UNIVERSIDADE DO ESTADO DE SANTA CATARINA
CENTRO DE CIÊNCIAS AGROVETERINÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA ANIMAL

IGOR RODRIGUES WALTRICK

IMPLANTAÇÃO DE MILHO PARA SILAGEM SOBRE PASTAGENS PERENES DE INVERNO E SEU IMPACTO SOBRE A PRODUÇÃO DE FORRAGEM E DIVERSIDADE DOS PASTOS

LAGES

2025

IGOR RODRIGUES WALTRICK

IMPLANTAÇÃO DE MILHO PARA SILAGEM SOBRE PASTAGENS PERENES DE INVERNO E SEU IMPACTO SOBRE A PRODUÇÃO DE FORRAGEM E DIVERSIDADE DOS PASTOS

Dissertação apresentada ao Programa de Pós-graduação em Ciência Animal, da Universidade do Estado de Santa Catarina, como requisito parcial à obtenção do título de Mestre em Ciência Animal, Área de Concentração: Produção Animal.

Orientador: André Fischer Sbrissia

LAGES

2025

AGRADECIMENTOS

É com profunda gratidão que dedico este espaço para expressar meu sincero reconhecimento a todos que, de alguma forma, contribuíram para a realização desta dissertação. Este trabalho é o resultado de um esforço coletivo, e sem o apoio e a dedicação de cada um, sua concretização não seria possível.

À minha amada família, meu porto seguro. Aos meus pais, pelo amor incondicional, pelos valores que me transmitiram, pelo constante incentivo aos estudos, pela alegria e motivação diárias que me impulsionaram a seguir em frente. Vocês são a base de tudo e a razão do meu empenho.

Ao Núcleo de Pesquisa em Pastagem (NUPEP), em especial aos meus colegas de laboratório, por tornarem possível a execução deste projeto de pesquisa. A colaboração, o companheirismo e o ambiente de troca de conhecimentos foram fundamentais para superar os desafios e alcançar os resultados aqui apresentados. Agradeço a cada um pela ajuda, pelas discussões enriquecedoras e pelo apoio mútuo.

Ao Professor Doutor André Fischer Sbrissia, meu orientador, pela confiança depositada em meu trabalho, pela orientação precisa e pelo conhecimento compartilhado. Sua vasta experiência e dedicação foram cruciais para o desenvolvimento desta pesquisa. Agradeço imensamente pela paciência, pelas valiosas discussões e pelo incentivo constante, que me permitiram crescer não apenas como pesquisador, mas também como indivíduo. Sua mentoria é um privilégio e um aprendizado inestimável.

Por fim, a todos os amigos e colegas que, direta ou indiretamente, contribuíram para esta jornada. O caminho da pesquisa é desafiador, mas com o apoio de pessoas tão especiais, torna-se uma experiência gratificante e enriquecedora.

Abstract

This study evaluated the impact of corn overseeding for silage production in established perennial cool-season pastures (Zea mays L.) on pasture production and diversity in the Cfb climate region of Southern Brazil. Three treatments were implemented over a 12-month grazing experiment: Corn Overseeding in Perennial Pasture (C), Seasonal Deferment (D), and Year-Round Grazing (YRG). The study was conducted on a >7-year-old pasture predominantly composed of tall fescue (Festuca arundinacea Schreb.), orchardgrass (Dactylis glomerata L.), and clover (Trifolium spp.). The Corn Integration treatment yielded the highest annual biomass production (13,360.68 kg DM/ha), effectively addressing the summer forage deficit. However, this intensive production model also resulted in a significant grazing gap, similar to the Deferment treatment, highlighting a need for strategic management to ensure year-round forage availability. The plant diversity dynamics assessed using Hill numbers (q=0, q=1, q=2) revealed complex response patterns. The Corn treatment showed a significant recovery in plant diversity, achieving higher final Hill numbers (q=0: 5.0±0.3; q=1: 3.6±0.2; q=2: 3.2±0.1) compared to Year-Round Grazing (q=0: 4.2±0.2; q=1: 3.0±0.2; q=2: 2.65±0.1) and Deferment (q=0: 3.7±0.2; q=1: 2.7±0.1; q=2: 2.4±0.1). In contrast, the Seasonal Deferment treatment showed the lowest final diversity, likely because of competitive exclusion during the rest period. These results suggest that the disturbance from the corn cycle may have activated the soil seed bank, promoting an increase in plant diversity, which aligns with the Intermediate Disturbance Hypothesis. However, the long-term sustainability of this effect requires further investigation to understand the full impact on the pasture ecosystem. Corn integration in pastures has the potential to enhance biomass and diversity, but it requires careful management to mitigate the associated grazing gap and to ensure the long-term ecological balance of the pasture system.

Keywords: integrated crop-livestock systems, plant diversity, soil seed bank, intermediate disturbance hypothesis

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

1 Introduction

The subtropical highlands of Southern Brazil present a unique agricultural landscape in which climate and ecology converge to create both challenges and opportunities for livestock production. Characterized by a humid temperate climate with mild summers (Cfb in the Köppen classification), this region has historically supported diverse forage production strategies, each with distinct ecological and economic implications.

For decades, livestock producers in this region have relied primarily on the region's remarkable native grasslands, locally known as "Campos." These natural ecosystems represent some of the world's most biodiverse temperate grasslands, where perennial grasses have evolved to support livestock production, while maintaining ecological resilience. These Campos have become fundamental to the region's agricultural identity, providing a sustainable low-input foundation for extensive grazing operations. A second conventional approach involves the strategic overseeding of cool-season (C3) annual grasses, particularly Italian ryegrass (*Lolium multiflorum* Lam.), and black oat (*Avena strigosa* Schreb.) onto established perennial warm-season pastures such as Tifton-85. This practice creates a complementary seasonal production cycle but requires annual re-establishment.

A third alternative has gained more attention in recent years: the establishment of perennial cool-season (C3) pastures using species such as tall fescue (*Festuca arundinacea* Schreb.), orchardgrass (*Dactylis glomerata* L.), and clover (*Trifolium* spp.). These perennial systems offer important advantages, including reduced establishment costs over time and improved nutritive value. However, their widespread adoption is subject to fundamental physiological constraints. Having evolved in cooler climates, these temperate species experience reduced growth rates when temperatures exceed their photosynthetic optima during the summer. This thermal stress, often exacerbated by periodic moisture deficits, creates what producers recognize as the "summer slump" a critical period of minimal pasture growth precisely when warm-season species would naturally thrive.

This seasonal production deficit represents a significant barrier to broader implementation of perennial C3 pastures in subtropical regions. Producers must either maintain lower stocking rates year-round (reducing economic efficiency), invest in expensive supplementary feeding during the summer months, or risk overgrazing that can lead to stand degradation and reduced persistence. Finding solutions to this seasonal growth limitation could help unlock the full potential of perennial pasture systems in the region.

Corn (*Zea mays* L.) was a promising candidate for addressing this challenge. With its C4 photosynthetic pathway and exceptional growth efficiency under warm conditions, corn thrives when perennial cool-season pastures struggle. This study investigates whether strategically oversowing corn directly into established perennial pastures during late spring allows producers to capture the high summer solar radiation and temperature conditions for maximum biomass production through corn silage, while maintaining a valuable perennial pasture base for production during cooler months..

Despite these compelling theoretical advantages, the practice of integrating corn production into perennial C3 pastures introduces complex ecological interactions that remain poorly understood. The implementation of such integrated systems raises critical questions regarding both short-term compatibility and long-term sustainability. Will competitive pressure from corn irreparably damage understory perennial pastures? Can perennial species recover sufficiently after corn harvest to maintain system productivity? How does plant community diversity respond to this novel disturbance regime? These questions must be addressed through rigorous scientific investigation before widespread adoption is recommended.

This study provides a comprehensive evaluation of the effects of corn integration on both productivity and ecological dynamics in established perennial C3 pastures. By examining total system productivity and plant community diversity responses throughout a complete annual cycle, we aimed to determine whether corn-perennial pasture integration represents a truly sustainable solution to seasonal forage challenges or a short-term productivity gain with hidden ecological costs.

2 Literature Review

The majority regions of Southern Brazil are characterized by a Cfb climate, defined by the Köppen-Geiger classification as a humid subtropical climate with temperate summers and no defined dry season (ALVARES *et al*., 2013). The native grasslands of Southern Brazil, commonly referred to as Campos or Campos sulinos, represent a vital natural resource for livestock production and biodiversity conservation. These highlands are species-rich, old-growth ecosystems that form the dominant natural vegetation in extensive areas of the region and occur predominantly in a Cfb climate (MENEZES *et al*., 2022; OVERBECK *et al*., 2007). Historically, these native pastures have been the primary forage base for cattle production system, supporting the establishment and development of the beef and dairy industries in the region (OVERBECK *et al*., 2007). Sustainable management of these native grasslands is crucial, not only for continued milk and beef production but also for the preservation of their unique ecological attributes, especially given the significant historical and ongoing conversion of these areas to other land uses (MENEZES *et al*., 2022; OVERBECK *et al*., 2007).

Another alternative is the use of perennial winter pastures as a resource for livestock production, particularly for beef and dairy cattle. These pastures are often composed of C3 grasses such as tall fescue (*Festuca arundinacea* Schreb.), orchardgrass (*Dactylis glomerata* L.), and legumes, such as white clover (*Trifolium repens* L.), provide high-quality forage during cooler months (COELHO, 1999; SBRISSIA, 2023).

However, the adoption of perennial C3 pastures in subtropical regions has fundamental physiological constraints. These temperate species evolved under cooler climates and exhibited dramatically reduced growth rates when temperatures exceeded their photosynthetic optima during the summer. This thermal stress, often compounded by periodic moisture deficits, creates what producers recognize as the "summer slump" (FONTANELI *et al*., 2012; KUNRATH *et al*., 2014), a period of minimal pasture growth when warm-season species are the most productive. This seasonal production deficit represents the primary obstacle to the widespread adoption of perennial C3 pastures in subtropical regions as it forces producers to maintain lower stocking rates, invest in expensive supplementary feeding, risk overgrazing, and stand degradation.

This study investigated the hypothesis that biomass production during the summer period is greater when corn silage is oversown in perennial winter pastures. Considering the challenge of the "summer slump" that affects C3 species in subtropical climates, we aim to evaluate whether this crop-livestock integration strategy represents a viable solution to optimize forage production during the warm season, when temperate pastures naturally reduce their growth.

2.1 Integrated Crop-Livestock Systems: A Pathway Forward

The principles of integrated crop–livestock systems (ICLS) offer an innovative framework for addressing these seasonal production challenges. ICLS recognizes that different plant species possess complementary growth patterns and resource-use strategies, suggesting opportunities for temporal and spatial integration to optimize total system productivity. In this context, the strategic integration of warm-season annual crops into established perennial C3 pastures has emerged as a particularly intriguing possibility (SANTOS *et al*., 2023).

Research indicates that these integrated systems can enhance overall system-wide productivity compared with specialized cropping systems, even if yields of the primary cash crop might occasionally be lower, and the inclusion of forage and subsequent livestock production often leads to greater total output (PETERSON *et al*., 2020). Furthermore, ICLS contributes to improved soil health through enhanced biological, physical, and chemical properties, better water and nutrient cycling, and can augment resilience to climate variability and change (CARVALHO *et al*., 2018, as cited in PETERSON *et al*., 2020). These systems are pivotal for both milk and beef production and offer a diversified and potentially more stable production base.

Addressing this summer forage gap through the strategic integration of high-yielding annual summer crops represents a key opportunity within the ICLS framework in Southern Brazil. Corn (*Zea mays* L.), a C4 species with high photosynthetic efficiency under warm conditions and substantial biomass potential, is a natural candidate, particularly in silage production (FRIBOURG *et al*., 1976; FRAME & BOYD, 1987). The direct sowing of corn in established perennial cool-season pastures during summer, it can produce large volumes of energy-rich silage. This practice serves as an alternative to bridge the winter forage gap and optimizes land utilization by producing two distinct forage resources (summer annual silage and perennial pasture) in the same area within a single year, a key feature of integrated crop-livestock systems (ASSMANN et al., 2003; MORAES et al., 2014)

Despite the evident productivity benefits, the ecological consequences of introducing a highly competitive annual crop such as corn into an established perennial pasture ecosystem deserve thorough examination. The intensive management practices required for corn cultivation, including minimal soil disturbance during no-till planting, substantial nutrient amendments, and inevitable shading imposed by the tall, dense corn canopy, may exert considerable ecological pressure on the underlying perennial vegetation community (GHASSEMI-GOLEZANI *et al*., 2010; ISBELL *et al*., 2015). Legitimate ecological concerns include the potential temporal suppression of valuable perennial species, compromised or delayed recovery of pasture following corn harvest, and persistent shifts in botanical composition that might favor ruderal, disturbance-adapted species over desirable forage components (TRACY & SANDERSON, 2004; SANDERSON *et al*., 2005). Consequently, rigorous assessment of the resilience capacity of a perennial pasture, defined as its ability to maintain or rapidly recover structural integrity and ecological function following disturbance, is essential for determining the long-term sustainability and ecological viability of this integration approach within agricultural landscapes.

A particularly relevant aspect of resilience in this context is the role of the soil seed bank, given the history of the experimental site. The pasture under investigation was established and managed with a diverse mix of perennial grasses and legumes for over seven years prior to the study. Such long-term establishment provides ample opportunities for the development of a persistent soil seed bank, a reservoir of viable seeds representing historical and current plant communities (BAKKER *et al*., 1996; FENNER; THOMPSON, 2006; TYLER *et al*., 2021). This ecological memory, often termed "hidden diversity" (PÄRTEL, 2014), can be a critical determinant of vegetation dynamics following disturbance. Disturbances such as those compounded with corn planting (e.g., temporary canopy removal, nutrient pulses, and minor soil disruption) can break seed dormancy and create regeneration niches, potentially triggering germination from the seed bank and influencing the trajectory of pasture recovery and subsequent community assembly (BOSSUYT; HERMY, 2003; WELLSTEIN *et al*., 2007; FABŠIČOVÁ et al., 2024).

Plant species diversity is increasingly recognized as a valuable ecological attribute and key component of agroecosystem functionality and resilience (ISBELL *et al*., 2015; HOOPER *et al*., 2005). Diverse pastures can exhibit enhanced productivity, improved nutrient cycling, greater resistance to weed invasion, and increased stability in the face of environmental fluctuations such as drought or pest outbreaks (TILMAN *et al*., 1997; SANDERSON *et al*., 2004). Therefore, understanding how management interventions such as corn integration affect pasture diversity is crucial.

Therefore, this study was designed to comprehensively evaluate the effects of integrating summer corn silage production into a long-established (7+ years) perennial winter pasture in the Cfb climate zone of Southern Brazil.

The core objectives were: (1) to quantify the impact of corn oversowing on total annual biomass production compared to traditional continuous grazing and a seasonal deferment strategy, and (2) to assess the consequences of pasture production and plant species diversity dynamics throughout a full annual cycle using the Hill number framework, while explicitly considering the potential mediating role of the established soil seed bank in the observed recovery patterns.

3 Material and Methods

3.1 Experimental Site Characterization and History

The experiment was conducted over a 12-month period at an experimental farm belonging to the Center of Agroveterinary Sciences (CAV) of Santa Catarina State University (UDESC), situated in the municipality of Lages, in the highland region of Santa Catarina State, Southern Brazil. Its precise geographical location is 27° 48′ 58″ South latitude and 50° 19′ 34″ West longitude, positioned at an altitude of approximately 930 m above sea level. The region is characterized by a humid subtropical climate, designated as Cfb, according to the Köppen-Geiger climate classification system. This climate features temperate summers, no distinct dry season, and frequent frosts during winter months, with an average annual precipitation of approximately 1,500 mm and an average annual temperature near 15.6°C (ALVAREZ et al., 2013). The soil at the experimental site was classified as Typic Hapludox (Latossolo Bruno Alumínico Típico in the Brazilian classification), which is known for its clayey texture and moderate natural fertility.

A critical aspect of the study site was its management history. The experimental area, totaling 5,670 m², was under a well-established perennial pasture regime for more than seven consecutive years prior to the commencement of this trial. This long-term sward was composed of a mixture of temperate (C3) forage species, predominantly tall fescue (*Festuca arundinacea* Schreb. cv. Rizomat), velvet grass (*Holcus Lanatus* L.), orchard grass (*Dactylis glomerata* L. cv. Ambar) interseeded with legumes, including white clover (*Trifolium repens* L. cv. Zapican) and red clover (*Trifolium pratense* L. cv. Estanzuela 116), birdsfoot trefoil (*Lotus corniculatus* L.), and forage peanut (*Arachis pintoi* Krapov. & W.C. Greg. cv. Amarillo).

The experimental timeline spanned a full year and was divided into four evaluation phases aligned with seasonal changes and key management interventions: "Beginning" (representing the initial pasture state immediately before summer treatments commenced), "Summer" (encompassing the summer period dedicated to corn growth or pasture deferment/grazing), "Winter" (the period following corn harvest and initiation of common grazing management across all plots), and "Spring" (marking the normally well-observed peak of biomass production).

3.2 Experimental Design and Treatments

A randomized complete block design (RCBD) was employed using three blocks to account for potential spatial heterogeneity across the site. Each block contained one experimental unit (paddock) assigned to each of the three treatments, resulting in nine paddocks, each measuring approximately 630 m² (21 × 30 m).

Before the experiment was set up, we standardized the area by mechanized mowing, where the pasture was standardized to around 12 cm in height.

The treatments were defined as follows:

Corn Overseeding in Perennial Pasture (C): This treatment implemented a strategic summer intensification approach by directly oversowing corn (Zea mays L.) intended for silage production in an established perennial cool pasture. The corn (cv. DKB230 pro 3) was established in 12/12/23 using no-till planting equipment specifically calibrated for precision seeding into existing vegetation with minimal soil disturbance. The technical specifications included narrow row spacing (0.5 m) to optimize canopy closure and light interception, along with a calibrated seeding rate designed to achieve a final plant population density of approximately 60,000 plants per hectare, corrected by seed quality. Oversown corn created a temporary overstory within the pasture ecosystem, where the tall C4 crop formed a dominant upper stratum above the suppressed C3 perennial understory during the summer growth period. This intercropping approach aims to take advantage of the complementary photosynthetic pathways and growth periods of both plant types within the same spatial unit, maximizing the productivity capacity of the land during the period when perennial cool-season species typically experience reduced growth rate and productivity.

Seasonal Deferment (D): This treatment implemented a strategic rest period for the established perennial pasture, during which the designated experimental paddocks were completely excluded from all defoliation pressures (both grazing and mechanical harvesting) throughout the summer period that corresponded precisely with the corn growth cycle in treatment “Corn Integration”. This management approach represents a common conservation practice in grassland systems, allowing complete photosynthetic recovery, carbohydrate reserve replenishment, and potential seed production while avoiding the stress of summer grazing.

Year-Round Grazing (YRG): This treatment functioned as an experimental control, representing the predominant conventional management practice employed by livestock producers throughout the region. Under this regime, the established perennial pasture was continuously subjected to rotational stocking by beef cattle throughout the 12-month experimental period without any seasonal rest or deferment. Management decisions are governed by a target sward height protocol that optimizes both forage production and stand persistence (Duchini *et al*., 2019). Cattle were introduced to the paddocks when the mean sward height reached approximately 20 cm, and animals were subsequently removed when the canopy was grazed down to approximately 12 cm. This grazing management strategy maintained the pasture within an optimal height range that balanced livestock intake requirements with photosynthetic recovery needs while preventing both undergrazing (which could lead to reproductive maturity and reduced forage quality) and overgrazing (which could deplete plant energy reserves and compromise stand persistence). The YRG treatment provided an essential baseline against which to evaluate alternative management strategies, representing the status-quo production system in the region.

Following the corn silage harvest (typically occurring in late summer/early autumn), all experimental units, including those previously under corn (M) and deferred (D) treatments, were subjected to the same grazing management protocol (pre-grazing target height of 20 cm and post-grazing target height of 12 cm), as described earlier.

3.3 Biomass and Botanical Composition Assessment

3.3.1 Botanical Composition Analysis

To evaluate the botanical composition, destructive sampling was conducted at four key points corresponding to the transitions between the defined evaluation phases: beginning (before corn implementation or deferment/grazing period initiation), 2) summer, 3) winter, and 4) spring.

In each of the nine experimental paddocks, three sampling points were randomly selected for each assessment. The selection process involved a zigzag transect walk across the paddock, with sampling locations determined at random intervals along the transect to ensure representativeness and avoid operator bias. Areas within two meters of the fences, water troughs, or paddock edges were excluded from the sampling to minimize edge effects.

At each designated sampling point, a standardized rectangular quadrat measuring 0.5 m^2 (1.0 m × 0.5 m) was positioned according to predetermined randomization protocols. All aboveground biomass within this delineated area was harvested to ground level, and the harvested biomass from all three quadrats within each experimental paddock was thoroughly consolidated and homogenized to create a representative composite sample for that experimental unit.

In the laboratory, a subsample was separated into predetermined functional and taxonomic categories: (1) Sown Grasses (species *Festuca arundinacea, Dactylis glomerata* and *Holcus Lanatus*); (2) Sown Legumes (encompassing the deliberately planted nitrogen-fixing species *Trifolium repens, T. pratense, Vicia sativa,* and *Arachis pintoi*); (3) Spontaneous Species (comprising any volunteer grasses, forbs, or other non-target species not intentionally established in the original seeding mixture); and (4) Non-living Biomass (consisting of senescent plant material, detached dead matter, and partially decomposed litter). Each separated botanical component was transferred to individually labeled paper bags permeable to moisture exchange and placed in a forced-air ventilation oven maintained at a constant temperature of 65°C for a minimum duration of 72 h or until successive weighings confirmed that a constant mass had been achieved, indicating complete moisture removal. The oven-dried mass of each separated fraction was determined using an analytical balance with a precision of 0.001 g. The proportional contribution of each botanical component provided a quantitative characterization of the structural and functional composition of the sward at each assessment point.

Perennial Pasture Biomass: We measured the amount of pasture biomass using a direct cutting method. At the start of each grazing period, we placed three sample frames, each with an area of 0.5 m², in each paddock. To define the sample area, the frame had a cutting height of 12 cm, meaning we collected all the plant material inside the frame that was above this height. This method helped us estimate the available biomass for the animals.

At the same time, we used pasture height to decide when to move the animals. We took 30 height measurements in each paddock with a measuring stick. The rule was to let the animals in when the pasture reached 20 cm and move them out when it was grazed down to 12 cm.

To calculate the total biomass production for the summer season, we added together the amount of biomass we collected from the frames at the start of each grazing period. After the summer treatments were over, we performed a final cut, after summer treatments collecting all the plant material left inside the frames to measure the total production for the entire season.

Corn Silage Biomass: For the Corn (M) treatment, the biomass yield intended for silage was estimated when the corn reached the appropriate physiological stage (half-milk line in the kernel). Three representative rows were selected within each corn paddock, and a 10-meter linear section of each row was harvested manually at a cutting height of approximately 40 cm above ground level to simulate mechanical silage harvesting. The total fresh weight of the plants from each 10m section was recorded. A representative subsample was chopped using a stationary biomass chopper, and a portion (approximately 500 g) was dried at 65°C to a constant weight to determine the dry matter percentage. The total dry matter yield of corn silage (kg DM/ha) was calculated based on the fresh weight per unit area and the dry matter percentage.

Deferred Pasture Biomass: At the time of corn harvest, the total dry weight of all components harvested from the 0.5 m × 1.0 m quadrats provided a direct, destructive measurement of the standing biomass mass (kg DM/ha) at each sampling point for the pasture components. Three samples per paddock were collected using the direct method to establish the baseline measurements. The sample was dried at 65°C to a constant weight to determine the dry matter.

After the summer treatments, all paddocks followed the perennial pasture protocol.

3.4 Fertilization Management

Summer Fertilization: The paddocks were fertilized to meet the nutrient requirements of the corn crop. Based on the expected yield and nutrient removal rates (adapted from FRIBOURG *et al*., 1976 and local recommendations), 150 kg N/ha (applied as urea), 80 kg P/ha (as P2O5, applied as triple superphosphate), and 100 kg K/ha (as K2O, applied as potassium chloride) were applied. Phosphorus and potassium were applied at planting in covering. Nitrogen was applied half 15 days after planting, and the remainder was applied as top-dressing approximately 40 days after emergence. All the treatments received the same amount on the same dates and quantities.

Winter Fertilization: Following the summer intervention period, all nine paddocks received a uniform application of nitrogen fertilizer to stimulate perennial pasture growth during the cooler autumn and winter months. A total of 100 kg N/ha (as urea) was applied, which was typically split into two applications (50 kg N/ha in early autumn and 50 kg N/ha in late winter/early spring) to optimize utilization and minimize potential losses.

3.5 Pest Management

During the corn growth phase in the Corn Integration (C) treatment, fall armyworms (*Spodoptera frugiperda*) were monitored regularly through visual inspection of plants for egg masses and early instar larvae. Chemical control was implemented when the economic thresholds were reached, with two insecticide applications performed during the experimental period. The applications were conducted using a tractor-mounted boom sprayer calibrated to deliver a consistent application rate of 1 L/ha for commercial products. The first application occurred at the V4 growth stage (four fully developed leaves), coinciding with the initial detection of significant larval presence, while the second application was performed approximately 21 days later during the V8-V10 stage when monitoring indicated renewed pest pressure. This management protocol was implemented to minimize yield losses from foliar damage, while maintaining the experimental integrity of the integrated system.

3.6 Soil Cover Measurement

The ground cover percentage was assessed within each experimental paddock using the step-point method, which is a widely recognized technique for rapidly and objectively determining vegetation and ground cover in grasslands and rangelands (EVANS & LOVE, 1957). The assessment was conducted after the corn was harvested.

Within each paddock, a predetermined transect route was followed in an x-pattern to ensure representative sampling across the area. At approximately every step along the transect, the observer recorded the cover type intercepted by a specific point on the toe of the boot. In total, 114 points were recorded per paddock during each evaluation period. At each point, the cover was classified into one of two categories: "covered" (intercepting live vegetation, litter, or plant residue) or "bare soil" (intercepting exposed soil). The percentage of soil cover for each paddock was then calculated as the number of points classified as "covered" divided by the total number of points sampled, expressed as a percentage.

3.7 Plant Diversity Analysis using Hill Numbers

Plant species diversity was quantitatively assessed using proportional dry matter contribution data derived from botanical composition analysis. The assessment utilized Hill numbers (qD), which represent the effective number of species, and were calculated using a single general formula based on Hill (1973) and further elaborated by Jost (2007) and Chao *et al*. (2014). The general formula for Hill numbers of order q is qD = (Σ pi^q)^(1/(1-q)), where pi is the proportional abundance (dry matter) of the i-th species or functional group, and q is the order of diversity, which determines the sensitivity of the measure to species relative abundances.

For q=0, the Hill number (0D) is simplified to the total count of species (or functional groups as separated) present in the sample (i.e., those with a non-zero proportion). This is equivalent to species richness. For q=1, the Hill number (1D) is undefined by the general formula because of division by zero (1-q = 0). However, its limit as q approaches 1 is exp(H'), where H' is the Shannon entropy index ($H' = -\Sigma (p_i * \ln(p_i))$). Thus, 1D is equivalent to the exponential of Shannon's entropy and reflects the number of 'common' or 'typical' species, weighing all species by their proportional abundance. For q=2, the Hill number (2D) was simplified to $1/(\Sigma p_i^2)$, which is equivalent to the inverse of the Simpson concentration index ($D = \Sigma p_i^2$). This index gives disproportionately more weight to the dominant 'species, reflecting the number of abundant' or' dominant species.

These calculations were performed for each experimental unit (paddock) at each of the four assessment periods (Summer, Corn, Winter, Spring), allowing for analysis of diversity dynamics over time and across treatments.

3.8 Comparative Analysis of Precipitation and Temperature in Lages-SC

Analyzing precipitation and temperature patterns in Lages, Santa Catarina, from December 2023 to December 2024, comparing them with historical climatological data from 1999 to 2017. Data was obtained from the National Institute of Meteorology (INMET). The period revealed significant variability in precipitation, with months like May, June, and July recording volumes substantially above average, which can negatively impact crops due to excess moisture and disease risk. Conversely, August and November showed notable water deficits, suggesting potential water stress for crops. Regarding temperature, a general upward trend was observed compared to climatological averages, especially in summer and autumn, which can accelerate the phenological development of summer crops and increase water demand. Although January and December 2024 recorded slightly below-average temperatures, which may benefit some winter crops, the overall warming trend requires attention. These climatic anomalies underscore the importance of continuous monitoring and the adoption of adaptive agricultural practices and the selection of adapted crops.

Table 1. Monthly Average and Experimental Precipitation (mm) and Temperature (°C) with Percentage Differences

Month	Avg. Precipitation (mm)	Experimental Precipitation (mm)	% Δ Precipitation	Avg. Temperature (°C)	Experimental Temperature(°C)	% Δ Temperature
January	159.69	193.0	+20.85%	19.62	19.90	+1.42%
February	144.42	153.2	+6.08%	19.68	21.50	+9.27%
March	122.43	170.2	+39.01%	18.43	20.20	+9.60%
April	112.12	168.4	+50.20%	15.90	18.60	+16.98%
May	115.98	260.0	+124.23%	12.12	14.70	+21.32%
June	116.40	188.8	+62.21%	11.03	13.90	+26.07%
July	145.22	195.6	+34.70%	10.48	11.70	+11.60%
August	118.10	48.6	–58.85%	12.14	13.20	+8.71%
September	172.16	114.4	–33.56%	13.16	16.70	+26.91%
October	199.19	219.4	+10.15%	15.38	17.00	+10.54%
November	131.33	70.0	–46.68%	16.97	18.50	+9.00%
December	136.16	190.2	+39.69%	18.71	18.40	–1.66%

3.9 Statistical Analysis Procedures

All statistical analyses and data processing were conducted using a combination of the R (version 4.2.2; R Core Team, 2022) and Python (version 3.10.8; Python Software Foundation) programming environments. The experimental design was a randomized complete block with three treatments and three replicates.

For biomass data, analysis of variance (ANOVA) was performed using the 'lme4' package in R, with treatment and evaluation period as fixed effects and blocks as random effects. When significant differences were detected ($p < 0.05$), the means were compared using Tukey's Honestly Significant Difference (HSD) test. Prior to analysis, data were tested for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test. When necessary, the data were log-transformed to meet the ANOVA assumptions.

Plant diversity metrics were calculated using the Hill number framework ($q = 0$, $q = 1$, $q = 2$) with the 'vegan' package in R. Species richness ($q = 0$) represents the total number of functional groups present, exponential Shannon entropy ($q = 1$) measures the effective number of common functional groups, and the inverse Simpson concentration ($q = 2$) quantifies the effective number of dominant functional groups

Custom Python scripts utilizing the 'pandas,' 'numpy,' and 'scipy' libraries were developed for data preprocessing, exploratory data analysis, and visualization. The 'matplotlib' and 'seaborn' libraries were used to generate publication-quality figures.

4 Results

The distinct management strategies imposed over the 12-month cycle – integrating corn silage production (Corn), implementing seasonal pasture deferment (deferred), and maintaining year-round grazing (grazing)–yielded statistically significant and ecologically relevant differences in both biomass production and the dynamics of plant species diversity within the established perennial pasture.

4.1 Biomass Production: Quantifying Treatment Impacts

4.1.1 Total Annual Biomass Accumulation

The corn treatment achieved the highest total biomass yield, accumulating 13,360.68 kg DM/ha/year (Figure 1). This was significantly greater than the Deferred treatment, which accumulated 11,231.64 kg DM/ha, and Year-Round Grazing, which yielded 10,229.18 kg DM/ha. Furthermore, the Deferred treatment accumulated more total biomass than the grazing treatment (P<0.05).

Figure 1. Total annual biomass dry matter production across three pasture management strategies in a subtropical perennial pasture system. Values represent the sum of all biomass harvested over the 12-month experimental period, including both perennial pasture biomass and corn silage (in the corn treatment).

Treatment	Total Production (kg DM/ha)
Corn	13,360.7 a
Deferred	11,231.6 b
YRG	10,229.1 c

Means followed by different letters are significantly different (Tukey's HSD test, $p < 0.05$).

4.1.2 Seasonal Dynamics of Biomass Accumulation

Corn Integration treatment exhibited the most pronounced seasonal variation in production, with a highly concentrated distribution pattern (Table 2). Summer production dominated this system, accounting for 50.5% of annual yield (6,752.5 kg DM/ha), comprising both corn silage (4,388.5 kg DM/ha) and pasture biomass (2,364.0 kg DM/ha). This summer concentration was followed by a total absence of harvestable forage in the autumn, as the newly harvested area needed time for pasture recovery. Winter production, with the share of autumn production included in its production, remained limited to 1,420.7 kg DM/ha (10.6% of annual production), before a substantial recovery in Spring produced 5,187.5 kg DM/ha (38.8% of the annual total).

In contrast, the deferred treatment demonstrated the most stable seasonal distribution, although it had a different production profile. A summer accumulation of 4,361.9 kg DM/ha (38.8% of annual production) represented standing biomass that accumulated during the deferment period. Unlike the other treatments, this deferred biomass remained available for autumn utilization, providing 962.3 kg DM/ha (8.6%) of mature but accessible forage. Winter and spring production were 1,074.7 kg DM/ha (9.6%) and 4,832.8 kg DM/ha (43.0%), respectively. This distribution pattern, which was more stable than the Corn treatment, still showed considerable seasonal variation, with nearly 82% of the production concentrated in the summer and spring.

The Year-Round Grazing treatment displayed an intermediate level of seasonal variation with a distribution pattern typical of continuously grazed C3 perennial pastures in subtropical climates. Summer production was 2,037.7 kg DM/ha (19.9% of annual production) and autumn and winter production remained relatively low but consistent at 1,074.8 kg DM/ha (10.5%) and 1,282.8 kg DM/ha (12.5%), respectively. The system exhibited strong compensatory growth in spring, producing 5,833.8 kg DM/ha, which was the highest spring yield among all the treatments, representing 57.0% of its annual production.

Statistical analysis revealed significant treatment effects on seasonal production, particularly during the summer and autumn periods (P < 0.001), whereas winter and spring production showed no significant differences among treatments (P > 0.05). During summer, all treatments differed significantly from each other, with Corn > Deferred > YRG. The autumn period highlighted the unique absence of production in the corn treatment, which differed significantly from both the Deferred and YRG treatments that maintained similar production levels.

Table 2. Seasonal biomass dry matter production (kg DM/ha) and distribution patterns across three pasture management strategies in a subtropical perennial pasture system over a 12-month period.

Season	Corn[1]	Deferred	YRG	SEM	P-value
Summer	6,752.5[a] (50.5%)[2]	4,361.9[b] (38.8%)	2,037.7[c] (19.9%)	245.3	<0.001
Autumn	0.0[b] (0.0%)	962.3[a] (8.6%)	1,074.8[a] (10.5%)	89.2	<0.001
Winter	1,420.7[a] (10.6%)	1,074.7[a] (9.6%)	1,282.8[a] (12.5%)	112.4	0.6369
Spring	5,187.5[a] (38.8%)	4,832.8[a] (43.0%)	5,833.8[a] (57.0%)	287.6	0.1648
Annual Total	13,360.7	11,231.6	10,229.2		

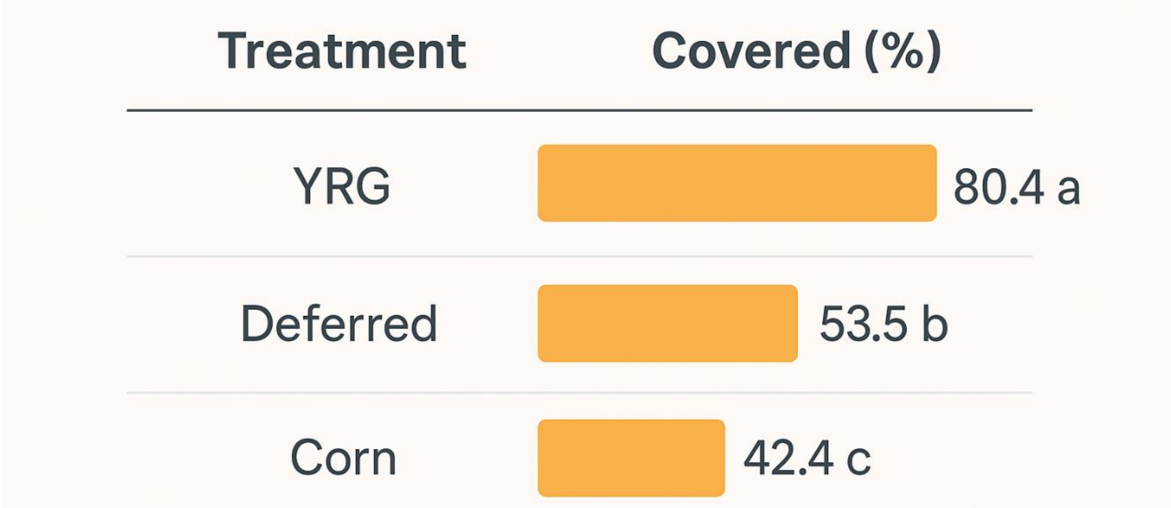
[1]Summer values for corn treatment included both corn silage (4,388.5 kg DM/ha) and residual pasture (2,364.0 kg DM/ha).
[2]Values in parentheses indicate the percentage contribution of each season to annual production.
SEM = Standard error of the mean; YRG = Year-round grazing.

4.1.3 Soil cover after summer

The percentage of soil cover following the different summer treatments showed significant variation among the management practices evaluated (Figure 2). Year-round ryegrass (YRG) treatment demonstrated superior soil protection capabilities, with 80.4% soil coverage, which was statistically higher ($p < 0.05$) than the other treatments.

The deferred treatment resulted in intermediate soil coverage (53.5%), which was significantly lower than that of YRG but higher than that of the corn treatment. While offering reasonable soil protection, the deferred treatment coverage was approximately 27% lower than that of YRG treatment. The corn treatment exhibited the lowest soil coverage percentage (42.4%), which was significantly lower than that of both alternative treatments. The difference between corn and YRG treatments was particularly pronounced, with corn providing approximately 38% less soil coverage than YRG.

Figure 2. Soil coverage by plant residues and living vegetation (%) measured at the end of the summer treatments in a subtropical perennial pasture system. Values represent the mean percentage of the soil surface protected by plant material across three management strategies: post-corn harvest residues (corn), accumulated biomass after seasonal deferment (deferred), and actively grazed pasture (YRG). Different letters indicate significant differences according to Tukey's honest significant difference (HSD) test ($p < 0.05$).



Means followed by different letters are significantly different (Tukey's HSD test, $p < 0.05$).

4.2 Plant Community Diversity: Responses to Disturbance and Recovery

Plant diversity was quantified using Hill numbers (q=0 for richness, q=1 for common species diversity, q=2 for dominant species diversity), revealing complex and dynamic responses to the management treatments over the annual cycle and providing insights.

4.2.1 Initial State and Immediate Post-Treatment Effects

Prior to treatment implementation ("Beginning" period), analysis of the plant community structure using Hill numbers confirmed the homogeneity of the experimental area across all assigned treatment plots (Figures 3). The mean species richness (q=0) across all experimental units was 6.45 ± 0.28 functional groups per sample, indicating a moderately diverse perennial pasture system typical of well-established mixed swards. Similarly, exponential Shannon entropy (q=1) averaged 3.86 ± 0.19, while inverse Simpson concentration (q=2) measured 3.17 ± 0.15. This initial uniformity in botanical diversity metrics was essential for the subsequent attribution of diversity changes to experimental treatments, rather than pre-existing site heterogeneity, thus strengthening the internal validity of the experimental design.

Following the implementation of experimental treatments during the summer intervention period, all treatments exhibited a measurable reduction in plant diversity metrics relative to the baseline conditions, although there were notable differences in both the magnitude and pattern of response (Figures 3). The corn integration treatment maintained comparatively higher median diversity values, particularly for common species diversity (q=1) and dominant species diversity (q=2), despite the substantial ecological perturbation associated with corn establishment. In deferred paddocks, the uninterrupted summer growth of vigorous perennial grasses led to a marked decline in the effective number of common species (q=1 decreased from 3.89 ± 0.21 to 2.14 ± 0.18) and the Year-Round Grazing treatment displayed an intermediate response, with diversity metrics decreasing moderately from initial values, but not as severely as observed in the deferred treatment.

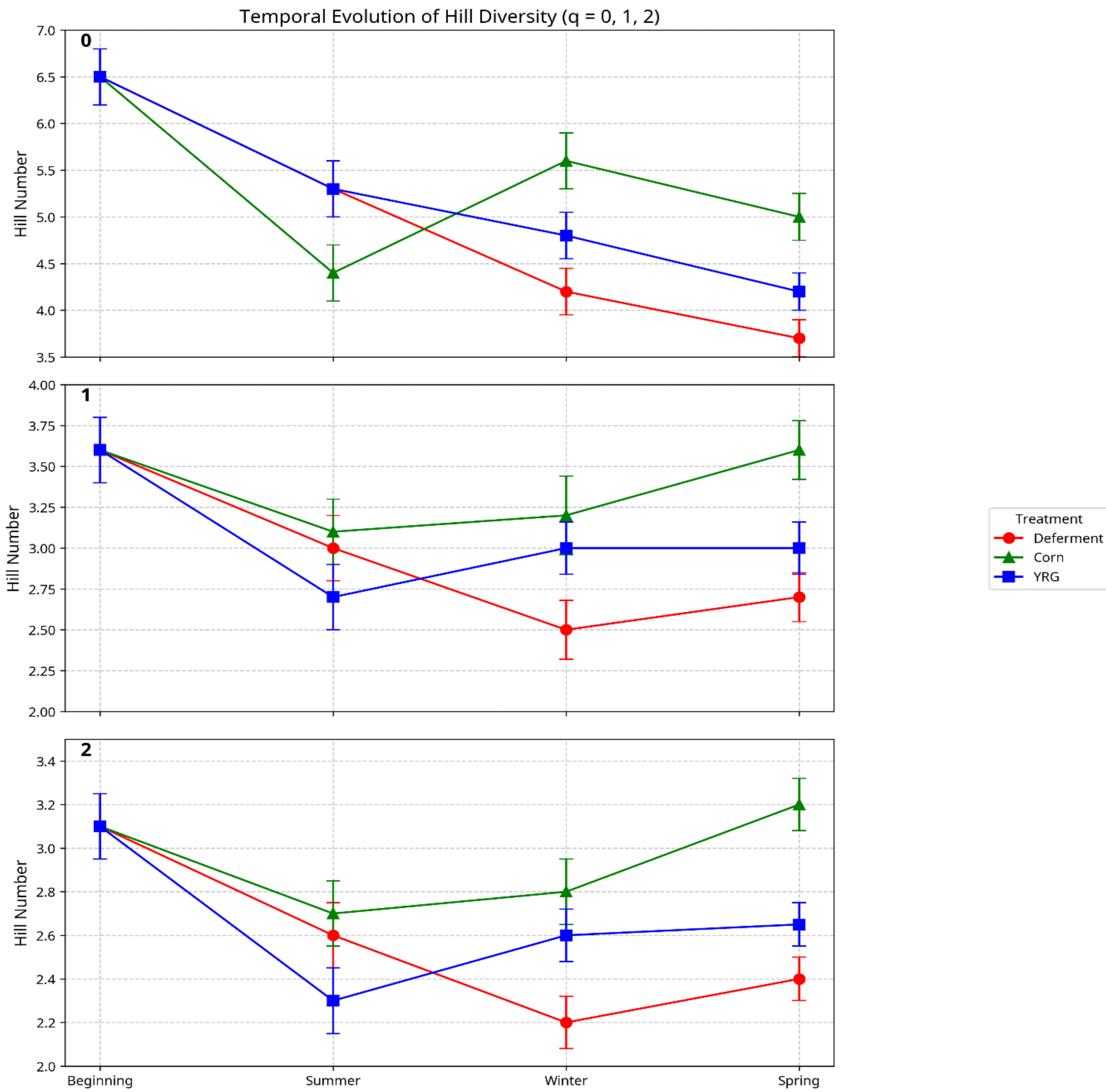
4.2.2 Recovery and Final Diversity Status

The most remarkable divergence in diversity trajectories manifested during the recovery phases ("Winter" and "Spring" periods), revealing profound treatment-specific effects on community reassembly processes (Figure 3). The corn integration treatment exhibited an exceptional resilience pattern, characterized by robust diversity recovery. Following corn harvest and alleviation of canopy suppression, all three diversity indices (q=0, q=1, q=2) increased significantly during winter (q=1 increased from 2.76 ± 0.24 4.32 ± 0.18). This positive trajectory continued throughout the remainder of the experimental period, culminating in elevated diversity levels by the "Spring" assessment at the conclusion of the 12-month cycle. At this terminal evaluation point, the Corn Integration treatment consistently demonstrated statistically superior diversity across all metrics compared to the alternative management approaches.

The Seasonal Deferment treatment exhibited minimal diversity recovery capacity. Following the pronounced initial diversity decline during summer deferment, diversity metrics particularly the effective number of common species (q=1) remained persistently depressed or continued their downward trajectory through both the Winter and Spring assessment periods (q=1 decreased from 2.14 ± 0.18 to 1.86 ± 0.15 by the spring assessment).

The Year-Round Grazing treatment exhibited an intermediate response pattern. Following moderate initial diversity reductions, this treatment showed partial recovery during the Winter and Final periods, eventually stabilizing at diversity levels significantly lower than the Corn Integration treatment but consistently higher than the Seasonal Deferment treatment (Final period q=1 values: 3.47 ± 0.16 versus 1.86 ± 0.15, respectively).

Figure 3. Temporal evolution of mean Hill diversity number q=0 (Species Richness), q=1 (Shannon effective diversity), and q=2 (Simpson effective diversity) over the four assessment periods for the three treatments.

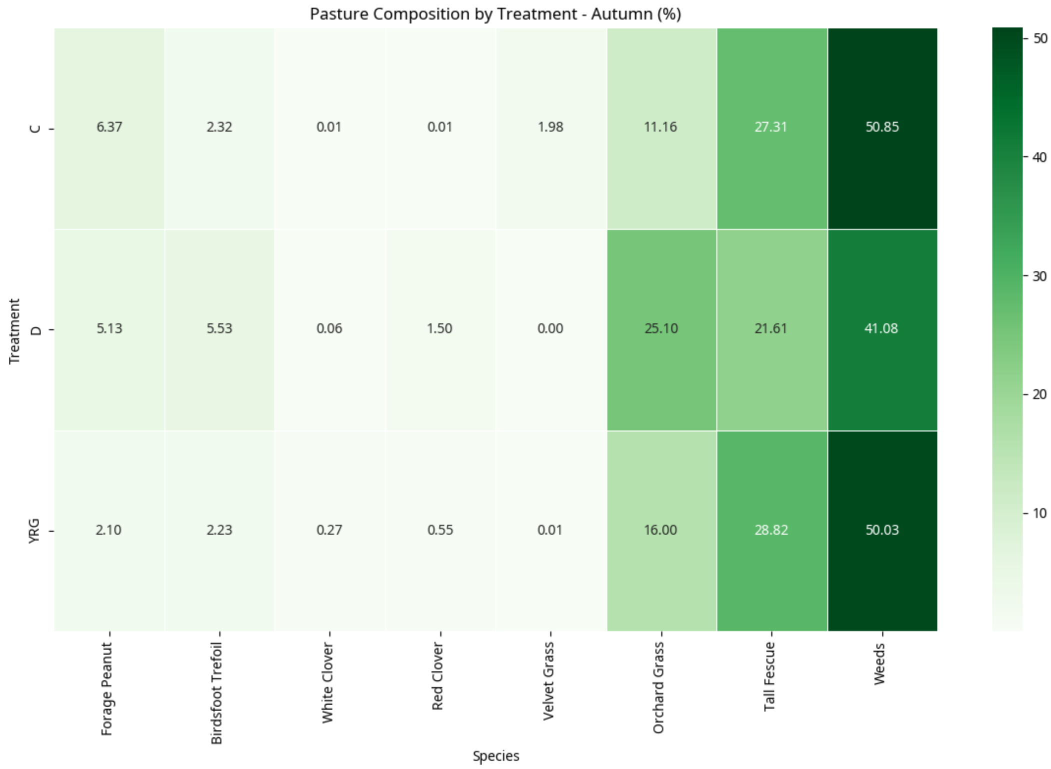

Temporal Evolution of Hill Diversity (q = 0, 1, 2)
0
1
2
Hill Number
Beginning
Summer
Winter
Spring
Treatment
Deferment
Corn
YRG

4.2.3 Pasture Composition Dynamics Under Different Management Strategies

A aspect of this study was the evolution of pasture composition across the different treatments, considering that all experimental units started with a uniform botanical composition. The heatmaps for spring, winter, and autumn reveal distinct trajectories for each management strategy, highlighting the impact of each treatment on the competitive dynamics of the pasture species.

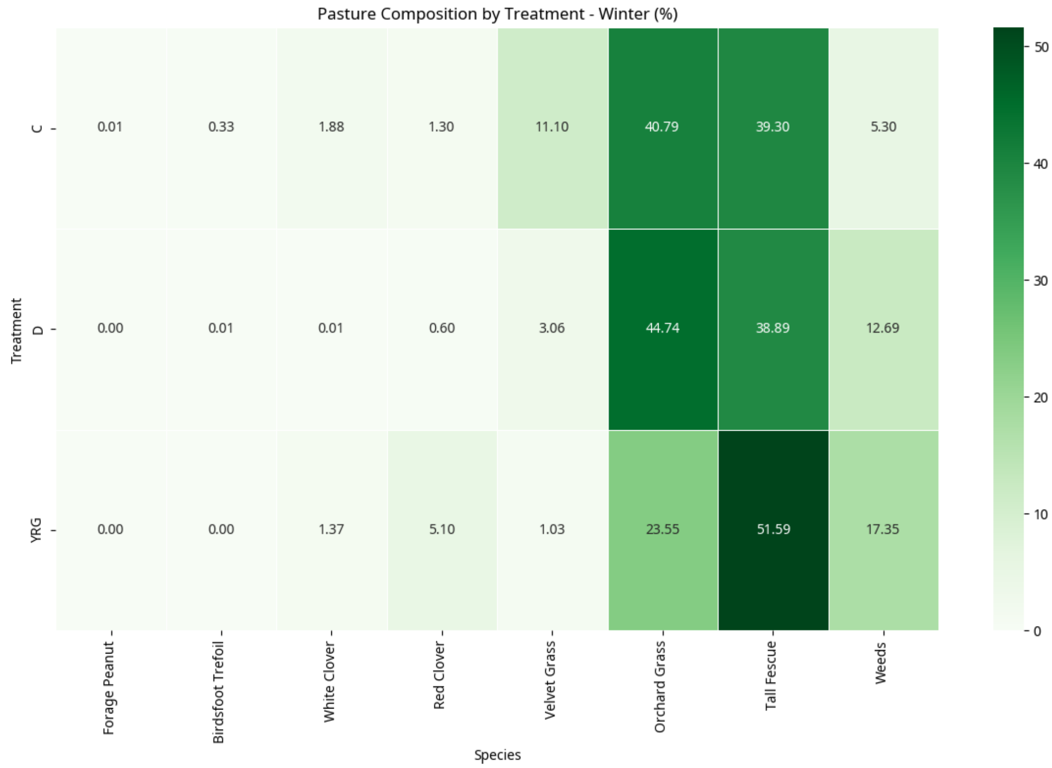
In the autumn (Figure 4), the impact of treatments on the proportion of invasive species becomes evident. The C and YRG treatments showed a high proportion of invasive species (50.85% and 50.03%, respectively), while the D treatment had a lower proportion (41.08%). This indicates that both the disturbance from the corn crop and the continuous grazing pressure in the YRG treatment created opportunities for the establishment of invasive species. The D treatment, by providing a period of rest, appears to have been more effective in suppressing the proliferation of these species.

Figure 4. Percentage composition of different pasture species during Autumn for the treatments. Darker green indicates a higher percentage of the species in the pasture composition.



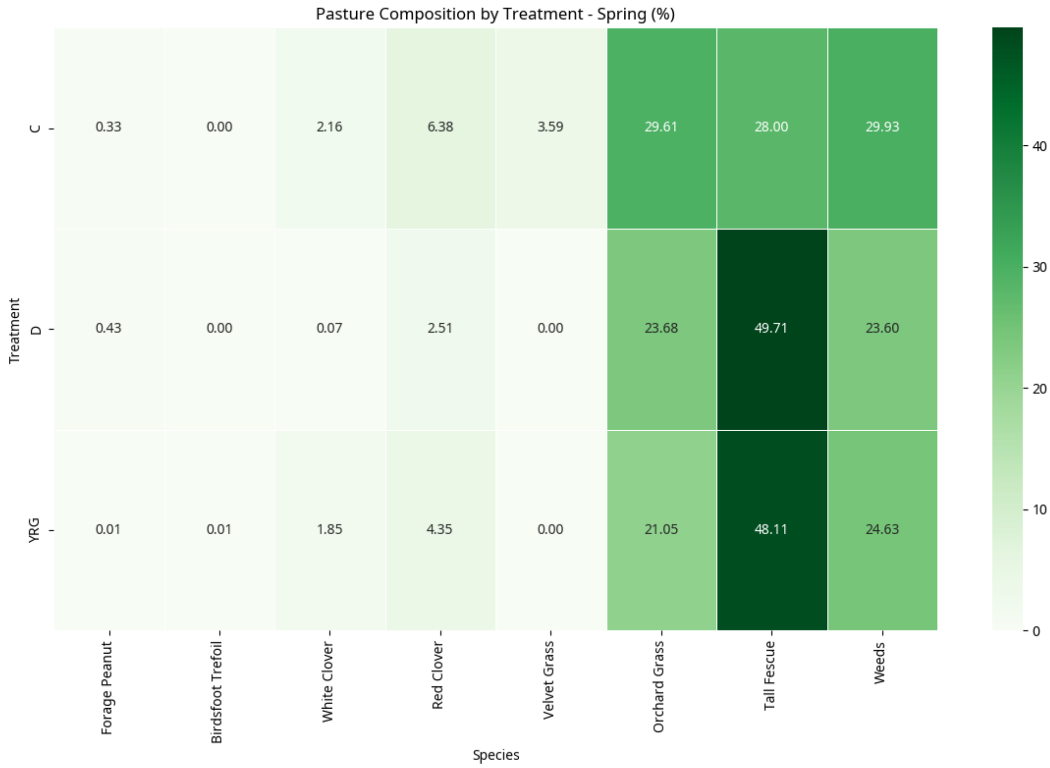
During the winter (Figure 5), a significant recovery of Dactylis and Festuca was observed in the C treatment, suggesting that these species were able to re-establish themselves after the corn harvest. The proportion of Dactylis in the C treatment (40.79%) was comparable to the D treatment (44.74%) and considerably higher than the YRG treatment (23.55%). This suggests that the disturbance caused by the corn cycle, followed by a period of rest, may have favored the recovery of Dactylis.

Figure 5. Percentage composition of different pasture species during Winter for the treatments. Darker green indicates a higher percentage of the species in the pasture composition.



In the spring (Figure 6), the Corn (C) treatment showed a marked reduction in all pasture species, which is an expected consequence of the corn crop's dominance. In contrast, the Year-Round Grazing (YRG) and Deferment (D) treatments maintained a relatively stable composition, with a high proportion of Festuca and Dactylis.

Figure 6. Percentage composition of different pasture species during Spring for the treatments. Darker green indicates a higher percentage of the species in the pasture composition.



5 Discussion

The findings from this year-long investigation into integrating summer corn silage within a long-established perennial pasture system offer compelling, albeit complex, insights into the interplay between agricultural management, productivity, and ecological dynamics, particularly concerning plant diversity and the often-underestimated role of the soil seed bank.

5.1 Productivity Enhancement via Integration

Corn Integration treatment significantly increased the total annual biomass (Figure 1), supporting our hypothesis. By incorporating a high-yielding C4 summer crop into the system, we favorable summer growing conditions, generating silage yield that for the temporary suppression of the C3 perennial pasture component. This approach exemplifies the core principles of Integrated Crop-Livestock Systems (ICLS), which address seasonal forage deficits common in Southern Brazil's Cfb climate zone through strategic diversification across growing seasons. This integration capitalizes on complementary physiological characteristics between different plant functional types, maximizing land productivity throughout the year (ALVES et al., 2020, SCHUSTER et al., 2019). Our seasonal production data (Table 2) demonstrate this temporal complementarity, showing corn dominance during summer, followed by robust perennial pasture recovery in spring. However, despite the increased biomass, the economic viability of this integration was limited due to lower-than-expected corn yields and the high costs associated with its implementation.

Superior summer production in the corn treatment can be attributed to several key physiological and ecological factors. First, the C4 photosynthetic pathway of corn provides a fundamental advantage in high-temperature and high-light environments, with approximately 40% greater theoretical maximum efficiency than C3 pathways (ROUQUETTE, 2023). This physiological advantage becomes particularly pronounced during the summer months when temperatures frequently exceed the photosynthetic optimum for C3 species (typically 15-25°C), while it remains well within the optimal range (30-35°C). Additionally, corn's vertical canopy architecture and greater height allow for more efficient light interception per unit ground area compared to the predominantly horizontal structure of pasture species, we found that corn intercepts approximately 65% of the light incident on the area, effectively increasing the photosynthetically active radiation captured during the peak solar radiation period of the year (GUAMÀN RIVERA et al., 2023). Furthermore, strategic fertilization applied to support corn growth (150 kg N/ha) provided nutrient conditions that maximized this physiological potential, resulting in biomass accumulation rates that far exceeded what the perennial pasture species could achieve, even under ideal management.

Conversely, the Year-Round Grazing treatment, despite maintaining greater soil coverage throughout the experimental period, failed to produce comparable summer biomass due to several limiting factors. The C3 perennial species dominating this treatment (primarily tall fescue, orchardgrass, and clovers) experienced significant metabolic limitations during summer, including increased photorespiration, reduced RuBisCO efficiency, and accelerated senescence rates when temperatures consistently exceeded 25°C (GILHAUS & HÖLZEL, 2016). These physiological constraints fundamentally limit productivity, regardless of management intensity or soil coverage. Additionally, although greater ground cover in the grazing treatment provided advantages in terms of soil protection and microclimate moderation, it simultaneously intensified intraspecific competition for soil resources during a period when root activity and nutrient uptake efficiency were already compromised by heat stress. The continuous defoliation pressure, even under rotational management, further reduced the ability of plants to maintain photosynthetic capacity during thermal stress, as the limited leaf area restricted carbon fixation and carbohydrate reserves needed for recovery (SBRISSIA et al., 2020).

While the Corn treatment maximized total annual biomass, its highly seasonal production pattern presents both opportunities and challenges for livestock management. The high summer silage yield provides a substantial reserve of feed that can be strategically used during periods of pasture scarcity, particularly the subsequent autumn/winter, or even during potential droughts in other years. However, near-zero pasture availability immediately following corn harvest necessitates careful planning to ensure that alternative feed sources are available for livestock during the transition period (MORAES *et al*., 2014). In contrast, the Deferred and Grazing treatments offered more continuous, albeit lower, forage availability from the pasture itself, which might simplify day-to-day grazing management but require supplementation during the summer slump (grazing) or offer a standing forage reserve of potentially declining quality (deferred) (FONTANELI *et al*., 2012).

The choice between these strategies depends heavily on the specific farm context, including livestock category and requirements, availability of labor and machinery for silage production, and the capacity for feed storage and targeted supplementation. The Corn integration strategy clearly favors systems capable of managing silage production and utilization effectively, potentially allowing for higher overall stocking rates or animal performance due to the increased total energy harvested per unit area.

5.2 Pasture Diversity Dynamics and the Soil Seed Bank as Ecological Memory

Our most ecologically significant findings were regarding pasture resilience and diversity dynamics. Contrary to the expectation that corn cultivation would degrade perennial swards, we observed a counterintuitive pattern of enhanced diversity. The perennial pasture not only demonstrated remarkable recovery capacity following corn harvest, but by the conclusion of the annual cycle, the Corn Integration treatment exhibited higher plant diversity across all Hill diversity orders (species richness, common species diversity, and dominant species diversity) compared to both Year-Round Grazing and, particularly, seasonal deferment treatments (Figures 3). This evidence suggests that the disturbance introduced by the corn cycle functioned as a catalyst for ecological regeneration rather than a purely disruptive force. Instead of diminishing biodiversity, corn integration appeared to stimulate community reassembly by activating the soil seed bank, an ecological legacy maintained throughout the pasture's 7+ year establishment. Studies have demonstrated that persistent soil seed banks can retain high biodiversity and act as reservoirs of ecological memory, even after decades of agricultural disturbance, thus playing a pivotal role in regeneration (MA et al., 2015). Their composition often differs from that of aboveground vegetation, reflecting latent diversity not yet expressed under stable conditions but activated through disturbance, indicating that the persistence of perennial plants decreases with increasing grazing intensity (LAMAS et al., 2020).

Soil seed banks represent a crucial component of ecosystem resilience and act as persistent reservoirs of genetic and species diversity that accumulates over time (BAKKER et al., 1996; FENNER; THOMPSON, 2006). In long-established grasslands, such as the one studied here, the seed bank potentially contains a rich assemblage of seeds from species currently present, previously dominant, or transiently occurring, including sown forage species, naturalized species, and native flora adapted to the local environment (TYLER et al., 2021; KALAMEES; ZOBEL, 2002). The 7+ year period of perennial management provided ample time for such a ‘memory’ to develop, potentially harboring species with varying dormancy requirements and longevity (THOMPSON; GRIME, 1979; BEKKER et al., 1997).

5.3 Disturbance as a Trigger for Seed Bank Expression

The sequence of events in the Corn treatment – including potential minor soil disturbance during no-till planting, application of fertilizers, the complete removal of the dense corn canopy at harvest, and the subsequent opening of gaps in the perennial sward – likely created a unique ‘window of opportunity’ or ‘regeneration niche’ (GRUBB, 1977). Changes in environmental factors (e.g., light availability, temperature fluctuations, nutrient levels, and potentially altered soil moisture) are known triggers for breaking seed dormancy and stimulating germination in soil seed banks (BOSSUYT HERMY, 2003; WELLSTEIN *et al*., 2007; RAYBUN *et al*., 2016). Species residing in the seed bank, perhaps suppressed under the previously dense perennial canopy or requiring specific cues provided by the disturbance, could germinate and establish in the postharvest environment. This influx of species germinating from the seed bank likely explains the sharp increase in richness (q=0) and overall diversity (q=1, q=2) observed in the corn treatment during the Winter and Final periods (Figures 2).

The divergent diversity trajectories among the treatments further reinforced the seed bank hypothesis. The deferred treatment, characterized by a lack of disturbance during the summer, experienced a decline and subsequent stagnation of diversity, particularly for common species (q=1) (Figures 1). This suggests that without disturbance, dominant perennial species likely consolidated their hold through competitive exclusion (ISBELL *et al*., 2015), preventing the expression of potential diversity stored within the seed bank. The continuously grazed treatment, representing a chronic but potentially less intense or temporally focused disturbance than the corn cycle, maintained an intermediate diversity level. Although grazing creates small-scale gaps, it might not provide the same strong, synchronized germination cues, or the same extent of niche availability as the post-corn harvest environment, thus potentially limiting the full expression of the seed bank compared to the Corn treatment.

5.4 Alignment with Ecological Theory

These observations resonate with the Intermediate Disturbance Hypothesis (IDH), which proposes that species diversity is often maximized at intermediate levels of disturbance frequency, intensity, or scale (CONNELL, 1978; ROSWELL; DUSHOFF; WINFREE, 2021). The annual cycle of corn planting and harvest in the corn treatment can be conceptualized as a relatively intense but temporally defined disturbance event that occurs once per year. This periodic disturbance appears to have prevented the competitive dominance observed under deferment while simultaneously creating sufficient regeneration opportunities for seed bank species, ultimately promoting higher diversity than either the low (deferred) or chronic disturbance (YRG) scenarios in this specific context (FABŠIČOVÁ *et al*., 2024).

5.5 Understanding the Low Diversity in the Deferred Treatment

The consistently lowest diversity observed in the deferred treatment at the end of the experiment warrants further investigation. Although deferment is often considered a conservation-oriented practice that allows pastures to rest and set seeds, prolonged deferment without any intermediate disturbance can lead to the dominance of highly competitive species (ISBELL *et al*., 2015; GÜSEWELL *et al*., 2005). In this established perennial pasture, the summer rest period allowed robust perennial grasses (e.g., Festuca and Dactylis) to form a dense, closed canopy, outcompeting less vigorous grasses, legumes, and forbs for light and other resources. This competitive exclusion process reduces species evenness (reflected in the low q=1 values) and can eventually lead to the loss of less competitive species (reduced q=0). The subsequent introduction of grazing in autumn/winter was insufficient to reverse this trend within the timeframe of the present study. This highlights that simply removing grazing pressure is not always beneficial for maximizing diversity, especially in productive environments, where competitive exclusion can proceed rapidly.

5.6 Seasonal Biomass Distribution and Management Implications

The distinct seasonal biomass distribution patterns observed under each management strategy (Table 2) necessitate tailored management approaches, beyond simply considering the total annual yield. The Corn integration strategy, while maximizing summer biomass, illustrates this with its pronounced autumn forage gap. As highlighted previously (Section 4.4), this gap, directly resulting from the corn harvest cycle within the ICLS framework, requires proactive management interventions, such as planned supplementation or access to alternative grazing areas, to bridge the feed deficit during this critical period (ASSMANN *et al*., 2020).

Conversely, the Deferred strategy highlights how managing seasonal biomass accumulation can effectively address feed shortage. By allowing summer growth to be stockpiled, it ensures biomass availability during autumn, offering more stability during this transitional period than the corn system. However, attention must be paid to the decline in forage nutritive value as stockpiled material matures, which can reduce its effectiveness without supplemental management strategies (GUAMÀN RIVERA *et al*., 2023; GILHAUS; HÖLZEL, 2016).

The Year-Round Grazing system, characterized by its summer slump and strong spring compensatory growth, requires a different management focus. Strategies under the YRG must concentrate on managing grazing pressure to navigate low summer productivity while optimizing the utilization of high biomass production during favorable spring conditions. The resilience observed, linked to tiller dynamics and recovery mechanisms (SBRISSIA *et al*., 2020; PITARO *et al*., 2025), highlights the importance of management practices that support pasture persistence and regrowth potential following periods of stress.

6 Conclusions and implications

Our findings demonstrate that corn integration significantly enhances total annual biomass production compared with traditional management strategies, effectively addressing the critical summer forage deficit characteristic of Southern Brazil's Cfb climate region. However, it is crucial to highlight that this production advantage comes with a significant management challenge: the corn treatment resulted in approximately half a year without grazing availability (only a single grazing event after the maize harvest). This extended period without pasture access creates substantial difficulties in maintaining consistent livestock feeding throughout the annual cycle, which requires careful planning and alternative feed resources.

The management implications of this grazing gap cannot be understated. Producers implementing corn integration must allocate only a fraction of their total pasture area to corn production (maintaining the remainder for continuous grazing), invest in supplementary feeding systems, or develop a staggered planting approach across multiple paddocks. Each of these strategies introduces additional complexity and potential costs that must be carefully weighed against production benefits.

Despite this significant limitation, our findings regarding plant diversity dynamics were remarkable, as we observed that the greatest diversity occurred in the corn-integrated system and not in the least disturbed treatment. This challenges the conventional wisdom regarding disturbance effects in established grasslands and highlights the importance of considering the role of soil seed banks in resilience and recovery. The disturbance created by the corn cycle appears to have stimulated dormant seeds while preventing competitive exclusion, creating favorable conditions for a diverse plant community to emerge post-harvest.

These results present a critical challenge for sustainable intensification strategies in temperate and subtropical regions. They indicate that the integration of annual crops within perennial pastures, despite its potential to address production gaps and enhance ecological attributes like plant diversity, is not an economically viable strategy for cost reduction or efficiency gains. The substantial financial outlay required for its implementation appears to negate the potential returns from increased productivity .

Future studies should investigate the long-term implications of repeated corn integration cycles on soil health, pasture diversity, and biodiversity over multiple years. Additionally, exploring different annual crop options, timing of integration, and management approaches could further optimize these systems for different agricultural contexts, particularly focusing on minimizing the grazing gap duration. Economic analysis can also help determine the practical feasibility of implementation for farmers across diverse operation types and scales, accounting for additional management requirements during the non-grazing period.

REFERENCES

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; GONÇALVES, J. L. M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2013. DOI:10.1127/0941-2948/2013/0507.

ALVES, L. C.; DENARDIN, L. G de O.; MARTINS, A. P. *et al*. The effect of crop rotation and sheep grazing management on plant production and soil C and N stocks in a long-term integrated crop-livestock system in Southern Brazil. **Soil & Tillage Research**, v. 203, 104678, 2020. DOI:10.1016/j.still.2020.104678.

ASSMANN, T.; JÚNIOR, P. R.; MORAES, A. *et al*. Rendimento de milho em área de integração lavoura-pecuária sob o sistema plantio direto, em presença e ausência de trevo branco, pastejo e nitrogênio. **Revista Brasileira de Ciência do Solo**, v. 27, n. 4, p. 675-683, 2003. DOI: 10.1590/S0100-06832003000400012.

PETERSON, C. A.; BELL, L. W.; CARVALHO, P. C. F. *et al*. Resilience of an Integrated Crop–Livestock System to Climate Change. **Frontiers in Sustainable Food Systems**, v. 4, 60409, 2020. DOI: 10.3389/fsufs.2020.604099.

BAKKER, J. P.; POSCHLOD, P.; STRYKSTRA, R. J.; BEKKER, R. M.; THOMPSON, K. Seed banks and seed dispersal: important topics in restoration ecology. **Acta Botanica Neerlandica**, v. 45, n. 4, p. 461-490, 1996. DOI: j.1438-8677.1996.tb00806.x

BEKKER, R. M.; VERWEIJ, G. L.; SMITH, R. E. N.; REINE, R.; BAKKER, J. P.; SCHNEIDER, S. Soil seed banks in European grasslands: does land use affect regeneration perspectives? **Journal of Applied Ecology**, v. 34, n. 5, p. 1293-1310, 1997. DOI:10.2307/2405239

BOSSUYT, B.; HERMY, M. The potential of soil seedbanks in the ecological restoration of grassland and heathland communities. **Belgian Journal of Botany**, v. 136, n. 1, p. 23-34, 2003.

CHAO, A.; CHIU, C.-H.; JOST, L. Unifying species diversity, phylogenetic diversity, functional diversity, and related similarity and differentiation measures through Hill numbers. **Annual Review of Ecology, Evolution, and Systematics**, v. 45, p. 297–324, 2014.

COELHO, Rogério Waltrick. **Manejo de pastagens melhoradas de inverno**. Pelotas, RS: Embrapa Clima Temperado, 1999. (Circular Técnica, n. 17).

CONNELL, Joseph H. Diversity in Tropical Rain Forests and Coral Reefs. **Science**, v. 199, n. 4330, p. 1302-1310, 24 mar. 1978. DOI: 10.1126/science.199.4330.1302.

DUCHINI, P. G.; GUZATTI, G. C.; RIBEIRO FILHO, H. M. N.; SBRISSIA, A. F. Experimental evidence that the perennial grass persistence pathway is linked to plant growth strategy. **PLoS ONE**, v. 14, n. 11, e0225506, 2019. DOI: 10.1371/journal.pone.0207360.

EVANS, R. A.; LOVE, R. M. The step-point method of sampling—A practical tool in range research. **Journal of Range Management**, v. 10, n. 5, p. 208-212, 1957. DOI: 10.2307/3894294.

FABŠIČOVÁ, Martina et al. The importance of soil seed banks for biodiversity restoration in degraded grasslands**. Folia Geobotanica**, 2024. DOI: 10.1007/s12224-024-09452-x.

FENNER, M.; THOMPSON, K. **The ecology of seeds**. Cambridge: Cambridge University Press, 2006. DOI: 10.1017/CBO9780511614101

FONTANELI, R. S.; SANTOS, H. P.; FONTANELI, R. S. **Forrageiras para integração lavoura-pecuária-floresta na região Sul- Brasileira**. 2. ed. Brasília, DF: Embrapa, 2012.

FRAME, J.; BOYD, A. G. The effect of fertilizer nitrogen rate, white clover variety and closeness of cutting on herbage productivity from perennial ryegrass/white clover swards. **Grass and Forage Science**, v. 42, n. 1, p. 85-96, mar. 1987. DOI: 10.1111/j.1365-2494.1987.tb02094.x.

FRIBOURG, H.A; BRYAN, W.E.; LESSMAN, G.M.; MANNING, D.M. Nutrient uptake by com and grain sorghum silage as affected by soil type, planting date, and moisture regime. **Agronomy Journal**, v.68, n.2, p.260-264, 1976.

GHASSEMI-GOLEZANI, K.; CHADORDOOZ-JEDDI, A.; NASROLLAHZADEH, S.; MOGHADDAM, M. Effects of hydro-priming duration on seedling vigour and grain yield of pinto bean (Phaseolus vulgaris L.) cultivars. **Notulae Botanicae**

Horti Agrobotanici Cluj-Napoca, v. 38, n. 1, p. 109-113, 2010. DOI:10.15835/nbha3813475

GILHAUS, K.; HÖLZEL, N. Seasonal variations of fodder quality and availability as constraints for stocking rates in year-round grazing schemes. **Agriculture, Ecosystems & Environment**, v. 234, p. 5-15, 2016. DOI:10.1016/j.agee.2016.03.013

GRUBB, P. J. The maintenance of species-richness in plant communities: the importance of the regeneration niche. **Biological Reviews**, v. 52, n. 1, p. 107-145, 1977. DOI:10.1111/j.1469-185X.1977.tb01347.x

GUAMÀN RIVERA, S. A.; GUERRERO-PINCAY, Á. E.; ORTIZ-NAVEDA, N. R.; GONZÁLEZ-MARCILLO, R. L. Prediction of the nutritional values by INRA (2018) feed evaluation system of Megathyrsus maximus subjected to different grazing strategies. **Journal of Agriculture and Environment for International Development - JAEID**, v. 117, n. 1, p. 117–140, 2023. DOI: 10.36253/jaeid-14203

GILHAUS, K.; HÖLZEL, N. Seasonal variations of fodder quality and availability as constraints for stocking rates in year-round grazing schemes. **Agriculture, Ecosystems & Environment**, v. 234, p. 5-15, 2016. DOI:10.1016/j.agee.2016.03.013

GÜSEWELL, S.; POHL, M.; GANDER, A.; STREHLER, C. Temporal changes in grazing intensity and herbage quality within a Swiss fen meadow. **Botanica Helvetica**, v. 115, n. 1, p. 15-30, 2005. DOI: 10.1007/s00035-007-0798-7

HILL, M. O. Diversity and evenness: a unifying notation and its consequences. **Ecology**, v. 54, n. 2, p. 427–432, 1973. DOI:10.2307/1934352

HOOPER, D. U.; CHAPIN, F. S.; EWEL, J. J.; *et al*. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. **Ecological Monographs**, v. 75, n. 1, p. 3-35, 2005. DOI: 10.1890/04-0922.

INSTITUTO NACIONAL DE METEOROLOGIA (**INMET**). Annual Historical Data. Available in: https://portal.inmet.gov.br/dadoshistoricos. Access :12 Aug. 2025.

ISBELL, F.; CRAVEN, D.; CONNOLLY, J.; *et al*. Biodiversity increases the resistance of ecosystem productivity to climate extremes. **Nature**, v. 526, n. 7574, p. 574-577, 2015. DOI: 10.1038/nature15374.

JOST, L. Partitioning diversity into independent alpha and beta components. **Ecology,** v. 88, n. 10, p. 2427–2439, 2007. DOI: 10.1890/06-1736.1

KALAMEES, R.; ZOBEL, M. The role of the seed bank in gap regeneration in a calcareous grassland community. **Ecology**, v. 83, n. 4, p. 1017-1025, 2002. DOI:10.1890/0012-9658(2002)083[1017:TROTSB]2.0.CO;2

KUNRATH, T. R.; CADENAZZI, M.; BRAMBILLA, D. M.; ANGHINONI, I.; MORAES, A.; BARRO, R. S.; CARVALHO, P. C. F. Management targets for continuously stocked mixed oat × annual ryegrass pasture in a no-till integrated crop-livestock system. **European Journal of Agronomy**, v. 57, p. 71-76, 2014. DOI: 10.1016/j.eja.2013.09.013.

LAMAS, M. I. B.; CARRERA, A.; BERTILLER, M. Sheep grazing differentially affects the canopy attributes and functional diversity of shrubs and perennial grasses in arid rangelands**. Plant Ecology**, [s. l.], v. 221, n. 10, p. 977-989, 4 out. 2020. DOI: 10.1007/s11258-020-01084-3.

LI-COR BIOSCIENCES. **LAI-2200C Plant Canopy Analyzer Instruction Manual**. Lincoln, NE: LI-COR Biosciences, 2016.

MA, M.; ZHOU, X.; DU, G. Role of soil seed bank along a disturbance gradient in an alpine meadow on the Tibet plateau. **Flora**, v. 212, p. 17-24, 2015.

MENEZES, L. S.; ELY, C. V.; LUCAS, D. B.; *et al*. Reference values and drivers of diversity for South Brazilian grassland plant communities. **Anais da Academia Brasileira de Ciências**, v. 94, n. 1, e20201079, 2022.

OLIVO, A. J. *et al*. Defining a green operational outcomes domain for nitrogen management in corn silage production. **Field Crops Research**, v. 310, p. 109495, 2025.

OVERBECK, G. E.; MÜLLER, S. C.; FIDELIS, A.; *et al*. Brazil's neglected biome: The South Brazilian Campos. **Perspectives in Plant Ecology, Evolution and Systematics**, v. 9, n. 2, p. 101-116, 2007.

PÄRTEL, M. Community ecology of absent species: hidden and dark diversity**. Journal of Vegetation Science**, v. 25, n. 5, p. 1154-1159, 2014.

PEREYRA-GODAY, F. *et al*. Nitrogen use efficiency in mixed crop-livestock systems. **Frontiers in Sustainable Food Systems**, v. 9, p. 1522557, 2025.

RAYBURN, Andrew P.; SCHRIEFER, Craig; ZAMORA, Aubrianne; LACA, Emilio A. Seedbank-Vegetation Relationships in Restored and Degraded Annual California Grasslands: Implications for Restoration. **Ecological Restoration**, v. 34, n. 4, p. 277-284, dez. 2016. DOI: 10.3368/er.34.4.277.

ROUQUETTE, M. Grazing management and stocking strategy decisions for pasture-beef systems: Experimental confirmation vs testimonials and perceptions. **Journal of Animal Science**, v. 101, n. 1, p. 109-120, 2023.

PITTARO, M. G. et al. Tiller population dynamics and self-thinning law reveal stability mechanisms in mixed grass swards under variable grazing management. **The Journal of Agricultural Science**, v. 163, n. 2, p. 160-170, fev. 2025. DOI: 10.1017/S0021859625000176.

PETERSON, C. A.; BELL, L. W.; CARVALHO, P. C. D. F.; GAUDIN, A. C. M. Resilience of an Integrated Crop–Livestock System to Climate Change: A Simulation Analysis of Cover Crop Grazing in Southern Brazil. **Frontiers in Sustainable Food Systems**, v. 4, 604099, 2020. DOI: 10.3389/fsufs.2020.604099.

ROSWELL, M.; DUSHOFF, J.; WINFREE, R. A conceptual guide to measuring species diversity. **Oikos**, v. 130, n. 3, p. 321-338, 2021. DOI:10.1111/oik.07202.

SANDERSON, M. A.; SKINNER, R. H.; BARKER, D. J.; EDWARDS, G. R.; TRACY, B. F.; WEDIN, D. A. Plant species diversity and management of temperate forage and grazing land ecosystems. **Crop Science**, v. 44, n. 4, p. 1132-1144, 2004. DOI: 10.2135/cropsci2004.1132.

SANDERSON, M. A.; SODER, K. J.; MULLER, L. D.; KLEMENT, K. D.; SKINNER, R. H.; GOSLEE, S. C. Forage mixture productivity and botanical composition in pastures grazed by dairy cattle. **Agronomy Journal**, v. 97, n. 5, p. 1465-1471, 2005. DOI:10.2134/agronj2005.0032.

SANTOS, Erick R. S. et al. Integrated crop-livestock systems result in less nitrate leaching than ungrazed crop systems in North Florida. **Journal of Environmental Quality**, 10 mar. 2023. DOI: 10.1002/jeq2.20474.

SBRISSIA, A. F.; SCHMITT, Daniel; DUCHINI, Paulo Gonçalves; SILVA, Sila Carneiro Da. Unravelling the relationship between a seasonal environment and the dynamics of forage growth in grazed swards. **Journal of Agricultural Science**, 23 mar. 2020. DOI: 10.1111/jac.12402.

SBRISSIA, André Fischer. Forragens: Produção e manejo. Curitiba: FAEP, 2023. Disponível em: https://www.sistemafaep.org.br/wp-content/uploads/2023/06/PR.0359-Forragens-Producao-e-manejo_web.pdf.

SCHUSTER, M. Z.; LUSTOSA, S. B. C.; PELISSARI, A.; *et al*. Optimizing forage allowance for productivity and weed management in integrated crop-livestock systems. **Agronomy for Sustainable Development**, v. 39, 18, 2019. https://doi.org/10.1007/s13593-019-0564-4.

THOMPSON, K.; GRIME, J. P. Seasonal variation in the seed banks of herbaceous species in ten contrasting habitats. **Journal of Ecology**, v. 67, n. 3, p. 893-921, 1979. DOI: 10.2307/2259220

TILMAN, D.; KNOPS, J.; WEDIN, D.; REICH, P.; RITCHIE, M.; SIEMANN, E. The influence of functional diversity and composition on ecosystem processes. **Science**, v. 277, n. 5330, p. 1300-1302, 1997. DOI:10.1126/science.277.5330.1300.

TRACY, B. F.; SANDERSON, M. A. Forage productivity, species evenness and weed invasion in pasture communities. **Agriculture, Ecosystems & Environment**, v. 102, n. 2, p. 175-183, 2004. DOI:10.1016/j.agee.2003.08.002.

TYLER, T.; HERBERTSSON, L.; OLOFSSON, J.; OLSSON, P. A. Ecological indicator and traits values for Swedish vascular plants. **Ecological Indicators**, v. 120, 106923, 2021. DOI: 10.1016/j.ecolind.2020.106923.

WELLSTEIN, C.; OTTE, A.; WALDHARDT, R. Seed bank diversity in mesic grasslands in relation to vegetation type, management and site conditions. **Journal of Vegetation Science**. 18, n. 2, p. 153-162, 2007. DOI:10.1111/j.1654-1103.2007.tb02527.x.