated as the ratio of the overhead and the development capacity.

For the ascendency calculation, all flows were converted in terms of N and P per year, expressed in kg ha^{-1} (Appendix A - Supplementary Data). The choice of the N and P flux resilience for the study was due to the great importance of the cycle of these elements within the context of sustainability in agricultural systems (Galloway et al., 2008; Bouwman et al., 2013; Fowler et al., 2013; Cordell and White, 2014). According to Stark et al., (2018) (from Ulanowicz et al., 2009), the resilience of nutrient flows (R_{flow}) in the system was calculated as the ratio between overhead (Φ – equation 1) and development capacity (C - equation 2).

Φ represents the actual reserve capacity of the system formed by the network of flows and C is the maximum potential capacity of the system for all flows that can be achieved. This relationship demonstrates the ability of a system to absorb variations imposed by the external environment of the system.

$$\Phi = -\sum_{i.j} T_{ij} \log\left(T_{ij}^2 / T_{i.}\, T_{.j}\right) \qquad (1)$$

$$C = -\sum_{i.j} T_{ij} \log\left(T_{ij} / T_{..}\right) \qquad (2)$$

where, $T_{i.}$ is the total inflow for compartment i; $T_{.j}$ is the total outflow for compartment j; and T_{ij} is the flux between the compartments i and j.

For R_{flow} calculations, values range from 0 to 1. Value close to 1 mean that the system requires a substantial amount of energy for the transition to an alternative state, i.e., greater ability to adapt to the effects of the environment.

2.5.3 Statistical analysis

To perform the ENA analysis for ascendency calculation, N and P flows matrices were built from the 75 networks obtained by combining all treatments and years, using spreadsheets, and the indicators Φ and C were calculated using the software R (R Development Core Team, 2016). Input and output data were processed and calculated using spreadsheets. Data were submitted to analysis of variance (ANOVA) according to the model $R_{ij} = \mu + B_i + T_j + \varepsilon$. The R_{ij} represents the average of flows and economic resilience of the five years, μ the overall experimental average, B_i the blocks, T_j the treatments effect and ε the experimental error.

When significant ($p < 0.05$), the means were compared using the Tukey test, at a significance level of 5%. The data set was analyzed using the software R.

3. Results and Discussion

Under production aspects, soybean production (SGY) was much more sensitive when facing climatic hazards and management variations, with a 49 to 53% CV, regardless of the treatment. Animal production (LAP) was more stable, with a CVs ranging from 8% (ICLS40) to 23% (ICLS10) (Table 1). Indeed, the animal production carried on corresponded to a short time of the process of beef cattle production, with only a period of a few months of the growth of young animals, during winter. Compared with all the processes of production of soybean, from germination to maturation of grains, during summer, this single animal growing process is less sensitive to climatic hazards. Growing animals presents some abilities, such as the classic process of compensatory growth, to cope with forage shortage, so this animal production exhibits some adaptive capacities to cope with a climatic hazards. Furthermore, the main climatic hazard observed was a drought during summer (year 2011/2012), so the forage production in winter, on which animal feeding depended entirely, was less exposed to the risk. The production of the forage biomass was not as impacted as that of the soybean. The biomass production of pasture was on average 6000 kg versus on average 600 kg for soybeans, representing only 10% of soybean biomass in the year 2011/2012 compared with other years. With a low animal density, the ICLS40 option is the system which presents the lowest CV and seems to have the least sensitivity to management for animal growth. Indeed, as the grazing density is the lowest, the animal – vegetation system exhibited here a buffering capacity, to cope with hazards. The availability of biomass was higher for each animal in the paddock in the ICLS40 management and enables animals to acquire an adequate daily diet. This effect of lower animal density has already been shown by Lurette et al. (2013) for dairy farms.

When considering the system input (ICV_S), under context of volatility of prices and management variations, for ICLS10, ICLS20 and ICLS30 the CV (ICV_S) was about 38%. They are the management that are the most dependent on purchases. For NG/CS, CV (ICV_S) is 33 %, with only one activity, the system was less dependent, i.e., mean of ICV_S of 470 US\$ ha^{-1} against 1800 to 3000 for 30 to 10 cm. This effect is explained largely by the system input of livestock (ICV_L), associated with animal density, since the average system input for soybean (ICV_C) is the same in all treatments. For ICLS40, the ICV_L was on average 799 US\$ ha^{-1} (treatment with lower density of animals) compared with averages ranging from 1373 to 2512 US\$ ha^{-1} for systems with higher density of animals. The ICLS40 is the more stable management, with a CV (ICV_S) of 27% (Table 1). With a balance between animal and soybean (in term of ICV_S), the integrated system is more stable, facing price volatility, than the crop Soybean specialized system.

Considering the gross production value of system (GPV_S), facing climatic, management and price variations represented by the several treatments, NG/CS (soybean specialized) is very sensitive, with a CV (GPV_S) of 47 %, having the same level of variation as yield. The ICLS20, ICLS30 and ICLS40 managements are the most stable, with CV (GPV_S) of 22, 25 and 23%, respectively. The interest of mixing two activities (crop and livestock), one rather sensitive (soybean), and the other more stable (livestock) is therefore highlighted. ICLS10 is intermediate, with a CV (GPV_S) of 30 %. When there are many animals in ICLS, the sensitivity to context variation of the ICLS is higher. Thus, for 10 cm the CV of the gross production value of livestock (GPV_L) was 30%, compared with 26, 27 and 24% for 20, 30 and 40 cm, respectively (Table 1).

For the gross value added of the system (GVA_S), facing all hazards and variations, NG/CS was most sensitive, with CV of 88%. For the ICLS, CV ranged from 39 to 45%. Finally, if there are various behaviours of the four ICLS systems for the several components of the GVA, they did not differ when considering the $Ꝛ_{US\$}$, given by 1 – CV of GAV_S. Combining crop and livestock activities within a farming system allowed lower sensitivity than what was observed in the specialised system. It results in more resilient ICLS (i.e. exhibiting higher values of $Ꝛ_{US\$}$) compared with NG/CS ($p < 0.01$) (Fig. 3).

$Ꝛ_{US\$}$ is a very interesting indicator because it addresses very different environmental factors, under complex and dynamic processes (local and global), which are within the scope of social, economic, political, agricultural and climatic scales (Fair et al., 2017), thus allowing for more consistent results for the understanding of agricultural resilience. Moreover, the economic approach of the productive system is usually the main point of interest of the farmer.

This analysis confirms the relevance of combining two productive activities in a farming system to improve its global resilience. When an activity faces hazards, the other activity might not be affected. Indeed, the second activity could be less exposed to the risk or less sensitive to the risk than the first one. We saw here that the animal operation was less sensitive to climatic hazards with more stable outputs over time than the soybean production. We could also consider that the integration of livestock with cropping was a good way to improve resilience. For instance, there was no purchase of feed for the animal, except for mineral salt. The animal production was based on the biomass production of the system, produced on the same area of land as soybean. This enabled decreasing the dependency of the animal operation on external inputs, which was in consequence less exposed to price volatility. Nevertheless, the animal production was highly dependent because of the purchase of animals to be raised; but, even with that exposure to external price volatility, the ICLS systems were more resilient than the soybean production. Those results show that there is not a direct link between the level of dependency, evaluated through the economic value of the intermediate consumptions, and the level of resilience.

In the resilience through ascendancy perspective (R_{flow}), facing climatic, management and input variations, there was a significant difference between ICLS (whatever the animal density) and NG/CS for N-R_{flow} ($p < 0.001$) and P-R_{flow} ($p < 0.001$). N-R_{flow} and P-R_{flow} presented similar results, i.e., N-R_{flow} and P-R_{flow} in the integrated systems was higher compared with the specialized crop system (Fig. 4 and 5). The N-R_{flow} in ICLS averaged 0.51 and in NG it averaged 0.45 (Fig. 4). The P-R_{flow} in ICLS averaged 0.56 against 0.49 for NG.

Stark et al. (2018) analyzing different productive systems, verified that the N-R_{flow} is linked to the diversity of flows of the system, thus providing, adaptive capacity to the system as alternative ways to the flows.

Thus, in the ICLS, the animal compartment acts as a promoter of the nutrient cycling through manure and urine, since small a amount of the nutrient intake during the grazing phase is exported out of the system (Sneessens et al., 2016). In addition, under grazing, there is an increase in availability as well as a gradual release of nutrients over time, and greater soil exploration by pastures, contributing to a greater recycling of nutrients (Assmann et al., 2015; Deiss et al., 2016; Assmann et al., 2017). This, in turn, promotes a more homogeneous distribution of flows between all compartments within the system. Martins et al. (2016) demonstrated that under ICLS soil acidification decreased in the long-term due to lower amounts of non-productive losses of calcium (Ca) and magnesium (Mg) and nutrient recycling, resulting in higher pH values and lower levels of aluminium (Al) saturation, suggesting that the presence of grazing animals promotes chemical resilience in agricultural soils.

According to Ulanowicz et al. (2009) a resilient system must have sufficient effective activity to maintain its integrity over time and have a pool of flexible actions that can be used to meet the demands of new disturbances.

Probably the statistical equality between the grazing intensity treatments (Figures 3, 4 and 5) is due to the large amounts of inflows (purchase of animals, fertilizers and seeds) and low density of "perennial" compartments in the system. Therefore, any effect of grazing management was of relatively short duration in the whole production system. This promotes a dissolution of the effects caused by grazing intensities.

Management strategies based on the improvement of ecological processes and functional characteristics are an interesting way to promote resilience, because under changes of disturbance regimes there is preservation of the functioning of the system, thus promoting less impact on the response variables (Altieri et al., 2015; Seidl et al., 2016).

Even under very different sources of environmental variation over the years - as changes in the quantities and moments of N and P applications, drought periods, rainfall above normal, natural oscillation of the region's climatic factors and variation in the prices of intermediate consumption values and of gross production value components (Fig. 1) - the results were consistent for the three calculated resilience indicators ($R_{US\$}$, N-$R_{flow}$, P-$R_{flow}$) tackled for economic, technical and environmental aspects. Thus, this study addressed a more realistic context of global agricultural resilience. The results suggest that regardless of the approach (ecological or socioeconomic), the indicators when measured individually, express an adequate analysis of general resilience. This can also be observed for the N-R_{flow} and P-R_{flow} under the temporal context (data not shown in the study). Similar responses are observed under the annual and multiyear analysis, i.e., higher values of R_{flow} (N and P) for integrated system in relation to specialised crop system in each year. Thus, the ascendency perspective, appraising R_{flow} (N and P) at a given time, is a good way to compare the global resilience of various agroecosystems. It could be used for instance in an *ex ante* evaluation of systems, to design more resilient innovative farming systems. We could consider that the appreciation of resilience through the analysis of the flow networks gives a good evaluation of the interest of diversity of activities and of their integration, even in an economic dimension, in order to cope with price volatility. Nevertheless, this statement is based only on the comparison of two systems, a specialized crop system and an integrated crop-livestock system. To generalize those first results, it would be relevant to compare a broader diversity of farming systems, with more complex animal production operations, with reproductive females, and more diversified cropping systems. According to Seidl (2014) under the scenario of high global uncertainties, the implementation of resilience in agroecosystems is a more robust strategy than anticipating and mitigating risks, because those risks are for the most part poorly understood and are unpredictable. Increasing resilience means making systems more capable of absorbing disturbances (Heller and Zavaleta, 2009; Poiani et al., 2011), an important issue especially from the perspective of climate change.

4. Conclusion

Based on results obtained from an input-output analysis (technical and economic perspectives) and the inter-annual variations of GVA components as a way to assess economic resilience: integrated systems are more resilient than specialized crop systems (first hypothesis). If grazing management options could explain differences between ICLS (10 to 40 cm), globally, considering the GAV, there is no difference between ICLS (the hypothesis that management practices have an impact on resilience was only partially validated)

In an ascendancy perspective to assess the resilience, from the network flows, the same conclusion emerges (integrated system more resilient than specialized, no difference between ICLS). The conclusions are the same, considering P or N flows. $Ꝛ_{flow}$ (N or P) is a good proxy to assess the general resilience of an agroecosystem.

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Appendix A. Supplementary data

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Tables and Figures

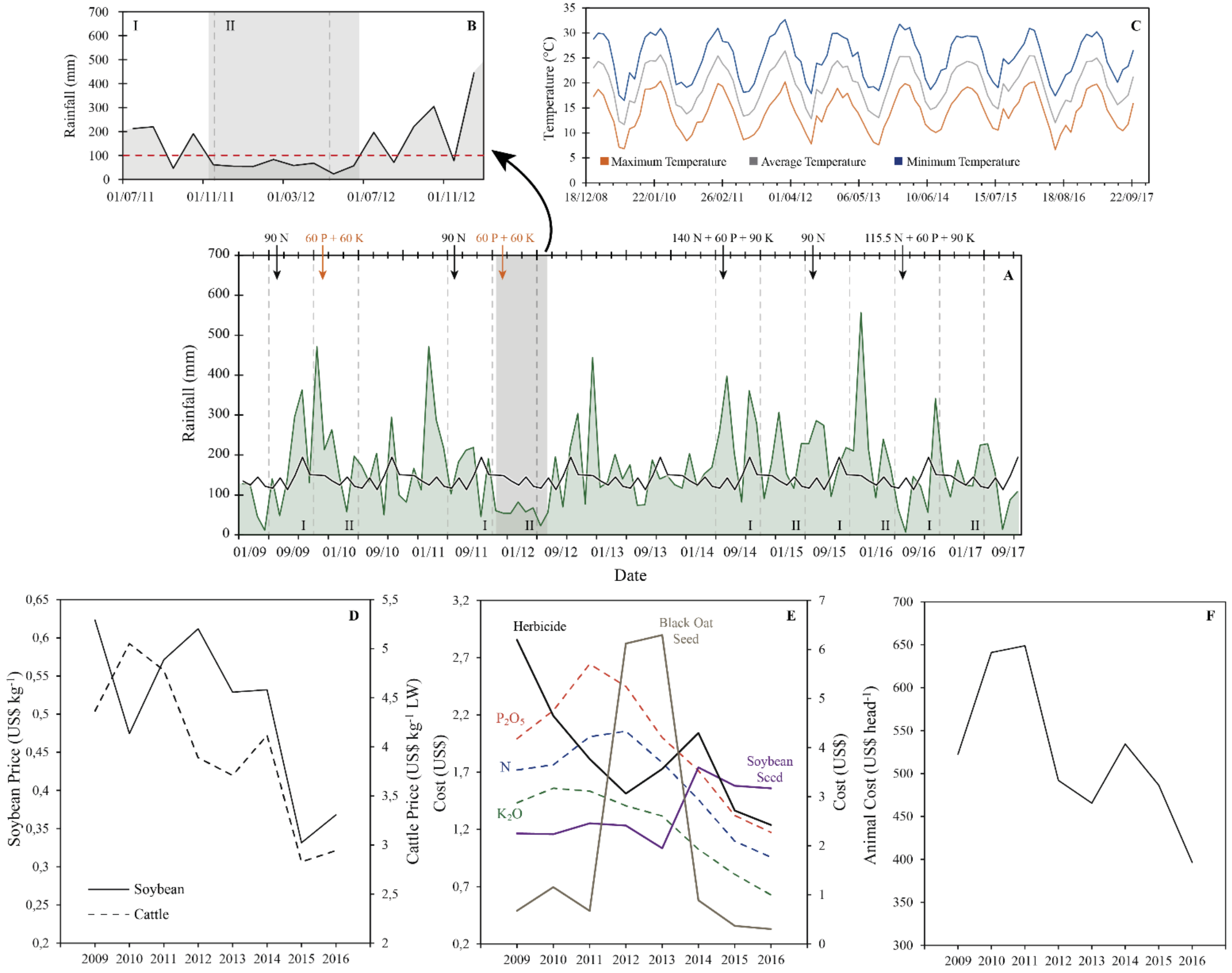

Fig 1. The central f graphic (*A*) shows the cumulative monthly rainfall (mm) from January 2009 to September 2017 (green line) and the average cumulative monthly average of the last 56 years (black line). The gray dashed lines delimit the period of cultivation of the winter pasture (I) and soybean (II) and the evaluated periods. The arrows at the top of figure *A* demonstrate the amounts of fertilization N, P_2O_5 and K_2O in kg ha^{-1} applied to winter pasture (black) and soybean (orange). The drought period between November 2011 and June 2012 is represented by the gray bands in figures *A* and *B*. Figure *C* shows the average monthly temperatures (°C) between 2009 and 2017. Rainfall and temperature data were provided by INMET (2018). Graph D shows the average prices of soybeans (US$ kg^{-1} of grains) and animals (US$ kg^{-1} of live weight) paid to the farmer at the time of sale, in relation to the years. Graph E shows the prices of nitrogen (US$ kg^{-1} of N), phosphorus (US$ kg^{-1} of P_2O_5), potassium (US$ kg^{-1} of K_2O), soybean seeds (US$ kg^{-1} of seed), oat seeds (US$ kg^{-1} of seed) and herbicides (US$ 100 g^{-1} of active ingredient) paid by the farmer in relation to the years. Graph F shows the cost of the animals (US$ $head^{-1}$) paid by the farmers, in relation to the years. The price of the products data were provided by CONAB and CEPEA.

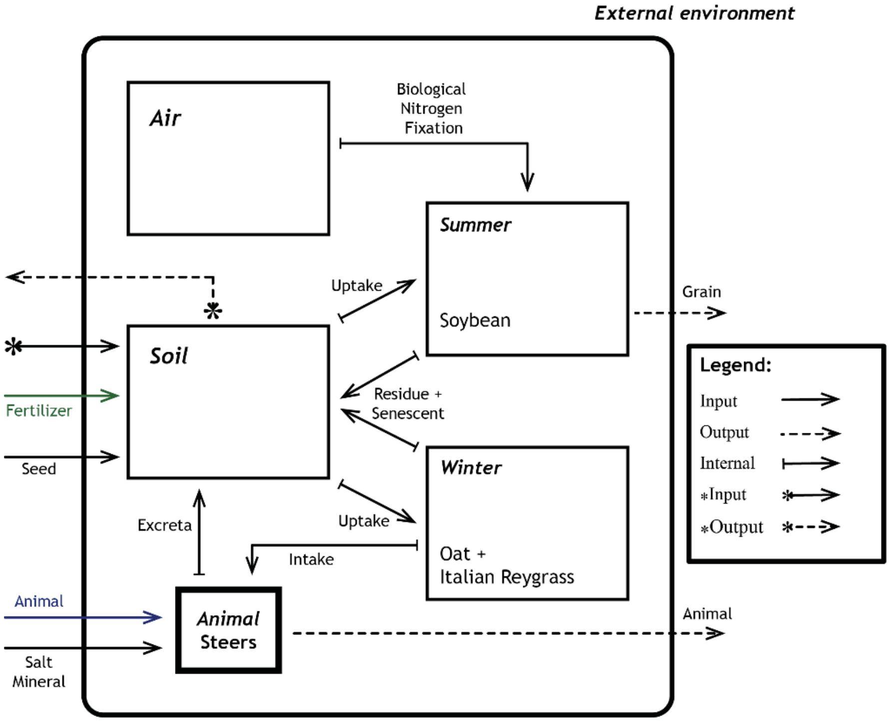

Fig 2. Conceptual model proposed for the ENA analysis applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The variation factors of the systems (treatments) are represented by the blue and green colorations, which represent the animal stocking (heights of pasture management) and different fertilization strategies in the years, respectively. The larger rectangle represents the boundary between the system and the external environment. The rectangles within the systems represent the compartments air, soil, animals, summer crop (soybean) and winter pasture (oat + italian ryegrass).

Input represents the inflow from the external environment to the system. *Output* represents the productive outflows from the system to external environment. *Internal* represents the flows between the compartments within the system. ∗*Input* represents the inflows of supply of minerals “stored” in the soil (nutrients unavailable) to the soil of the system (nutrients available). ∗*Output* represents non-productive outflows from the system to the external environment.

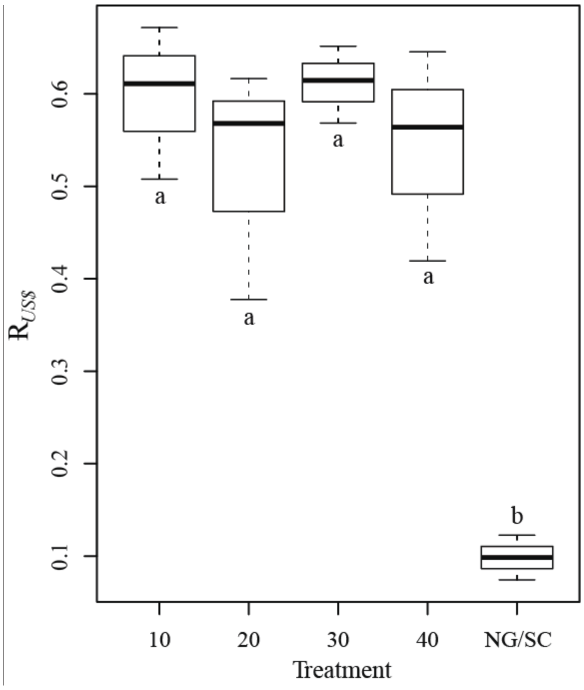

Fig. 3. Economic resilience ($R_{US\$}$) in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). Same lowercase letters represents a no significant difference between the treatments (Tukey test, $p < 0.01$). For each treatment, horizontal bold lines indicate the median values, boxes include the central 50% of the distribution, and vertical dashed lines the central 95% of the distribution. p-value = 0.015.

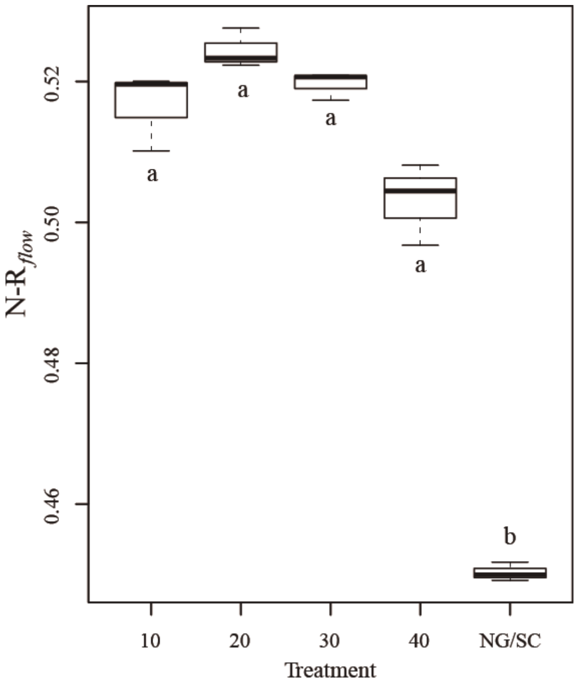

Fig. 4. Nitrogen resilience (N-R_{flow}) in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). Same lowercase letters represents a no significant difference between the treatments (Tukey test, $p < 0.05$). For each treatment, horizontal lines indicate the median values, boxes include the central 50% of the distribution, and vertical dashed lines the central 95% of the distribution. *p*-value = 0.0004.

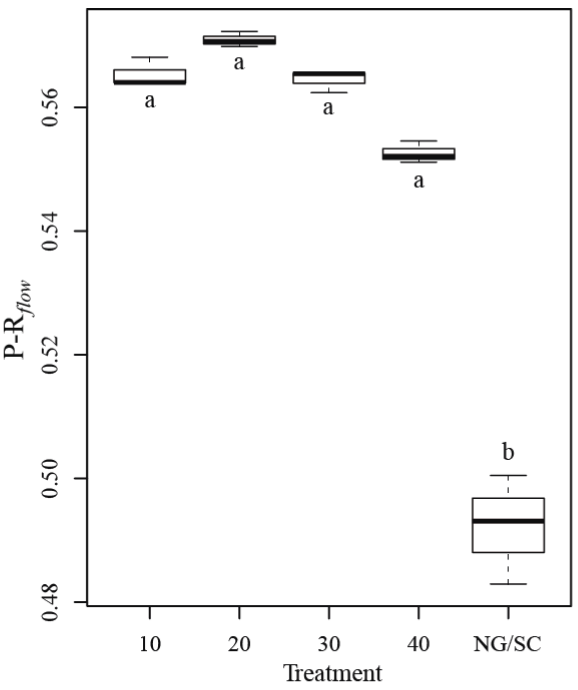

Fig. 5. Phosphorus resilience (P-R_{flow}) in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). Same lowercase letters represents a no significant difference between the treatments (Tukey test, $p < 0.05$). For each treatment, horizontal lines indicate the median values, boxes include the central 50% of the distribution, and vertical dashed lines the central 95% of the distribution. p-value = 0.0004.

Table 1 Soybean grain yield (SGY), gross production value of crop (GPV_C), intermediate consumption value of crop (ICV_C) live animal production (LAP), gross production value of livestock (GPV_L), intermediate consumption of livestock (ICV_L), gross production value of system (GPV_S), intermediate consumption value of system (ICV_S), gross added value of system (GVA_S) and economic resilience ($R_{US\$}$) as a function integrated crop-livestock system (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS), in five years different.

	Years					μ^a	σ^b	CV^c (%)	$R_{US\$}^d$
	2009/2010	2011/2012	2014/2015	2015/2016	2016/2017				
			ICLS10^e						0.60
SGY (kg ha^{-1})	3266	227	3673	3129	3931	2845	1498	0.53	
LAP (kg ha^{-1})	1772	1089	1542	1355	2003	1552	355	0.23	
GPV_S (US$ ha^{-1})	8030	4447	8148	4294	6158	6216	1861	0.30	
GPV_C (US$ ha^{-1})	1519	139	1333	1148	1204	1069	539	0.50	
GPV_L (US$ ha^{-1})	6511	4308	6815	3146	4954	5147	1532	0.30	
ICV_S (US$ ha^{-1})	4848	2683	2946	1768	2670	2983	1134	0.38	
ICV_C (US$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV_L (US$ ha^{-1})	4304	2096	2348	1522	2295	2513	1053	0.42	
GVA_S (US$ ha^{-1})	3182	1764	5203	2527	3488	3233	1285	0.40	
			ICLS20^e						0.55
SGY (kg ha^{-1})	3303	300	3650	3697	4123	3014	1545	0.51	
LAP (kg ha^{-1})	1212	1177	1114	991	1287	1156	112	0.10	
GPV_S (US$ ha^{-1})	5437	3775	5962	3524	4597	4659	1046	0.22	
GPV_C (US$ ha^{-1})	1537	184	1325	1356	1262	1133	540	0.48	
GPV_L (US$ ha^{-1})	3900	3592	4637	2168	3334	3526	903	0.26	
ICV_S (US$ ha^{-1})	3503	2859	2166	1291	1828	2329	868	0.37	
ICV_C (US$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV_L (US$ ha^{-1})	2958	2271	1568	1046	1452	1859	756	0.41	
GVA_S (US$ ha^{-1})	1934	916	3795	2233	2768.58	2329	1061	0.45	
			ICLS30^e						0.61
SGY (kg ha^{-1})	3494	257	3678	3266	4284	2996	1577	0.53	

LAP (kg ha^{-1})	1015	724	926	799	896	873	114	0.13	
GPV$_{S}$ (US\$ ha^{-1})	4666	2922	5020	2939	3631	3835	971	0.25	
GPV$_{C}$ (US\$ ha^{-1})	1626	158	1335	1198	1312	1126	564	0.50	
GPV$_{L}$ (US\$ ha^{-1})	3041	2765	3684	1741	2319	2710	734	0.27	
ICV$_{S}$ (US\$ ha^{-1})	2921	1889	1886	1124	1397	1843	686	0.37	
ICV$_{C}$ (US\$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV$_{L}$ (US\$ ha^{-1})	2376	1301	1288	879	1021	1373	589	0.43	
GVA$_{S}$ (US\$ ha^{-1})	1746	1034	3133	1815	2234	1992	770	0.39	
			ICLS40^{e}						0.58
SGY (kg ha^{-1})	3567	339	3928	3652	4330	3163	1607	0.51	
LAP (kg ha^{-1})	489	502	570	521	560	528	35	0.08	
GPV$_{S}$ (US\$ ha^{-1})	3247	1913	3525	2434	2719	2767	642	0.23	
GPV$_{C}$ (US\$ ha^{-1})	1659	208	1426	1340	1326	1192	566	0.47	
GPV$_{L}$ (US\$ ha^{-1})	1588	1706	2099	1094	1393	1576	373	0.24	
ICV$_{S}$ (US\$ ha^{-1})	1645	1482	1379	819	1022	1269	340	0.27	
ICV$_{C}$ (US\$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV$_{L}$ (US\$ ha^{-1})	1100	895	782	574	646	799	209	0.26	
GVA$_{S}$ (US\$ ha^{-1})	1602	431	2145	1615	1697	1498	637	0.42	
			NG/CS						0.12
SGY (kg ha^{-1})	3442	393	3501	3768	4157	3052	1513	0.49	
LAP (kg ha^{-1})	-	-	-	-	-	-	-	-	
GPV$_{S}$ (US\$ ha^{-1})	1601	241	1271	1382	1273	1153	528	0.46	
GPV$_{C}$ (US\$ ha^{-1})	1601	241	1271	1382	1273	1153	528	0.46	
GPV$_{L}$ (US\$ ha^{-1})	-	-	-	-	-	-	-	-	
ICV$_{S}$ (US\$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV$_{C}$ (US\$ ha^{-1})	545	588	598	245	376	470	154	0.33	
ICV$_{L}$ (US\$ ha^{-1})	-	-	-	-	-	-	-	-	
GVA$_{S}$ (US\$ ha^{-1})	1057	-347	673	1137	897	683	602	0.88	

[a] μ represent average value between years 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017

[b] σ represent standard error between years 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017

[c] CV represent coefficient variation between years 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017.

[d] R_{US} represents average economic resiliency (1-GAV_S) of the years 2009/2010, 2011/2012, 2014/2015, 2015/2016 and 2016/2017.

[e] ICLS10, ICLS20, ICLS30 and ICLS40 represents grazing intensity in integrated crop-livestock system (ICLS) at 10, 20, 30 and 40 cm, respectively.

Supplementary material

Table A1. Indices obtained by nitrogen and phosphorus estimation of variables used on construction of conceptual model proposed for the ENA analysis applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS).

Variable	Indices	References
	Nitrogen	
Soybean DM	0.08 kg kg^{-1} Grain	Hungria et al., 2005
Soybean Residue	0,0121 kg kg^{-1} DM	Salvagiotti et al., 2008
Soybean Fixed	83,17% of N input	Hungria et al., 2005
Soybean Grain	0.0559 kg kg^{-1}	Assmann et al., 2014
Soybean Seed	0.06 kg kg^{-1}	Sbardelotto and Leandro, 2008
Animal Intake	0.0349*; 0.0339⁑; 0.0325⁂; 0.0293⁑⁑ kg kg^{-1} DM	Souza Filho, 2017
Animal Exportation	2.8 kg 100 kg^{-1} LW	NRC, 2001
Pasture DM	0.0272*; 0.0251⁑; 0.0255⁂; 0.0248⁑⁑; 0.0269# kg kg^{-1} DM	Lemaire, 2008; Reyes et al., 2015
Pasture Residue	0.0193 kg kg^{-1} DM	Assmann et al., 2014
Black Oat Seed	0.024 kg kg^{-1}	Pedo and Sgarbieri, 1997
	Phosphorus	
Soybean DM	0.0087 kg kg^{-1} Grain	Malavolta et al., 1997
Soybean Residue	0.0009 kg kg^{-1} DM	Assmann et al., 2017
Soybean Grain	0.0064 kg kg^{-1}	Flanery, 1986; 1989
Soybean Seed	0.0061 kg kg^{-1}	Gibson and Mullen, 2001
Dung	0.0066 kg kg^{-1} DM	Assmann et al., 2017
Animal Exportation	0.73 kg 100 kg^{-1} LW	Price and Schweigert, 1994
Pasture DM	0.0051*; 0.0034⁑; 0.0029⁂; 0.0021⁑⁑; 0.0016# kg kg^{-1} DM	Mazza et al., 2012
Pasture Residue	0.0026 kg kg^{-1} DM	Assmann et al., 2017
Black Oat Seed	0.00335 kg kg^{-1}	Pedo and Sgarbieri, 1997

*10 cm

⁑20 cm

⁂30 cm

⁑⁑40 cm

#No-grazing (NG)

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6. FINALS CONCLUSIONS

In the first study it was possible to understand the dynamics in the herbage intake process at the bite level, from the perspective of optimization of animal herbage harvest. It was verified that the sward surface height of 22.30 cm of *S. arundinaceus* maximizes the short-term intake rate of sheep. Thus, as pasture management target in a rotational grazing system, it is suggested the surface sward height pre- and post-grazing of 22.30 and 13.38 cm (data not presented in the thesis), respectively, it should be adopted in maintaining high amount of herbage intake by the animals.

In the second study, it was verified that there are high herbage accumulation rate in the autumn and spring periods, with a maximization of the instantaneous herbage accumulation rate in the sward surface height between 19 and 25 cm.

The results of the two chapters suggest that the adoption of the pre-grazing criterion at the surface sward height of 22.30 cm increases the efficiency of the ecological processes of the plant-animal interface.

According to Altieri and Nicholls (2005) agricultural management based on understanding the relationships of ecological processes of ecosystems can be manipulated to produce in a sustainable way.

In this way, in the third chapter, found that agricultural systems that adopt diversification with grazing animals are important promoters of agricultural resilience under the nutrient flow and economic context. The grazing intensity had no influence on the promotion of resilience. The significant equality between the grazing intensities tested may be related to the high dependence of the external factors and the low perennially of the compartments belonging to the studied systems.

Future works, on the integrated system context, should focus on the impact of different management strategies on "perennial" crop and livestock components to promote efficiency, resilience, and productivity of agroecosystems. In addition, studies should analyze the impact of management on the diversity of biological interactions in the network flow.

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8. ATTACHMENTS

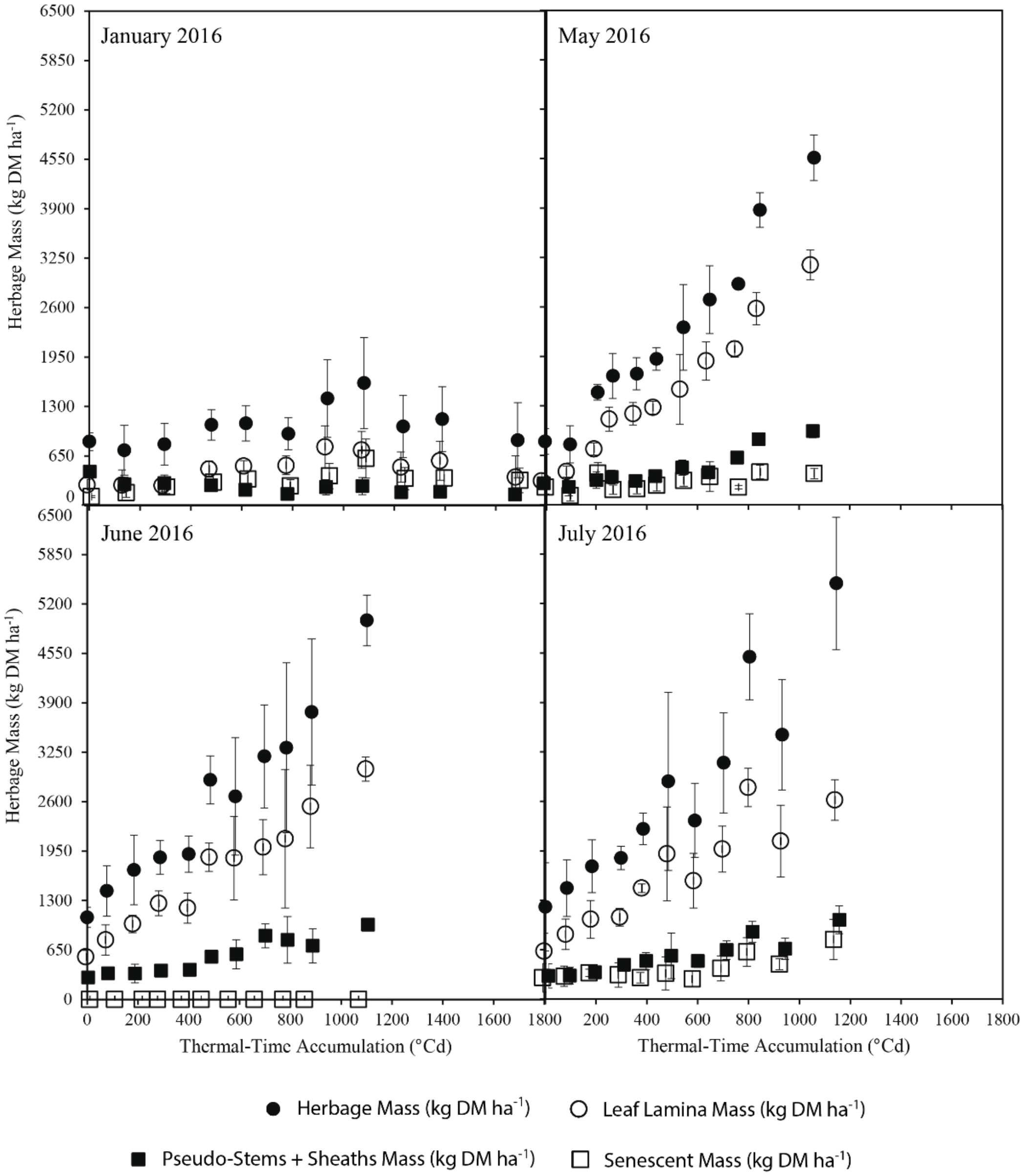
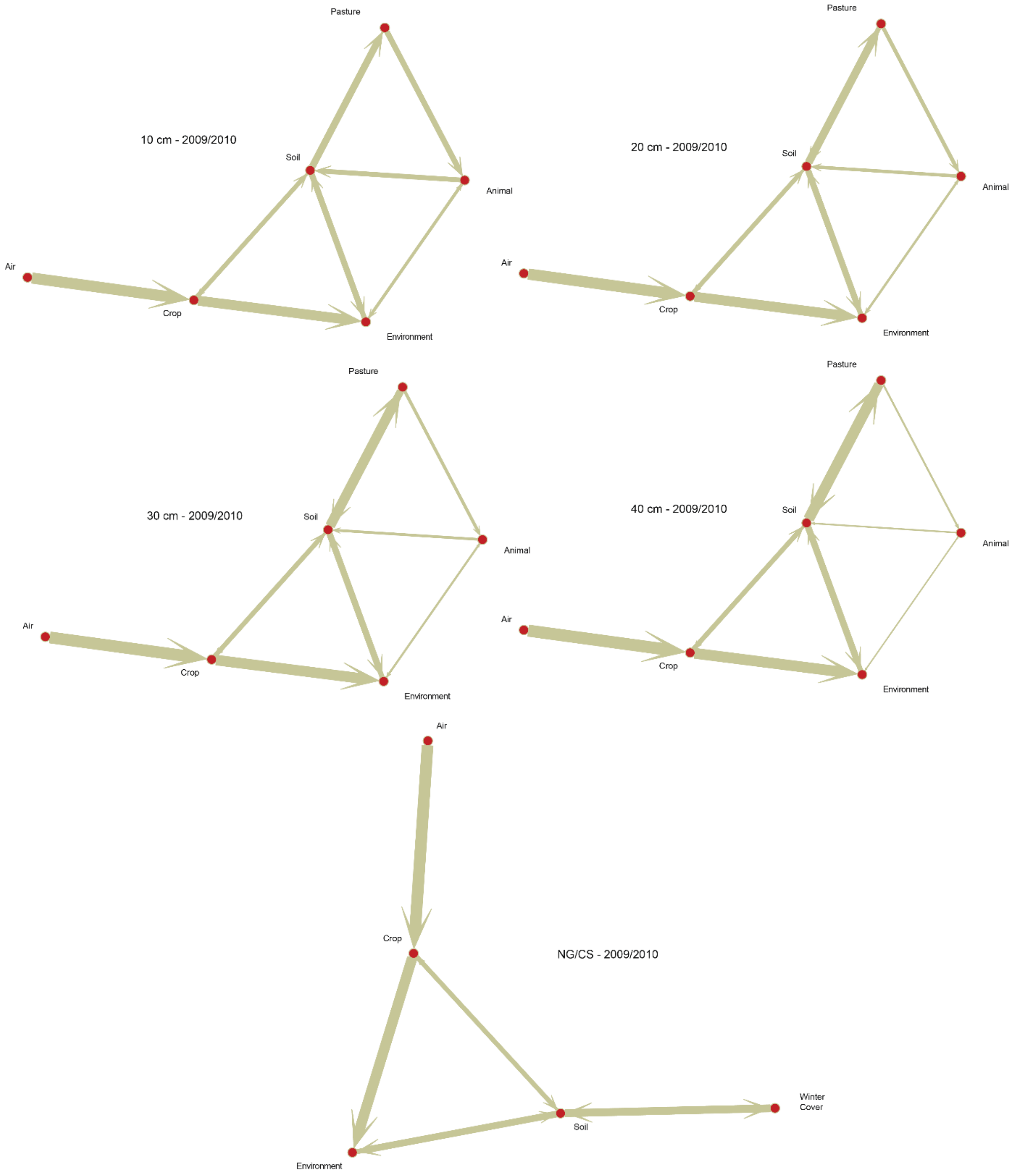


Fig. 1. Average above ground herbage mass (kg DM ha^{-1}), leaf lamina mass (kg DM ha^{-1}), pseudo-stems + sheath mass (kg DM ha^{-1}) and senescent mass (kg DM ha^{-1}) of *Schedonorus arundinaceus,* for January, May, June and July 2016. The bars represent the standard error of the mean for each week. Non-modeled data.



10 cm - 2009/2010

20 cm - 2009/2010

30 cm - 2009/2010

40 cm - 2009/2010

NG/CS - 2009/2010

Fig. 2. Network models applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The orientation and width of the arrows means the direction and amount of nutrients between the compartments in 2009/2010, respectively.

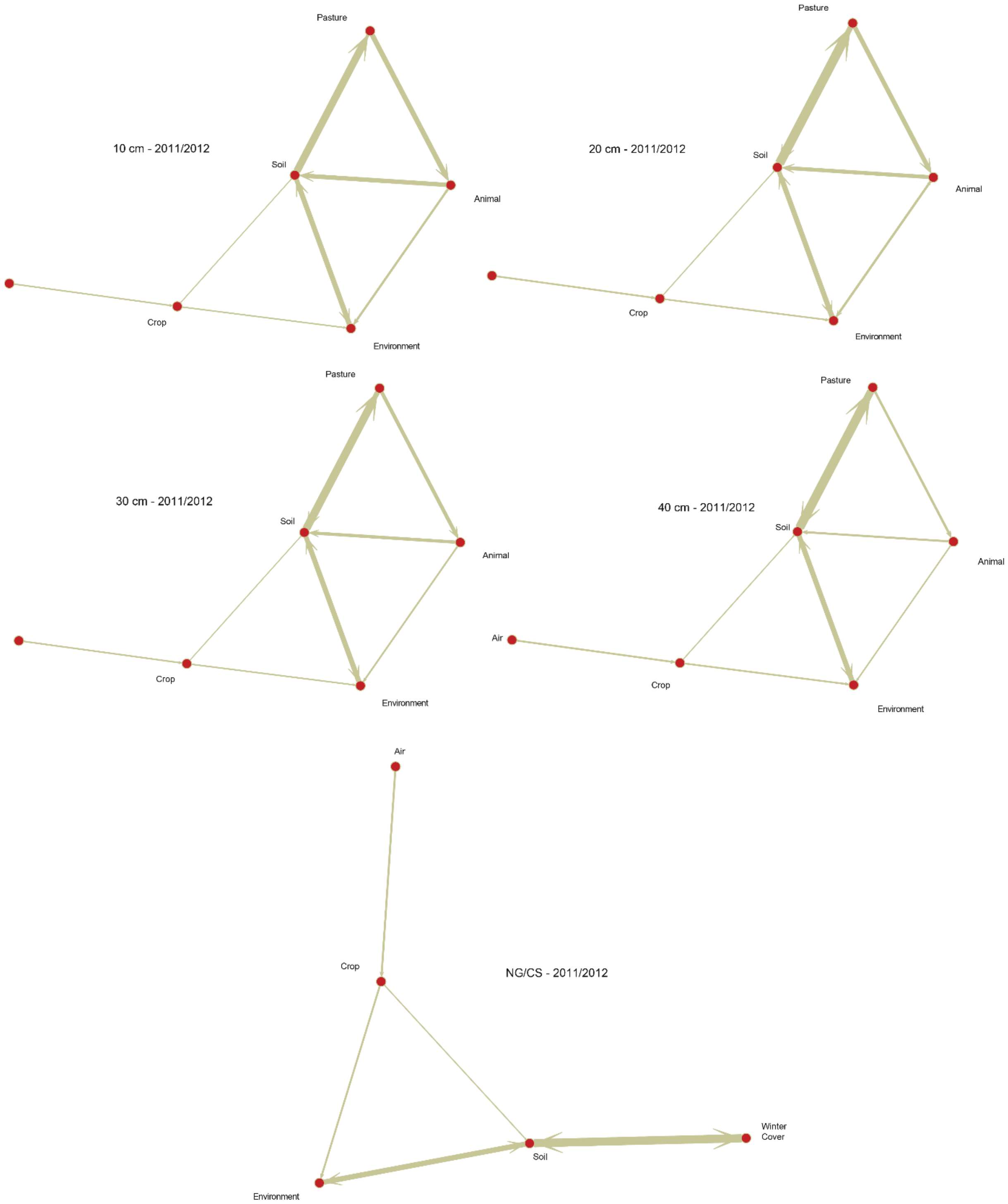


Fig. 3. Network models applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The orientation and width of the arrows means the direction and amount of nutrients between the compartments in 2011/2012, respectively.

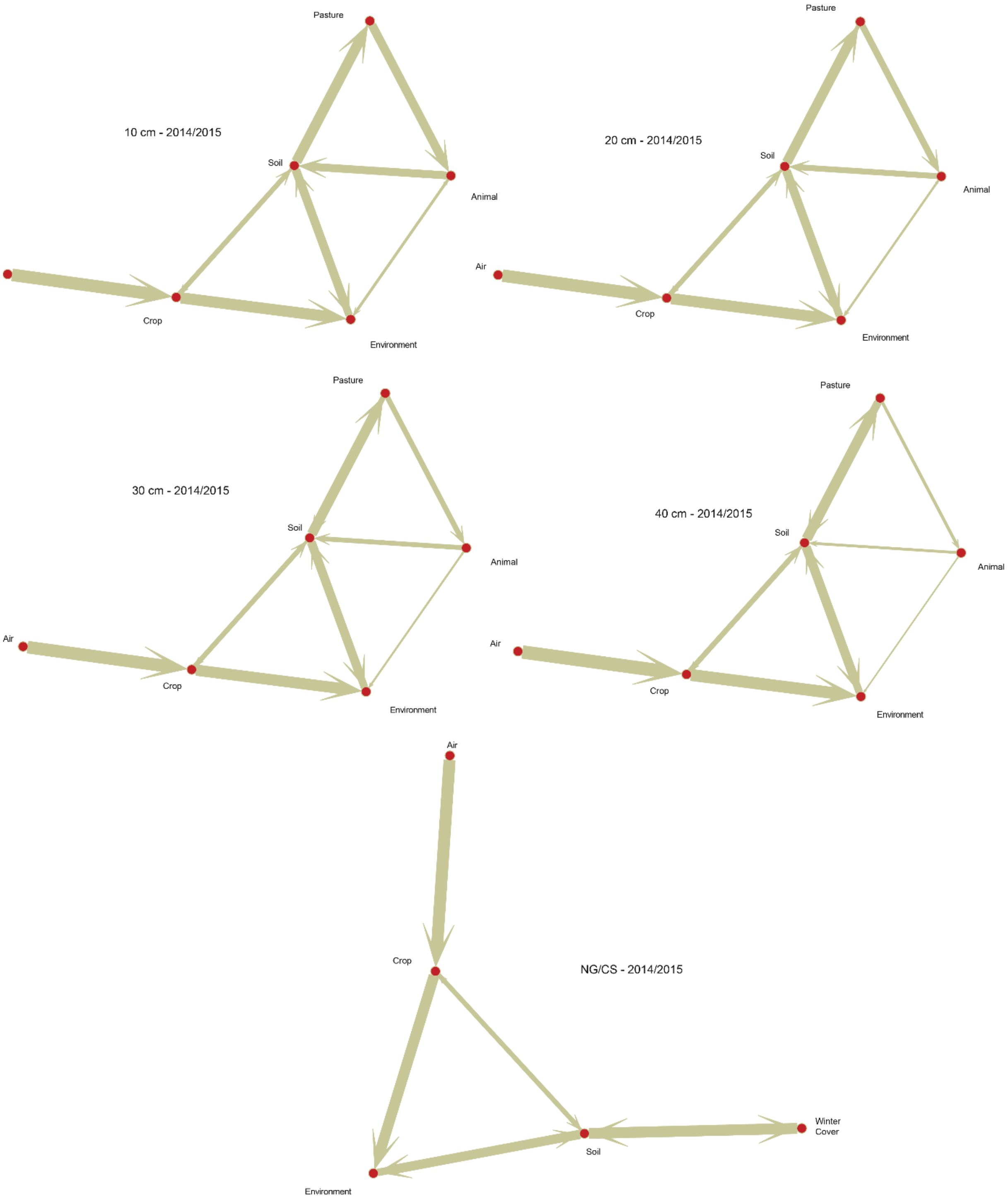


Fig. 4. Network models applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The orientation and width of the arrows means the direction and amount of nutrients between the compartments in 2014/2015, respectively.

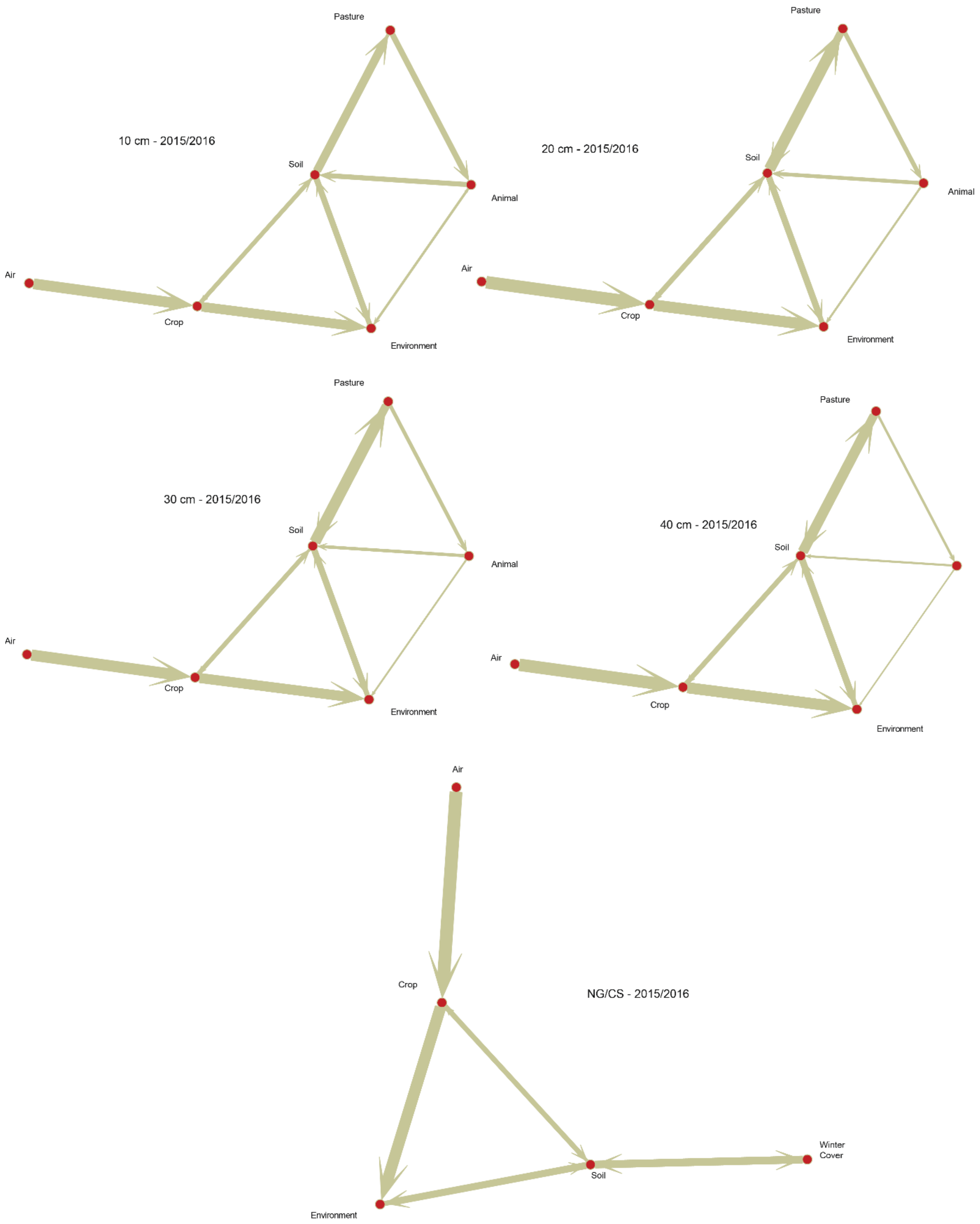


Fig. 5. Network models applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The orientation and width of the arrows means the direction and amount of nutrients between the compartments in 2015/2016, respectively.

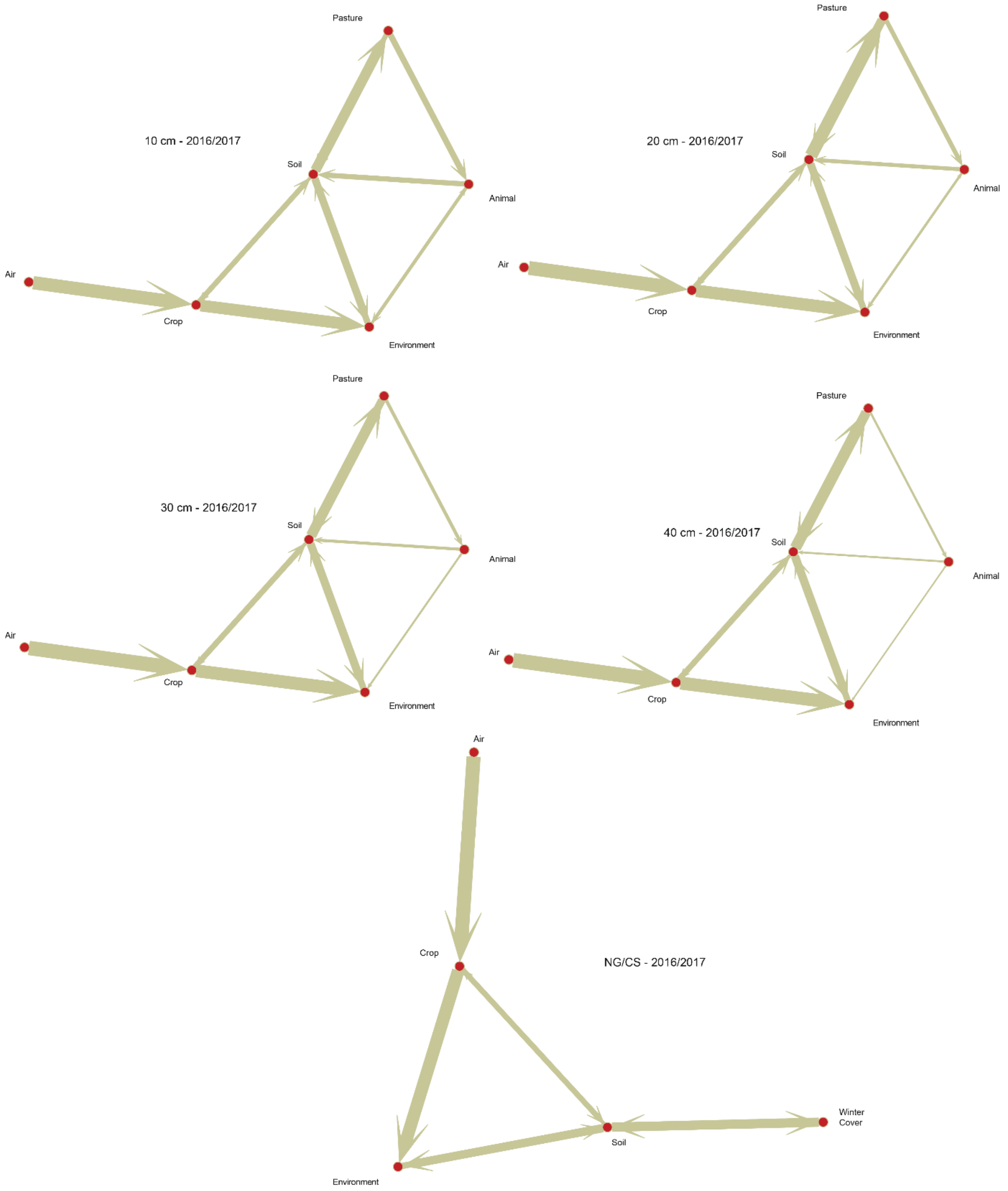


Fig. 6. Network models applied in an integrated crop–livestock system with different grazing intensities (10, 20, 30 and 40 cm) and in a no-grazing/crop system (NG/CS). The orientation and width of the arrows means the direction and amount of nutrients between the compartments in 2016/2017, respectively.

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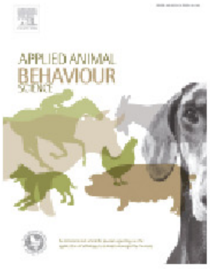

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AUDIENCE

Animal Ethologists, Animal Scientists, Zoologists.

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2. Review Articles
3. Letters to the Editor
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AUTHOR INFORMATION PACK

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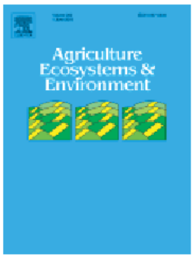

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