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Effect of Varying Dairy Cow Size and Live Weight on Soil Structure and Pasture Attributes

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Abstract

Grazing systems' production efficiency is a dynamic interaction between soil, pasture, livestock, and climate. The magnitude of the changes is related to the mechanical stress applied by the livestock and their feeding behaviour. In Southern Chile, dairy cattle present a high heterogeneity in breeds, size, live weight, and milk production. This study investigated whether cows of contrasting size/live weight can improve degraded pasture and positively modify soil (Andosol-Duric Hapludand) physical features. Three pasture types were used as follows: (i) cultivated fertilised *Lolium perenne* L. (perennial ryegrass) and *Trifolium repens* L. (white clover) mixture (BM); (ii) cultivated fertilised *L. perenne*, *T. repens*, *Bromus valdivianus* Phil. (pasture brome), *Holcus lanatus* L. (Yorkshire fog), and *Dactylis glomerata* L. (cocksfoot) mixture (MSM); and (iii) naturalised fertilised pasture *Agrostis capillaris* L. (browntop), *B. valdivianus*, and *T. repens* (NFP). Pastures were grazed with two groups of dairy cows of contrasting size and live weight: light cows (LC) [live weight: 464 ± 5.4 kg; height at the withers: 132 ± 0.6 cm (average ± s.e.m.)] and heavy cows (HC) [live weight: 600 ± 8.7 kg; height at the withers: 141 ± 0.9 cm (average ± s.e.m.)]. Hoof area was measured, and the pressure applied by cows on the soil was calculated. Soil differences in penetration resistance (PR) and macro-porosity (wCP > 50 µm) between pastures were explained by tillage and seeding, rather than as a result of livestock presence and movement (animal trampling). The PR variation during the year was associated with the soil water content (SWC). Grazing dairy cows of contrasting live weight caused changes in soil and pasture attributes, and they behaved differently during grazing. Light cows were linked to more intense grazing, a stable soil structure, and pastures with competitive species and greater tiller density. In MSM, pasture consumption increased, and the soil was more resilient to hoof compression. In general, grazing with heavy cows in these three different pasture systems did not negatively impact soil physical properties. These findings indicate that volcanic soils are resilient and that during renovation, the choice of pasture type has a greater initial impact on soil structure than the selection of cow size, but incorporating lighter cows can be a strategy to promote denser pasture swards in these grazing systems.

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1. Introduction

Dairy cow size and performance are closely related; however, optimal performance does not always correlate directly with size [1]. Livestock size and live weight significantly impact milk production, feed efficiency, health, and overall farm economics [2–4]. Pasture plant species composition, persistence, and soil properties may be negatively impacted by livestock feeding behaviour and stocking density, depending on prevailing climatic conditions [5–7]. Pasture systems involve complex interactions between herbivores, plants, soil, and climate [8,9]. For example, pasture species diversity/composition and palatability, coupled with intensity and duration of grazing/plant defoliation events, drive dung and urine distribution and deposition, while soil health and type (physical, chemical, and biological properties), and prevailing climatic conditions/season drive nutrient turnover, soil water availability, and pasture regrowth [10–12].

Animal size, stocking rate, grazing management (grazing event duration and rest period), and pasture species availability and diversity, coupled with livestock preference and selectivity, drive grazing/defoliation events [13,14], both in the short and long term. Grazing livestock spend ~38% of the day engaged in some form of active grazing, walking ~3 km per day [15]. Livestock weight and movement influence soil pressure due to the hoof area, which may lead to compaction if soil precompression stress is exceeded. Pressure generated by the mass of the animal (either standing or walking) is distributed by the size of the hoof, which is distributed by the size of the hoof/claws [medial claw (inner) and lateral claw (outer)], and the number of hooves/claws in contact with the ground. For example, when livestock is stationary (standing), livestock mass/weight is usually distributed on all four hooves/claws, but when an animal is in motion (walking, etc.), the weight is distributed over two or three hooves/claws, which are in contact with the soil at the same time [10,16]. If the pasture is flat (not sloping), then the pressure/weight applied to the soil will be spread equally between the hooves/claws that are in contact with the soil surface [17]. However, when the pasture/soil surface is uneven (micro-reliefs, pugging, etc.) and/or sloping, pressure may be spread unevenly between hooves/claws [18]. Furthermore, during grazing, if the applied pressure (animal weight through the hoof/claw) is higher than the soil precompression stress (Pc; the maximum load that the soil can resist before plastic deformation) [19], then the soil structure degrades and pore functions (e.g., water infiltration) are potentially lost [20,21]. However, if the applied load (down-pressure) is lower than the soil Pc, then the soil is able to tolerate/resist the impact of animal hooves/claws without losing its functions.

The degree of soil compaction through livestock treading is affected by increasing soil water content. For example, when a dairy cow walks on loamy soil (in a friable state), pressure is transmitted to the top 5 cm of soil (depth). However, when the soil is saturated, this transmission increases to a greater depth than 15 cm of soil [22]. A grazing event with high soil moisture is related to mechanical losses of soil and its structure; this facilitates water runoff and can potentially generate significant erosion events, as well as soil and nutrient losses [23–25]. Additionally, water infiltration can be restricted by up to 80% [26], as the internal porosity of the soil is decreased through compaction [27–29]. Furthermore, as internal porosity declines, the ability of the soil to store and conduct water is reduced [23,30], while mechanical soil strength increases [20], which may restrict soil root penetration, resulting in reduced plant growth, performance, and persistence [31].

Pasture production has been reported to decline by 25–40% when soil is compacted [32,33], resulting in a decline in plant growth and loss of plant density and persistence, coupled with the appearance of bare/uncovered soil, which may be colonised/occupied by opportunistic weed species [34]. Weeds are undesirable in permanent pastures, as they compete with more desirable plant species for resources (water, nutrients, and light) and reduce the quality and quantity of available forage for livestock, thereby lessening animal performance [35]. Furthermore, some weed species may negatively affect livestock health and performance, while some weed species may also reduce biodiversity, negatively affect soil health [36], and are commonly considered to be a sign of ecosystem degradation [37]. Factors driving soil resilience and its ability to withstand/resist compaction and maintain structure are key components for understanding how grazing affects the soil-pasture continuum, and thus, pasture and livestock performance, and resilience [38,39]. Wetting and drying cycles [23], coupled with plant root growth and turnover (decay), and soil fauna activity [40], are the natural regenerative processes that promote recovery and ameliorate soil structure.

In southern Chile, Andosols (soils derived from volcanic ash) dominate and are ideally suited for the development of pastoral production due to their inherent, high resilience capacity [41], high organic matter (OM) content [42,43], well-defined inter- and intra-aggregate pores [44,45], high hydraulic conductivity [46,47], stable soil aggregates [48], and high shrinkage capacity [23] when compared to other soils. Shrinkage capacity is a measure of a soil volume change as it goes from fully saturated to a dry state (volume decreases per unit mass of soil as it dries) [49]. Soils with a high shrinkage capacity are more able to recover soil structure after mechanical impacts due to the soil structure dynamics related to natural wetting and drying events [1,20]. This is particularly important when we consider management, quality, sustainability, and resilience of pasture systems, which can be grazed throughout the whole year at a wide range of soil water contents. However, a high heterogeneity in dairy cattle size, live weight, and milk production within these pasture systems may complicate management, as livestock of different body size differ in daily movement because they present differences in kinematics and locomotion [50], as well as energetic and metabolic requirements, thereby resulting in differences in feed requirement, ingestion rates, and defaecation rates [51]. Therefore, grazing cows of contrasting live weights, in an intensive grazing system, can negatively affect the soil-pasture continuum through compaction and loss of soil structure, depending on mass and duration of livestock grazing. However, there is limited information available supporting this phenomenon. Here, we describe two studies (i) to investigate the pressure exerted on the soil by a wide range of dairy cows [light cows (LC) and heavy cows (HC)] of contrasting size and live weight; and (ii) evaluate the effect of LC and HC grazing dairy cows on soil physical properties and pasture attributes.

2. Materials and Methods

2.1. Study 1: Effect of Cow Size and Mass on Hoof Pressure

2.1.1. Hoof Area and Live Weight Determination

Hoof area and the live weight was determined from 33 dairy cows [23 Black Friesian x Holstein Friesian cows from the Agropecuaria Austral Research Station (AARS; 39°47′ S, 73°13′ W; altitude 14 m.a.s.l.), Universidad Austral de Chile, Valdivia, Chile; and 10 NZ Jersey cows from the Oromo Research Station (EEO; 41°08′ S, 73°09′ W; altitude 149 m.a.s.l), Universidad de Chile, Purranque, Chile]. Briefly, cows were weighed, and the hoof area was determined by positioning them in trimming chutes and applying refracting paint to the sole (bottom part) of the right hind hoof. A hoof print was then collected from each animal by placing the painted hoof onto architectural vellum paper. The area of the hoof print was then precisely determined with a planimeter.

2.1.2. Statistical Analysis

Regression analysis was then used to link the hoof area with the weight of each cow. The weight and pressure exerted on each cm^2 of hoof were calculated and related to the weight of each cow using a regression equation (as described by Cumming and Cumming [50]). All statistical analyses were performed using the SAS program version 9.3 [52].

2.2. Study 2: Effect of Cow Size and Mass on Soil Physical Properties and Pasture Attributes

2.2.1. Site Description

This study was carried out at EEAA for 1.5 years (April 2008–October 2009). Rainfall and mean temperature during the experimental period were 4084 mm and 10.9 °C, respectively (Figure 1). Soil was an Andosol, classified as a Petroduri-Silandic Andosol according to [53]. Soil was sampled (0–20 cm) prior to the start of the study (March 2008). Initial soil pH was 5.2, with an OM content of 15.4%, Olsen-P [available soil phosphorus (P)] of 12.3 mg kg^{-1}, exchangeable potassium (K) of 72 mg kg^{-1}, and 10.1% aluminium (Al) saturation. For more detailed descriptions of soil physical properties and background information for the study site, please refer to [54].

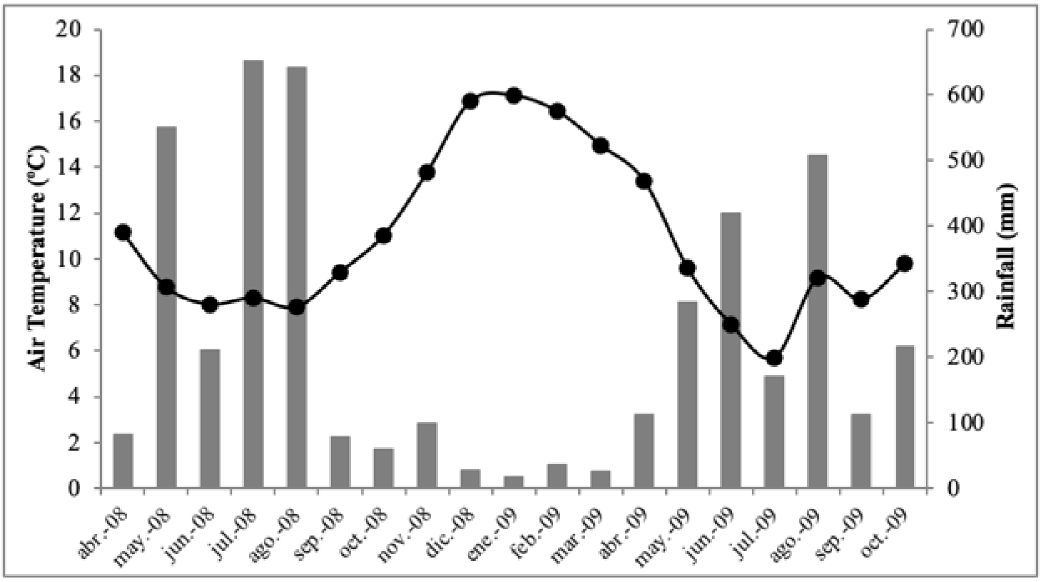

Figure 1. Development of mean temperature (black line) and rainfall (grey columns) during the experiment (April 2008–October 2009).

2.2.2. Experimental Design and Treatments

This study consisted of 18 plots (20 × 20 m), with three pasture treatments: the existing naturalised pasture and two new pasture species mixtures. The existing naturalised pasture was fertilised [naturalised fertilised pasture (NFP; control treatment)], consisting of 80% *Agrostis capillaris* L. (browntop), 8% *Bromus valdivianus* Phil. (pasture brome), and 5% *Trifolium repens* L. (white clover) [botanical composition on (DM) basis]. For the remaining two treatments, the existing naturalised pasture was cultivated, and two different types of pasture mixes were sown: (i) a mixed binary species (BM) composed of *Lolium perenne* L. cv. Alto (25 kg ha^{-1}) and *T. repens* cv. Huia (2 kg ha^{-1}) and cv. Will (2 kg ha^{-1}); and (ii) a multispecies mixture (MSM) composed of *L. perenne* (6.3 kg ha^{-1}), *T. repens* cv. Huia (2 kg ha^{-1}), and *T. repens* cv. Will (2 kg ha^{-1}), *B. valdivianus* (22.5 kg ha^{-1}), *Holcus lanatus* L. (1 kg ha^{-1} [Yorkshire fog]) and *Dactylis glomerata* L. cv. Starly (3.2 kg ha^{-1} [cocksfoot]). The seeds of *B. valdivianus* and *H. lanatus* were collected during the summer of 2008 from naturalised pastures in southern Chile. All the pastures were equally annually fertilised with 180 kg N ha^{-1}, 52 kg P ha^{-1}, 100 kg K ha^{-1}, and 2 tons $CaCO_3$ ha^{-1}.

Two groups of dairy cows (Black Friesian x Holstein Friesian) of contrasting size and live weight (average ± s.e.m.) ("light cows" (LC live weight: 464 ± 5.4 kg; height at the withers: 132 ± 0.6 cm) and "heavy cows" (HC; live weight: 600 ± 8.7 kg; height at the withers: 141 ± 0.9 cm)) were utilised to graze the pastures. The stocking density was equivalent: 9 LC and 7 HC per plot (4.2 t LW plot^{-1}). During the spring, pastures were grazed when they reached an average herbage mass of 2200–2600 kg DM ha^{-1}, and grazing was terminated with a residual of 1400–1600 kg DM ha^{-1}. During the following summer, pastures were grazed at 2000–2400 kg DM ha^{-1}, and grazing was terminated at 1400–1800 kg DM ha^{-1} residual. During autumn and winter, grazing was performed at 1800–2000 kg DM ha^{-1} and finalised at 1000–1200 kg DM ha^{-1} [1]. If the pasture did not reach the pre-grazing herbage mass criteria, it was grazed 60 days after the previous grazing event.

2.2.3. Field Measurements and Soil Sampling

Botanical composition, pasture density, and forage quality were seasonally determined. A pooled sample of each plot was obtained from ten random quadrats (20 × 20 cm) that were cut to ground level; the botanical composition of these samples was determined by manual separation, and the proportion of each species that made up the DM was calculated [55]. In each plot, a set of 4 circles of (79 cm^2) was arranged at the corners of a square, and the number of tillers, legume shoots (growing points), and the number of weeds were determined using the CORE technique [56] and ranked as described by ref. [57]. Forage quality samples were taken using the same technique as described for botanical composition; however, herbage mass was cut at 5 cm above ground level. These samples were analysed at the Animal Nutrition Laboratory, Universidad Austral de Chile, Chile.

For each grazing event, pre- and post-grazing herbage mass (kg DM^{-1} ha^{-1}), soil water content (SWC), penetration resistance (PR), animal grazing behaviour, and bite rate and herbage intake were determined. Herbage mass was estimated (100 measurements per plot) with a calibrated rising plate metre (Jenquip, Feilding, New Zealand). The rising plate metre was calibrated as described by [58]. Briefly, 5 samples were collected from each plot (before and after grazing events), and herbage within each ring (0.1 m^2, equivalent area and shape to the rising plate metre) was cut to ground level. Samples were then dried at 60 °C for 48 h, DM was determined, and the relationship between compressed height and herbage mass was estimated. Seasonal herbage accumulation and total herbage mass accumulation (kg DM ha^{-1} year^{-1}) were determined as described by [59]. Pasture growth rate (kg DM ha^{-1} d^{-1}) was calculated as herbage accumulation between two successive grazing events divided by the grazing interval. Soil water content (TDR 200 Soil Multimeter FOM/mts, Easy Test Ltd., Lublin, Poland) (3 measurements per plot) and PR (06.01 Hand Penetrometer, Eijekelkamp Agrisearch Equipment, Giesbeek, The Netherlands) (10 measurements per plot) were measured pre- and post-grazing at 10 cm depth.

Livestock behaviour was determined through observation [14]. Briefly, livestock was allowed to equilibrate (15 min.) to their new surrounding once entering a new grazing plot. Livestock behaviour [grazing (G), walking (W), and standing (Stdi), which resulted in the addition of ruminating and resting] was then recorded every 5 min for 1 h. Bite rate was also measured from 4 cows in each plot by timing how long an animal takes to make 60 bites. Apparent herbage intake was estimated as the difference between pre-grazing herbage mass and the post-grazing residual herbage mass from the same grazing event.

In August 2009, undisturbed soil samples were collected in steel cylinders to evaluate soil hydraulic (v = 220 cm^3; h = 5.6 cm; d = 7.2 cm) and mechanical (v = 120 cm^3; h = 3.0 cm;

d = 7.1 cm) properties. The samples were covered and capped immediately after removal from the plots to prevent additional mechanical disturbance and reduce evaporation.

2.2.4. Laboratory Analysis

Forage quality samples (n = 4) were evaluated for key quality parameters. Briefly, DM content, crude protein (CP) [60], digestible OM on a DM basis (DOM) [61], and acid detergent fibre (ADF) [62] were determined for each forage quality sample. The water retention curve (WRC) was determined from undisturbed soil samples (n = 3 for each plot). Soil samples were carefully saturated (from below; capillary rise) and then drained at water potential values of −1, −2, −3, −6 (on sand tables), −15, −33, and −50 kPa (in pressure chambers). The water content was recorded with an electronic balance at each water potential. The bulk density (d_b) was determined by drying at 105 °C (in an oven) for 24 h [63]. The volume of wide coarse pores (wCP, $\phi > 50$ µm), narrow coarse pores (nCP, ϕ: 50–10 µm), medium pores (MP, ϕ: 10–0.2 µm), and fine pores (FP, $\phi < 0.2$ µm) were derived from the water retention curve [63].

Soil consolidation curves were determined using an oedometer (Controls T303, Serial# 91051378, Controls, Milan, Italy). The undisturbed soil samples (n = 3, for each plot) were water saturated by capillary rise, then drained at −6 kPa, weighed, and the air conductivity (k_l) was measured. Samples were first stressed by static loading with 6, 12, 25, 50, 100, 200, and 400 kPa, and thereafter, the stresses were removed until 200, 100, 50, 6, and 1 kPa were reached. Each stress during the loading and unloading cycle was applied for 6 min, and the soil vertical deformation was measured (0.001 mm accuracy). The precompression stress (Pc) was determined from the consolidation curve using the mathematical method proposed by [64], based on the graphical method of [65]. The RETC v6.02 (2005–2009) software was used to perform all these calculations.

Air conductivity (k_l) was measured (Key Instruments, Croydon, PA, USA) before and after the determination of the consolidation curve to define the effect of mechanical stresses on pore functions. In samples used in the determination of the WRC, k_l was measured at tensions of 6, 15, 33, and 50 kPa. An airflow metre with different scales was used, which allowed for the measurement of the range of air conductivity between 0.1 and 10 L min^{-1} when a pressure difference of 0.1 kPa was applied. The k_l was expressed as air permeability (k_a) as explained by [66].

2.2.5. Statistical Analysis

The experimental design corresponded to a randomised complete block design with factorial arrangement of the treatments (n = 18; 3 types of pastures × 2 cow groups × 3 blocks). All statistical analyses were performed using the SAS program version 12.3 [52]. The normality of the data and the homogeneity of variance were verified. When the data did not represent a normal distribution, they were transformed using natural logarithm or the square root transformation to obtain a normal distribution of the data [67]. Univariate statistics were applied through an ANOVA to detect statistical differences between types of pasture (BM, MSM, and NFP), cow groups (LC and HC), and their interaction. When differences were significant between the treatment means of BM, MSM, and NFP or between the LC and HC means, Fisher's least significant difference test (LSD) was carried out ($p \leq 0.05$). When their interaction presented differences, means were separated using the "Probability of the difference" (PDIFF) test. As the measured variables are not independent, Canonical Variate Analysis (CVA) was performed on the data to determine the extent to which each variable explained the variation between the treatments.

3. Results

3.1. Study 1: Effect of Cow Size and Mass on Hoof Pressure

Hoof/claw area was strongly correlated with cow mass (R^2: 0.91, $p \leq 0.001$), in that the surface area of the hoof/claw in contact with the soil was proportionally greater in heavier cows (Figure 2A), with pressure ranging between 200 and 350 kPa. However, in general, the pressure per area unit (hoof/claw) exerted on the soil by a cow standing on all four hooves/claws was similar for all ranges of live weight (Figure 2B), with some variations between 160 and 200 kPa.

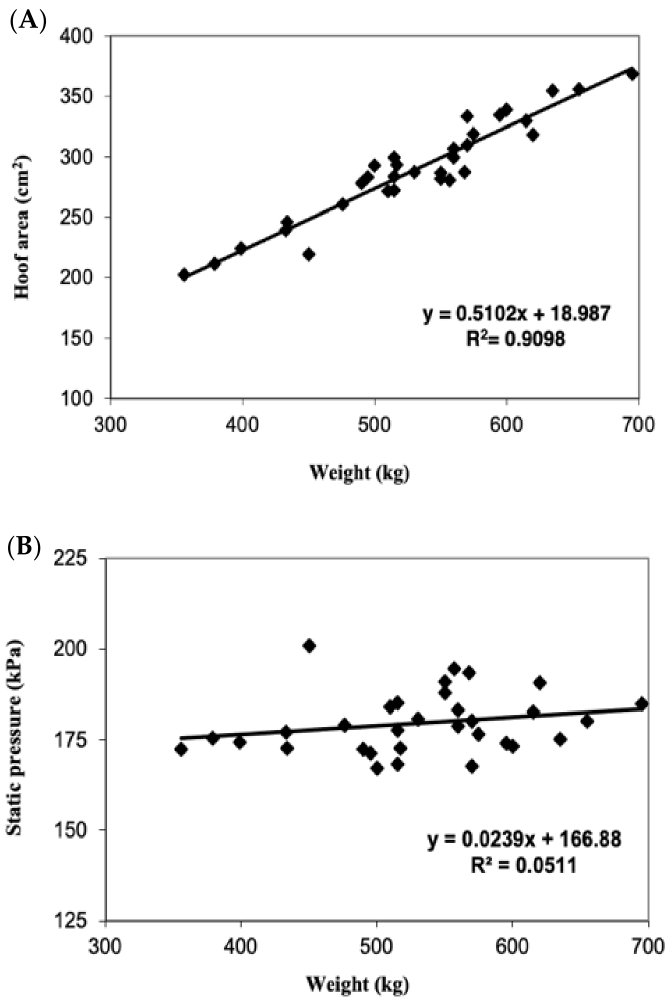

Figure 2. (**A**) Relationship between dairy cow live weight (kg) and their hoof area (cm^2), and (**B**) pressure exerted per unit area by dairy cows of different live weights.

3.2. Study 2: Effect of Cow Size and Mass on Soil Physical Properties and Pasture Attributes

3.2.1. Soil Physical Properties

Precompression stress, d_b, TP, k_la/k_lb, nCP, MP, and FP did not show significant differences (p > 0.05) among BM, MSM, NFP, LC, and HC or their interaction, unlike wCP [wide coarse pores (>50 μm)], and PR (Table 1). However, the Pc of the LC grazed treatments was, in general, higher (p = 0.069). The difference between soil PR ($p \leq 0.01$) was higher in NFP when compared to sown pastures (BM and MSM; Table 1). After a year of grazing events, the MSM showed PR values similar to those presented at the beginning of the study, whereas BM and NFP showed higher values, demonstrating a degree of compaction (Figure 3A). Furthermore, this degree of soil compaction had a seasonal pattern and varied according to the soil water content (Figure 3B). In that, increasing soil moisture decreased PR for all pasture types in this study.

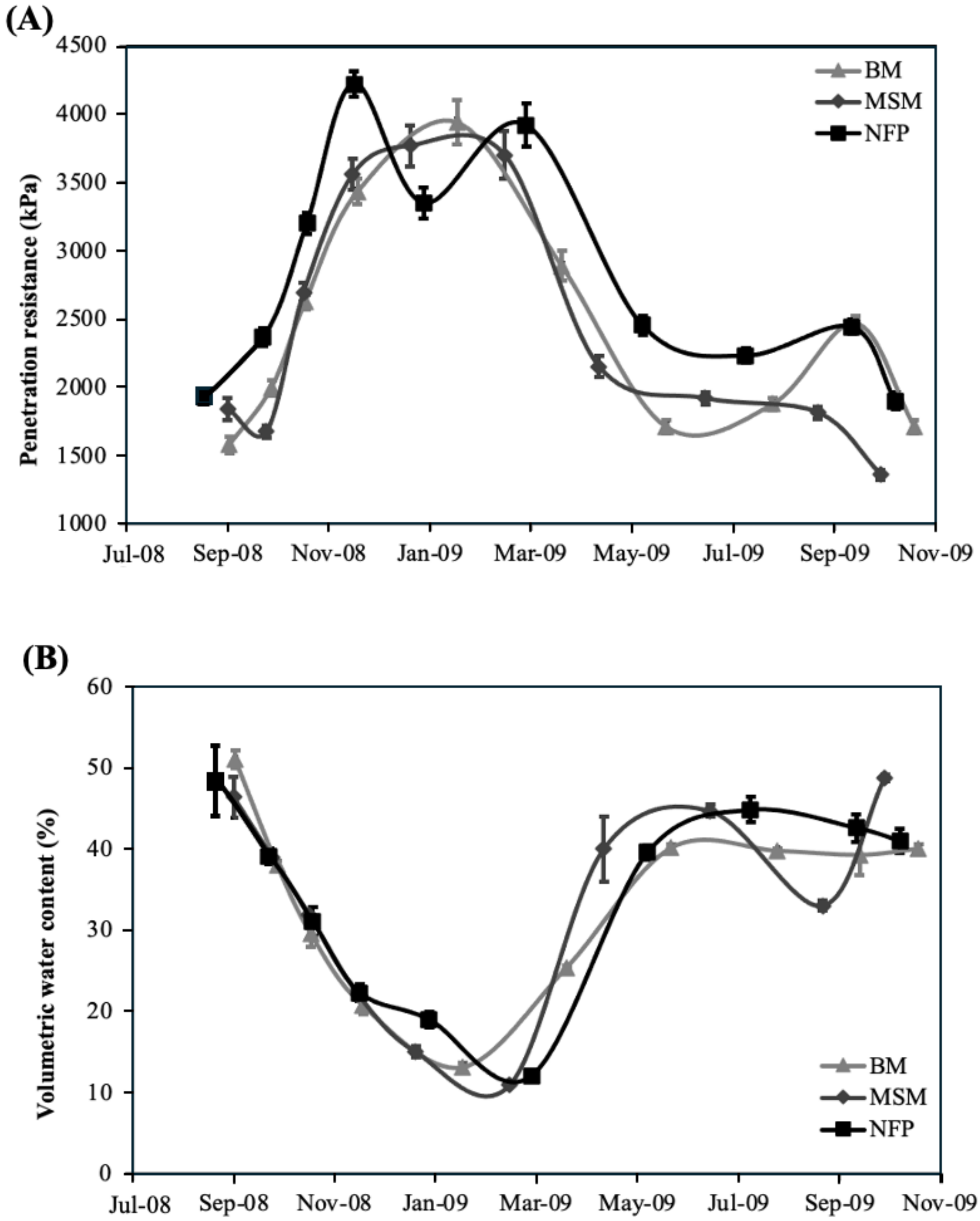

Figure 3. (**A**) Soil penetration resistance and (**B**) volumetric water content functions of time registered on pastures (BM: Binary mixture pasture; MSM: multiple species mixture pasture; NFP: naturalised fertiliser pasture). Averages are presented, bars indicate ± s.e.m. (standard error of the mean).

Table 1. Effects of pasture, cow live weight, and their interaction on physical soil properties, August 2009 (Pc: Precompression stress; PR: Penetration resistance; k_la/k_lb: Relationship between air conductivity before and after consolidation; d_b: Bulk density; TP: Total porosity; wCP: Wide coarse pores (ϕ > 50 µm); nCP: Narrow coarse pores (ϕ: 50–10 µm); MP: Medium pores (ϕ: 10–0.2 µm); FP: Fine pores (ϕ < 0.2 µm)).

	Pc (kPa)	PR (kPa)	k_la/k_lb	d_b (g/cm^3)	TP (%)	wCP (%)	nCP (%)	MP (%)	FP (%)
Pastures									
BM	30.22 ± 2.85	1896 **b** ±33.55	0.15 ± 0.14	0.69 ± 0.01	69.87 ± 0.41	8.82 **b** ± 0.56	13.21 ± 1.63	21.80 ± 1.13	26.04 ± 0.35
MSM	30.78 ± 3.07	1899 **b** ± 56.86	0.08 ± 0.04	0.70 ± 0.01	69.84 ± 0.37	9.38 **b** ± 0.69	13.93 ± 1.21	20.46 ± 1.15	26.06 ± 0.32
NFP	30.77 ± 0.97	2173 **a** ± 43.49	0.13 ± 0.06	0.70 ± 0.01	69.78 ± 0.27	13.03 **a** ± 0.62	10.78 ± 0.82	19.87 ± 0.83	26.11 ± 0.23
Significance	**NS**	**	**NS**	**NS**	**NS**	**	**NS**	**NS**	**NS**

Table 1. *Cont.*

	Pc (kPa)	PR (kPa)	k_la/k_lb	d_b (g/cm^3)	TP (%)	wCP (%)	nCP (%)	MP (%)	FP (%)
Cows									
LC	33.26 ± 2.28	2016 ± 59.25	0.12 ± 0.09	0.69 ± 0.01	69.99 ± 0.29	10.49 ± 1.02	13.00 ± 1.26	20.58 ± 0.97	25.93 ± 0.25
HC	27.93 ± 0.86	1962 ± 56.14	0.12 ± 0.06	0.70 ± 0.01	69.67 ± 0.25	10.33 ± 0.56	12.28 ± 0.91	20.84 ± 0.77	26.21 ± 0.22
Significance	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Interaction									
BM-LC	33.78 ± 5.11	1931 ± 19.82	0.13 ± 0.29	0.71 ± 0.02	69.44 ± 0.66	8.90 ± 1.15	12.51 ± 3.18	21.63 ± 1.78	26.40 ± 0.57
BM-HC	26.67 ± 1.35	1860 ± 62.84	0.17 ± 0.13	0.69 ± 0.01	70.23 ± 0.45	8.74 ± 0.51	13.92 ± 1.61	21.97 ± 1.80	25.67 ± 0.39
MSM-LC	35.00 ± 5.33	1889 ± 81.64	0.15 ± 0.01	0.68 ± 0.01	70.36 ± 0.49	8.57 ± 1.14	14.79 ± 2.37	21.38 ± 2.15	25.61 ± 0.43
MSM-HC	26.56 ± 0.95	1909 ± 97.06	0.01 ± 0.06	0.71 ± 0.01	69.32 ± 0.40	10.20 ± 0.67	13.07 ± 0.96	19.55 ± 1.08	26.51 ± 0.34
NFP-LC	31.00 ± 1.92	2228 ± 31.21	0.08 ± 0.08	0.69 ± 0.01	70.18 ± 0.31	13.99 ± 0.79	11.70 ± 0.83	18.72 ± 0.91	25.77 ± 0.26
NFP-HC	30.56 ± 0.99	2119 ± 74.18	0.17 ± 0.10	0.71 ± 0.01	69.39 ± 0.33	12.06 ± 0.59	9.86 ± 1.34	21.01 ± 1.15	26.45 ± 0.29
Significance	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Different letters in the same column indicate significant differences at **, $p \leq 0.01$; NS, $p > 0.05$. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

The percentage of wCP varied between the pastures (Table 1). Non-tilled pasture (NFP) presented higher levels of wCP ($p \leq 0.01$) than tilled pastures (BM and MSM), with the lower percentage of pore size associated with higher values of narrow coarse pores (nCP) and medium pores (MP); however, there was no significant difference between pastures (Table 1).

3.2.2. Pasture Attributes

Total herbage accumulation was significantly higher ($p \leq 0.001$) for sown pastures (BM and MSM) than for NFP (Table 2). Herbage growth curves (Figure 4) showed a similar behaviour for the study period, and the differences observed were generated by the type of pasture and not by cow weight. Sown pastures (BM and MSM) had higher growth rates when compared to NFP. Pasture species in BM and MSM mixes had high growth potential, with BM reaching the highest growth rate at 65 kg DM ha^{-1} day^{-1}.

Table 2. Effects of pasture, cow weight, and their interaction on pasture attributes. Total herbage mass corresponds to all experimental periods. Residual herbage mass corresponds to the average of post-grazing herbage mass during the experimental period.

	Total Herbage Mass (kg MS ha^{-1})	Tiller Density (N° Tiller m^{-2})					Residual Herbage Mass (kg MS ha^{-1})
		Spring 1	Summer	Autumn	Winter	Spring 2	
Pasture							
BM	7927 **a** ± 194.85	6510 ± 457.37	4223 **a** ± 367.11	8361 **b** ± 490.99	10,197 **b** ± 905.27	8621 ± 273.11	1469 **a** ± 29.20
MSM	8382 **a** ± 190.83	6642 ± 322.86	3093 **b** ± 167.08	6791 **b** ± 462.41	10,706 **b** ± 1050.60	7178 ± 407.92	1350 **b** ± 19.69
NFP	6048 **b** ± 83.73	7692 ± 718.25	4541 **a** ± 565.36	12,838 **a** ± 948.73	15,687 **a** ± 1261.62	9623 ± 711.98	1471 **a** ± 22.04
Significance	***	**NS**	**	***	***	**NS**	**
Cow							
LC	7528 ± 390.95	7328 ± 440.30	3374 **b** ± 192.76	10,129 **a** ± 1161.61	12,099 ± 1150.67	8333 ± 602.90	1412 ± 22.62
HC	7376 ± 367.09	6568 ± 430.75	4531 **a** ± 420.46	8531 **b** ± 834.84	12,294 ± 1293.11	8616 ± 441.56	1448 ± 30.37
Significance	**NS**	**NS**	**	*	**NS**	**NS**	**NS**
Interaction							
BM-LC	7931 ± 322.45	7289 ± 601.94	3523 **b** ± 294.92	8891 ± 813.52	8891 **c** ± 813.52	8297 ± 230.01	1440 ± 42.15
BM-HC	7923 ± 292.99	5730 ± 274.70	4923 **a** ± 310.86	7831 ± 512.14	11,502 **b,c** ± 1316.19	8945 ± 463.97	1498 ± 40.68
MSM-LC	8573 ± 169.93	6748 ± 514.42	3173 **b** ± 275.67	7225 ± 31.67	12,457 **b** ± 1252.00	7003 ± 730.36	1361 ± 37.31
MSM-HC	8190 ± 341.18	6536 ± 495.27	3013 **b** ± 239.26	6356 ± 937.56	8955 **c** ± 940.88	7353 ± 517.62	1339 ± 20.76
NFP-LC	6081 ± 165.62	7947 ± 1157.08	3427 **b** ± 500.18	14,271 ± 1403.88	14,950 **a,b** ± 2094.37	9698 ± 1399.76	1435 ± 31.82
NFP-HC	6014 ± 80.56	7438 ± 1084.32	5655 **a** ± 327.07	11,406 ± 691.37	16,425 **a** ± 1740.25	9549 ± 754.79	1507 ± 11.42
Significance	**NS**	**NS**	*	**NS**	*	**NS**	**NS**

Different letters in the same column indicate significant differences at the following levels: *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$; NS, $p > 0.05$. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

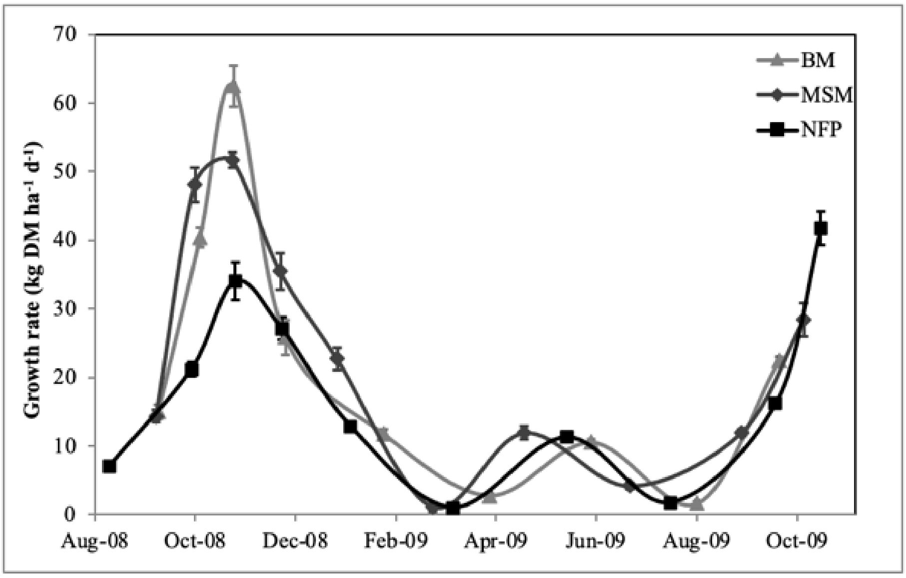

Figure 4. Seasonal variation in the growth rate of the pastures. BM, binary mixture pasture; MSM, multiple species mixture pasture; NFP, naturalised fertilised pasture. Averages are presented, bars indicate ± s.e.m. (standard error of the mean).

Tiller density significantly changed according to the seasons (Table 2). During the spring of both years, BM, MSM, and NFP presented similar tiller density, and cow weight did not affect pasture tiller density. During the summer, there was a significant interaction between pasture type and cow weight ($p \leq 0.05$), in that tiller density of BM and NFP was higher than MSM, and the pastures grazed by LC had a lower tiller number than the pastures grazed by HC ($p \leq 0.01$). BM-HC and NFP-HC showed higher tiller density ($p \leq 0.01$). The opposite occurred in autumn, with pastures grazed by LC presenting higher tiller density than those grazed by HC ($p \leq 0.05$), while BM and MSM had lower tiller density than NFP ($p \leq 0.001$). The differences in tiller density shown by the pastures during autumn related to pasture type remained similar during winter ($p \leq 0.001$); however, tiller density was not affected by cow weight during this season ($p > 0.05$).

The MSM pasture had a significantly lower average post-grazing herbage mass ($p \leq 0.01$) than BM and NFP, suggesting more intense grazing. Seasonal pasture nutrition analysis was significantly ($p \leq 0.001$) different between BM, MSM, and NFP for all the parameters tested, but not for cow weight and the pasture type and cow weight interaction.

Pasture nutritional quality was not affected by animal size (LC and HC), and there was no significant interaction between pasture type and cow size (Table 3). However, across seasons, CP, DOM, and ADF were significantly affected by pasture type (BM, MSM, and NFP).

Table 3. Effects of pasture, cow weight, and their interaction on pasture nutritional quality. CP, crude protein; DOM, digestible organic matter; ADF, acid detergent fibre.

	Nutritional Quality								
	Spring			Summer			Winter		
	CP (%)	DOM (%)	ADF (%)	CP (%)	DOM (%)	ADF (%)	CP (%)	DOM (%)	ADF (%)
Pasture									
BM	19.53 **b** ± 0.36	82 **a** ± 0.39	24 **c** ± 0.42	12.50 **a** ± 0.38	70 **a** ± 0.47	34 **b** ± 1.00	23.32 **b** ± 0.50	72 **a** ± 0.31	29 **a** ± 0.36
MSM	21.28 **a** ± 0.51	80 **b** ± 0.25	25 **b** ± 0.56	13.18 **a** ± 0.65	62 **c** ± 0.22	37 **a** ± 0.40	25.83 **a** ± 0.65	69 **b** ± 0.19	28 **a** ± 0.46
NFP	18.48 **c** ± 0.27	77 **c** ± 0.16	29 **a** ± 0.29	6.88 **b** ± 0.45	67 **b** ± 0.35	37 **a** ± 0.35	21.72 **b** ± 0.36	72 **a** ± 0.45	26 **b** ± 0.25
Significance	***	***	***	***	***	**	**	***	**
Cow									
LC	19.92 ± 0.65	80 ± 0.82	26 ± 0.83	11.05 ± 1.17	66 ± 1.19	36 ± 1.01	23.72 ± 0.80	71 ± 0.53	28 ± 0.44
HC	19.59 ± 0.31	80 ± 0.73	26 ± 0.74	10.66 ± 0.97	67 ± 1.16	36 ± 0.39	23.53 ± 0.64	71 ± 0.62	27 ± 0.57
Significance	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Table 3. *Cont.*

	Nutritional Quality Spring			Summer			Winter		
	CP (%)	**DOM (%)**	**ADF (%)**	**CP (%)**	**DOM (%)**	**ADF (%)**	**CP (%)**	**DOM (%)**	**ADF (%)**
Interaction									
BM-LC	19.69 **bc** ± 0.76	83 ± 0.49	24 ± 0.62	12.99 ± 0.56	70 ± 0.81	32 ± 1.61	23.02 ± 0.54	72 ± 0.29	29 ± 0.20
BM-HC	19.36 **c** ± 0.17	82 ± 0.64	25 ± 0.64	12.02 ± 0.42	70 ± 0.66	35 ± 0.66	23.62 ± 0.94	72 ± 0.61	28 ± 0.66
MSM-LC	22.00 **a** ± 0.61	80 ± 0.44	25 ± 0.49	13.56 ± 1.06	62 ± 0.30	37 ± 0.72	26.56 ± 0.54	69 ± 0.25	27 ± 0.34
MSM-HC	20.55 **b** ± 0.63	79 ± 0.28	26 ± 1.11	12.80 ± 0.91	62 ± 0.32	37 ± 0.51	25.11 ± 1.13	69 ± 0.22	28 ± 0.90
NFP-LC	18.07 **d** ± 0.43	77 ± 0.10	29 ± 0.41	6.60 ± 0.16	67 ± 0.32	37 ± 0.58	21.59 ± 0.77	72 ± 0.41	26 ± 0.27
NFP-HC	18.88 **c,d** ± 0.15	77 ± 0.35	29 ± 0.47	7.15 ± 0.96	68 ± 0.67	36 ± 0.20	21.86 ± 0.23	72 ± 0.81	25 ± 0.34
Significance	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

Different letters in the same column indicate significant differences at the following levels: **, $p \leq 0.01$; ***, $p \leq 0.001$; NS, $p > 0.05$. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

3.2.3. Animal Behaviour

Herbage intake calculated based on kg DM consumed in relation to the metabolic weight of the livestock showed significant differences for the study period, except for spring in the first year (Table 4). Herbage intake varied between seasons and pastures; during summer, intake was higher on BM when compared to MSM and NFP; however, during autumn and winter, this was reversed, with BM having significantly lower herbage intake ($p \leq 0.001$) when compared with the other pastures (MSM > NFP > BM). In the spring of the second year, NFP showed significantly higher herbage intake values ($p \leq 0.01$) than those presented by the sown pastures (BM and MSM).

Table 4. Effects of pasture, cow weight, and their interaction on apparent herbage intake [estimated based on kg DM consumed in relation to metabolic weight (MW) of the animals].

	Herbage Intake (kg DM MW^{-1} ha^{-1}) Spring 1	Summer	Autumn	Winter	Spring 2
Pasture					
BM	0.83 ± 0.05	0.62 **a** ± 0.05	0.65 **c** ± 0.01	0.37 **c** ± 0.01	0.79 **b** ± 0.03
MSM	1.04 ± 0.07	0.41 **b** ±0.03	1.01 **a** ± 0.03	0.52 **a** ± 0.02	0.71 **b** ± 0.04
NFP	0.78 ± 0.04	0.43 **b** ± 0.03	0.90 **b** ± 0.02	0.46 **b** ± 0.02	0.93 **a** ± 0.03
Significance	**NS**	**	***	***	**
Cow					
LC	0.89 ± 0.06	0.52 ± 0.05	0.85 ± 0.06	0.44 ± 0.03	0.79 ± 0.04
HC	0.88 ± 0.06	0.45 ± 0.04	0.85 ± 0.05	0.46 ± 0.02	0.82 ± 0.04
Significance	**NS**	**NS**	**NS**	**NS**	**NS**
Interaction					
BM-LC	0.74 ± 0.04	0.68 ± 0.08	0.64 ± 0.01	0.36 ± 0.02	0.74 ± 0.06
BM-HC	0.91 ± 0.05	0.55 ± 0.06	0.66 ± 0.02	0.39 ± 0.01	0.84 ± 0.01
MSM-LC	1.13 ± 0.02	0.45 ± 0.03	1.02 ± 0.03	0.51 ± 0.03	0.73 ± 0.06
MSM-HC	0.96 ± 0.13	0.37 ± 0.02	0.99 ± 0.05	0.52 ± 0.03	0.68 ± 0.05
NFP-LC	0.79 ± 0.02	0.42 ± 0.06	0.90 ± 0.03	0.45 ± 0.02	0.91 ± 0.03
NFP-HC	0.76 ± 0.09	0.43 ± 0.04	0.90 ± 0.05	0.47 ± 0.03	0.95 ± 0.05
Significance	**NS**	**NS**	**NS**	**NS**	**NS**

Different letters in the same column indicate significant differences at the following levels: **, $p \leq 0.01$; ***, $p \leq 0.001$; NS, $p > 0.05$. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

Bite rate was not statistically different between pastures except during summer ($p \leq 0.01$), where livestock on MSM had a higher bite rate (63.4 bites min^{-1}) when compared to BM and NFP (57.7 and 55.2 bites min^{-1}, respectively) (Table 5). In relation to grazing behaviour, the univariate statistics did not show significant differences between time spent by livestock in the different activities: grazing, walking, and standing by [ruminating (standing or lying) + resting] (Table 6).

Table 5. Effects of pasture, cow weight, and their interaction with bite rate (Bite number min^{-1}).

	Bite Rate (Bite Number min^{-1})				
	Spring 1	**Summer**	**Autumn**	**Winter**	**Spring 2**
Pasture					
BM	60.40 ± 2.16	57.69 **b** ± 1.29	68.68 ± 1.56	71.76 ± 3.32	-
MSM	62.40 ± 0.68	63.36 **a** ± 1.78	68.88 ± 1.59	66.82 ± 1.56	68.23 ± 2.48
NFP	60.89 ± 1.30	55.24 **b** ± 1.75	68.88 ± 1.59	66.82 ± 1.56	63.92 ± 1.18
Significance	**NS**	**	**NS**	**NS**	**NS**
Cow					
LC	60.98 ± 1.15	58.00 ± 1.82	70.25 ± 0.96	68.27 ± 1.66	68.95 ± 2.34
HC	61.48 ± 1.31	59.52 ± 1.65	67.38 ± 1.30	68.66 ± 2.28	63.20 ± 0.78
Significance	**NS**	**NS**	**NS**	**NS**	**NS**
Interaction					
BM-LC	61.00 ± 3.02	57.56 ± 2.11	71.78 ± 0.81	74.23 ± 1.98	-
BM-HC	59.80 ± 3.73	57.82 ± 1.97	65.59 ± 1.37	69.28 ± 6.70	-
MSM-LC	62.98 ± 1.24	61.91 ± 3.64	69.48 ± 2.09	65.29 ± 1.15	72.62 ± 3.00
MSM-HC	61.82 ± 0.68	64.82 ± 0.70	68.27 ± 2.82	68.36 ± 2.92	63.84 ± 1.57
NFP-LC	58.95 ± 1.03	54.55 ± 2.92	69.48 ± 2.09	65.29 ± 1.15	65.28 ± 2.24
NFP-HC	62.83 ± 1.91	55.94 ± 2.51	68.27 ± 2.82	68.36 ± 2.92	62.56 ± 0.36
Significance	**NS**	**NS**	**NS**	**NS**	**NS**

Different letters in the same column indicate significant differences at **, $p \leq 0.01$; NS, $p > 0.05$. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

Table 6. Livestock behaviour evaluated as the time invested in grazing, walking, and standing by [ruminating (standing or lying) + resting] according to the type of pasture, cow weight, and their interaction, over a 70 min period.

	Livestock Behaviour		
	Grazing (min)	**Walking (min)**	**Standing (min)**
Pasture			
BM	56.89 ± 1.38	1.56 ± 0.31	16.53 ± 2.33
MSM	57.19 ± 1.85	1.13 ± 0.20	16.20 ± 2.70
NFP	53.27 ± 1.22	1.48 ± 0.22	21.18 ± 1.82
Significance	**NS**	**NS**	**NS**
Cow			
LC	57.59 ± 1.36	1.66 ± 0.20	15.02 ± 1.97
HC	53.98 ± 0.99	1.12 ± 0.16	21.25 ± 1.40
Significance	**NS**	**NS**	**NS**

Table 6. *Cont.*

	Livestock Behaviour		
	Grazing (min)	**Walking (min)**	**Standing (min)**
Interaction			
BM-LC	59.02 ± 2.14	2.15 ± 0.37	12.67 ± 3.41
BM-HC	54.75 ± 0.65	0.97 ± 0.09	20.39 ± 0.81
MSM-LC	59.46 ± 2.68	1.39 ± 0.26	12.18 ± 3.39
MSM-HC	54.93 ± 2.20	0.87 ± 0.24	20.21 ± 2.97
NFP-LC	54.28 ± 1.47	1.44 ± 0.33	20.20 ± 1.81
NFP-HC	52.26 ± 2.07	1.53 ± 0.36	23.16 ± 3.34
Significance	**NS**	**NS**	**NS**

NS, No sig. Mean values ± s.e.m. (standard error of the mean). BM, mixed binary species; MSM, multispecies mixture; NFP, naturalised fertilised pasture; LC, light cows; HC, heavy cows.

3.2.4. Canonical Variate Analysis

A canonical variate analysis (CVA) was performed to determine the extent to which each variable explained the variation between treatments. CVA indicated significant differences (Wilk's Lambda = 0.0015) and explained 89% of the differences found between treatments. The first canonical variate (CAN 1) explained 77% of the total variation, while the second canonical variate (CAN 2) explained 14%. Tiller density (Td), macroporosity (wCP), time spent walking (W), and precompression stress (Pc) were highly positively correlated with CAN 1. CAN 2 was highly positively correlated with annual penetration resistance (PRa), residual herbage mass (ReHM), ruminating and resting time (Stdi), and tiller density (Td), while it was highly negatively correlated with grazing time (G) (Figure 5A).

The largest differences between treatments were accounted for by CAN 1 by Td, W, wCP, and Pc, attributes that were highly positively related to NFP for both LC and HC, but they were negatively related to BM-HC and MSM-HC. CAN 2 indicated that increasing G was positively related to MSM-LC and negatively related to ReHM and Stdi. When the cow category was compared within each pasture type, CVA showed that LC had a greater G and increased pasture in terms of Td compared to HC for both BM and MSM, but LC and HC in NFP had similar grazing behaviour in terms of G, W, and Stdi and produced a similar pasture in terms of Td (Figure 5B). This meant that BM and MSM influenced cows' grazing behaviour and affected pasture structure, which was significantly modified by cow weight, but it was not the case with NFP.

The soil of NFP presented more wCP; however, there are no differences in the percentage of MP between treatments. Macro-porosity increased in the treatments grazed with LC and MSM, which had less PRa, while BM was more susceptible to compaction. Soil of the sown pastures, BM and MSM, grazed with LC, had higher Pc than those grazed with HC (Figure 5B).

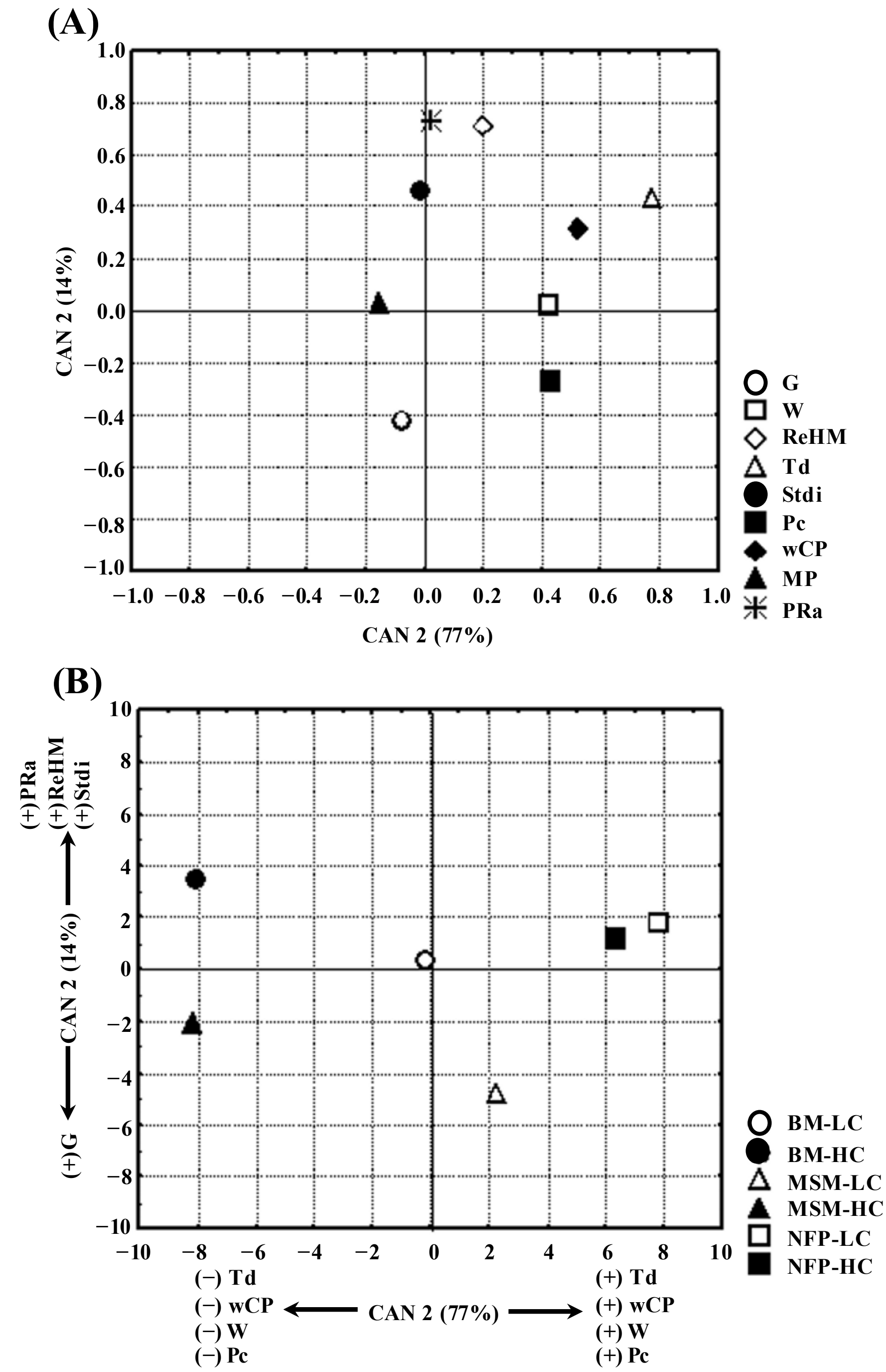

Figure 5. Effects of cow live weight and its grazing behaviour on pasture attributes and soil physical features. (**A**) Variables that explain the differences between treatments. G: grazing time (min), W: walking time (min), ReHM: residual herbage mass (kg DM ha^{-1}), Td: Tiller density (N° tillers m^{-2}), Stdi: ruminating and resting time (min), Pc: Precompression stress, wCP: wide coarse pores (%), MP: medium pores (%), PRa: annual penetration resistance (kPa). (**B**) Interaction between pasture type and cow weight, as affected by variables on CAN 1 and CAN 2. BM: mixed binary species pasture, MSM: multispecies mixture pasture, NFP: naturalised fertilised pasture, LC: light cows, HC: heavy cows.

4. Discussion

4.1. Relationship Between Live Weight and Hoof Area

This increased cow weight was closely related to greater hoof area, in that cows of 350 kg LW presented a hoof area of 200 cm^2 and a static pressure of 169 kPa was exerted, while cows of 700 kg LW had 370 cm^2 of the hoof area and exerted a static pressure of

183 kPa (Figure 2). It was reported that an animal of 300 kg LW has a hoof area of 264 cm^2 and exerts a static pressure of 98 kPa, while a heavier animal (610 kg LW) has a hoof area of 460 cm^2 and exerts a static pressure of 192 kPa on the ground [11]. Livestock with a 380 kg LW and a hoof area of 264 cm^2 exerted a static pressure of 144 kPa [68]. While livestock with 610 kg LW and a hoof area of 364 cm^2 generated a pressure of 168 kPa [69]. We suggest that the differences between published results reflect variability in livestock breed and age between studies. Furthermore, the relationship between animal weight and hoof area was maintained, such that a heavier animal had greater hoof area [10].

The results of our current study showed that the static pressure per unit of area exerted by cows was similar across the whole range of animal body weights evaluated (Figure 2B). As each treatment was grazed with the same amount of kg LW, the soil was subjected to similar static pressure per cm^2 of hoof area. We believe that differences in soil physical properties due to the treatments were probably caused by the movement of the cows within each treatment [27,28].

4.2. Effects of Tillage and Animal Treading on Soil Structure

Penetration resistance and wCP were higher ($p \leq 0.01$; Table 1) for the soils in the NFP treatments when compared to the sown pastures (BM and MSM). Tillage produces inherent effects on the soil, including the breaking of the spatial arrangement of the soil particles, the alteration or removal of the vegetal cover, and the volumetric arrangement of the roots in the soil, and loss of soil aggregation and stability [70–72]. The effect of animal treading has been reported to be greater on soil with low structural stability, with treading reducing soil macro-porosity [73]. Similarly, in our current study, sown pastures had lower wCP and Pc when compared to NFP (Figure 5B). The significant increase in PR measured in the sown pastures (BM and MSM) during the summer period (Figure 3) probably reflects the interaction of wCP and Pc, which was enhanced by the increase in soil cohesion between particles due to soil water deficit [20,41]. The impact of the autumn tillage on soil structure persisted into the following summer and impaired the persistence of shallow-rooted species (*L. perenne* and *T. repens*) during that period [74].

The PR soil variation observed during the year reflects seasonal and climatic changes in water content in the soil profile [20,75]. In the present study (Figure 3A), the lowest values were observed when the soil had the highest water content (winter, WC: 51%; PR: 1579 kPa), while the highest values were measured during the summer when the water availability in the soil was minimal (WC: 11%, PR: 3917). These changes in soil PR are considered normal [75] and reflect the ability of expansion and contraction of each soil type in response to precipitation (or irrigation) and drying events, and the filling and emptying of soil pores [20,41,76]. Root exploration in the soil profile, measured at field capacity in soils with 1.3 g cm^{-3} bulk density and Pc values higher than 60 kPa, was 2 MPa. Usually higher Pc values indicate a restriction to root growth and decreased productivity of the pasture [77]; however, we believe that our PR values do not restrict root growth when the specific physical properties of an andosol are considered, i.e., Pc values are classified as low [23,78], along with the temporal and spatial variation in soil PR [20]. In that, refs. [20,41] reported similar SWC and PR for the same soil type under grazing. Higher PR-values in irrigated pastures under grazing when compared to mowing were attributed to differences in trampling effects observed in the grazed and irrigated treatments [20]. Other studies have found greater PR values (>5000 kPa) on the same soil type but with different land uses and SWC [79,80].

Wide coarse pores (macroporosity) regulate soil air capacity (AC), defined as the ratio of the relative volume of air to the total volume of soil. In a laboratory setting, air capacity is determined when rapid soil drainage has ceased, and the soil contains the maximum amount of water that can be held against gravity [81]. Macroporosity values of 5–8% restrict soil aeration and negatively affect plant growth [77]. The presence and function of structural pores within a soil are dependent on soil management (tillage method, equipment size, livestock stocking density, and grazing duration, etc.), and interactions with climatic conditions. In the current study, the wCP values of BM that almost reached the critical level (5–8%) suggest that this was probably related to the pasture botanical composition, in that both pasture species (*L. perenne* and *T. repens*) had relatively shallow root systems. While MSM pasture mixes were composed of two additional plant species (*B. valdivianus* and *H. lanatus*), both of which are deep-rooted species [82,83] that confer higher mechanical stability to the soil [74,84], this function may also be performed by other deep-rooting species, such as *D. glomerata* [85,86]. In addition, these larger and deeper root systems may favour the development of wCP [54,87].

When physical properties of andosol were compared under different land uses (native forest and pasture), the native forests have a higher aggregate stability and wCP when compared to pasture systems, reflecting the inherent higher soil structure stability as a result of deep and extensive tree root systems, high OM inputs, lack of heavy equipment use on site, and/or limited movement/presence of large herd animals [88]. While lower wCP in the pasture systems was attributed to livestock trampling [88], a decrease of 41% was reported in the top 5 cm of the soil profile in wCP when land use changed from native forest to pasture over a 50-year period [44]. Differences in wCP between tilled and non-tilled pastures in the first year (6% and 10%, respectively) were also reported, with tilled pastures reaching critical levels for wCP [54]. Tillage damages the pore system, pore interconnections and continuity, reduces pore size and induces pore-size redistribution, and, thereby, negatively affects soil structure [1]. Lower AC levels were associated with higher values of PAW, whereas the non-tilled soils (NFP) showed a porous system capable of conducting more water and air into the soil profile (higher ka value than tilled soils), with more functional pores, higher continuity, and with a pore-size distribution different from MSM [1]. In that, air permeability values at −6 kPa of matric potential are higher than 1 mm2, which are considered critical for soil aeration by convection [89].

In the present study, the average rate of d_b ranged from 0.68 to 0.71 g cm^{-3} ($p > 0.05$, Table 1), where values < 0.9 g cm^{-3} are usual for Andosols [90]. The results of the $k_l a/k_l b$ showed a high resilience capacity of these soils [38]. Physical and biological components of Andosols, e.g., wetting and drying cycles [41], and the action of roots and soil organisms [24,91,92] are crucial for maintaining resilient soil health and structure [93,94].

4.3. Dynamics of Pasture Growth and Tiller Density

Sown pastures had higher annual accumulated herbage mass when compared to the NFP ($p < 0.001$; Table 2). Growth curves were similar for all pastures except in spring, where maximum growth rates were BM > MSM > NFP (Figure 4). Early spring temperatures stimulated increased pasture growth rates, which diminished towards summer due to water stress [95,96]. These pasture growth curves resulted from the interaction between temperature, soil moisture, and botanical composition of each pasture [74,97]. As all pastures had a similar soil fertility condition throughout the study, it is probable that soil fertility did not directly influence pasture performance.

Greater growth rates of the sown pastures when compared to NFP were attributed to the addition of fast-growing species (complementary supporting information provided in Figure 4: Year 1, Spring: BM 77% *L. perenne*, 1% *T. repens*, 1% *B. valdivianus*, 17% *A. capillaris*; MSM: 67% *L. perenne*, 1% *T. repens*, 14% *B. valdivianus*, 9% *A. capillaris*; NFP: 3% *L. perenne*, 5% *T. repens*, 2% *B. valdivianus*, 82% *A. capillaris*; Year 1, Summer: BM 57% *L.*

perenne, 1% *T. repens*, 1% *B. valdivianus*, 10% *Dactylis glomerata*, 29% *A. capillaris*; MSM: 29% *L. perenne*, 1% *T. repens*, 39% *B. valdivianus*, 6% *Dactylis glomerata*, 3% *Holcus lanatus*, 21% *A. capillaris*; NFP: 3% *L. perenne*, 3% *T. repens*, 1% *B. valdivianus*, 3% *Holcus lanatus*, 89% *A. capillaris*). In fertilised pastures of southern Chile, *L. perenne*, *B. valdivianus*, *H. lanatus*, and *D. glomerata* can have annual accumulated herbage mass of 11, 13, 9, and 6 ton DM ha^{-1} yr^{-1}, respectively, while *A. capillaris* (dominant species in NFP) have been reported to produce 5 ton DM ha^{-1} yr^{-1} [98]. A drought occurred (November to May; Figure 1), which constrained pasture growth; however, it is likely that the growth of fast-growing species with shallow roots systems, such as *L. perenne*, were more affected when compared to the deeper-rooted pasture species present (e.g., *B. valdivianus* and *D. glomerata*; refer to Figure 4 and its complementary botanical composition findings provided early in this paragraph). It has been reported that fertiliser application can enhance the growth and performance of naturalised pasture to rates similar to sown pastures [74,98], which was observed in our study, except during the spring (Figure 4). The maximum growth rates for the NFP were 35 kg DM ha^{-1} day^{-1}, while BM and MSM growth rates were 63 kg DM ha^{-1} day^{-1} and 50 kg DM ha^{-1} day^{-1}, respectively. Differences in growth rates between pasture treatments were attributed to the dominant plant species (for example, *A. capillaris* in NFP, *L. perenne* in BM, and *L. perenne* and *B. valdivianus* in MSM) in each treatment. It was expected that during the second year, as a consequence of the fertiliser application and grazing management, the population of fast-growing species would increase in NFP, thereby performing similarly to the sown pastures.

Differences in tiller density occurred in summer, autumn, and winter due to the type of pasture and the grazing cow's weight; NFP had the highest number of tillers m^{-2}, probably reflecting that this pasture treatment was not altered by tillage and received fertilisation, and so had a dense tiller population dominated by *A. capillaris,* which can form dense clumps of small tillers and short stolons in spring and autumn [99]. One year after establishment, BM and MSM pastures had lower densities than NFP; this was mainly observed during autumn and winter (Table 2). Furthermore, all pastures showed reduced tiller density from spring to summer, with MSM having the lowest tiller density during the summer. Tillering usually decreases at high temperatures, reflecting depletion of carbohydrate reserves for growth and osmotic regulation [100]. The residual herbage mass (Table 2) showed that MSM was more intensively grazed than the other pastures. A high grazing intensity during summer (5 cm) could trigger further plant stress and even tiller death [95]. Furthermore, low residual heights (<5 cm) may not contain enough carbohydrate reserve to ensure summer tiller growth and/or survival [95,101].

Pasture tiller density varied across the seasons, linked to grazing cow mass. During the spring, the pastures showed similar tiller densities; however, during summer, tiller density of the pastures grazed by LC was significantly lower when compared to those grazed by HC. Autumn and winter showed that grazing LC generated denser pastures than HC grazing. Pastures with higher tiller density were associated with less pasture residual herbage mass and grazed by LC (Figure 4), which were able to more intensively graze the pastures, resulting in a denser pasture sward, with pasture performance varying according to the environmental conditions of each season. Since pastures had similar tiller density in spring, a more intense summer grazing generated a more negative balance between tiller death in relation to tiller generation and survival in the LC pastures when compared to the HC pastures. Under soil water restriction, tiller and plant survival are strongly conditioned by the amount of soluble carbohydrate reserves, tiller length, and size [102]. Higher tiller death of LC pastures compared to those of HC pastures during summer may reflect earlier tiller depletion of the soluble carbohydrate reserves. However, during autumn, plant density resilience was faster in LC pastures than in HC pastures, and LC pastures remained denser during winter. This suggests that, in LC pastures, lower residual pasture height during autumn supported faster tillering and regrowth by allowing greater light penetration into the pasture canopy, which stimulates tiller bud development (Table 2) [100,103].

The nutritional quality consistently differed between the types of pastures and through the seasons ($p < 0.001$; Table 3). The pasture species differed in their nutritional value, which is determined by their phenological stage, components of the yield, chemical composition, and digestibility [13,62,104]. The transition from vegetative to the reproductive stage in pasture species causes variations in the relationship between cell content and cell wall, generating changes in nutritional value, for example, increased complex fibres such as cellulose, hemicellulose, and lignin, and decreased soluble carbohydrate content [82,101,105]. The nutritional value of pastures decreases as the temperature increases [14,82]. In that, the proportion of cell wall lignin content is greater, and the digestibility and energy concentration decrease, which negatively affects herbage intake by the animal [14,62]. However, fertilisation and grazing/pasture management, including the incorporation of legumes and fast-growing grass species with high forage value, result in positive changes in plant nutritional quality, growth, and performance [106].

Throughout the study period, MSM had the highest CP content, reaching the highest level in winter (25.83%) and then decreasing from spring to summer (21.28 and 13.10%, respectively). As pasture species mature, N and soluble carbohydrate content in plant tissues decrease [13,105]. Nitrogen content is commonly reported as higher in vegetative regrowth and in fertilised grasses (particularly during autumn and winter), and decreased as pasture maturity progresses [14,105], with changes in DOM following a similar trend to the N content [14,104]. Content of 26% CP in winter and 18% in summer is common in permanent pastures in southern Chile, with botanical composition mainly consisting of grass species (80%) and white clover (10%) [106].

4.4. Grazing Behaviour of Dairy Cows with Contrasting Size and Live Weight

During grazing, herbage intake is the product of grazing time and the mass and number of bites [104,105,107]. In the current study, the herbage intake was statistically different between pastures and varied throughout the year, but it was consistent for LC and HC ($p < 0.01$; Table 4). However, grazing time and bite rate were not statistically different, except for HC during the summer period (Table 5). In pastures that have a greater contrast in nutritional value due to botanical composition and components of the yield (i.e., lamina%), which are also verified across seasons, grazing, expressed as morning and afternoon activity, and bite rate should be sensitive enough to capture adjustments of animal grazing to changing pasture offer (herbage mass and pasture height) and quality to meet animal requirements [107,108].

During autumn and winter, dairy cows had the largest herbage intake in MSM, which was associated with the lowest residual herbage mass (Table 2) and the highest CP content (Table 3). During this period (autumn and winter), herbage intake increased based on the larger proportion of green leaves, with the preference exerted by the livestock correlating positively with the protein content of the pasture [98,109–111]. In summer, herbage intake of BM was significantly greater ($p < 0.01$; Table 4) when compared to MSM and NFP, which was probably related to the higher tiller density (Table 2), CP, and DOM, and low ADF content (Table 3). This suggests that the BM pastures were more palatable to the livestock than the other pastures [104]. Increase in fibre content is the most nutritionally limiting factor affecting herbage intake because it decreases digestibility and increases the retention time of the fibrous fraction in the rumen [62].

After the first half of spring, the pastures began flowering, which adversely affected the intake of grass species, such as *B. valdivianus* and *D. glomerata* (which were dominant species in MSM), but not late flowering species, for example, *L. perenne* [112]. In spring, the bite rate in MSM pastures was significantly higher ($p < 0.01$; Table 5), which may reflect a lower DOM and greater ADF content when compared to BM, which would be expected in a more mature forage [105,107].

Bromus valdivianus and *H. lanatus* seeds utilised in this study were from established, naturalised pastures from the south of Chile and included a wide range of germplasm, which resulted in variable flowering stage (November to March), which is normal for native and naturalised species [1,74]. Dead plant material, stems, and spikes may impede feeding behaviour through irritation of the muzzle (nose, mouth, and surrounding areas) and eyes, and may reduce feeding by reducing the penetration of the muzzle into the pasture profile, thereby reducing bite rate [112]. In that, when available herbage is restricted, livestock may only be able to obtain small 'light bites', and thus, to maintain herbage intake, livestock increases the bite rate as a compensatory mechanism [15]. The bite rate increased results in lower residual pasture height [98,107,108].

4.5. Relationship Between Treatments and Variables

The results provided by CVA and ANOVA did not always correspond, and there were discrepancies in the delivered results. We believe that this reflects the difference in statistical methods, in that CVA statistically analyses all the variables together, while ANOVA analyses each variable individually [113,114]. In the present study, CVA showed significant differences for soil attributes (e.g., precompression stress and wide coarse pores), pasture attributes (e.g., tiller density), and grazing behaviour (e.g., in MSM, the group of LC spent more time grazing than HC, and HC spent more time ruminating and resting [Figure 5]).

In addition, the CVA related to MSM increased with increasing grazing time and decreasing ReHM when compared to the other pastures. This probably reflected that herbage intake in MSM was higher. In that, a more intense grazing involves a decline in the weight and size of the bites, and livestock must spend more time grazing to maintain their herbage intake [111]. While BM and NFP were related to denser soil, pastures with more tiller density had higher ReHM. The greater tiller number and density of these pastures were associated with the dominant plant species, in that both *L. perenne* in BM and *A. capillaris* in NFP have superficial root systems, potentially resulting in soils with less structural stability, which are more susceptible to damage by compaction, as demonstrated by a greater Pr [115].

In contrast to MSM, where the cows spent more time grazing which was related to greater herbage intake, in BM, cows spent more time ruminating and resting, while in NFP, as this pasture was composed of multiple species, cows spent more time in motion (walking) 'searching' for a more suitable/desirable feeding locations, probably with more palatable species that provide high herbage mass and nutritional value per bite [116–118]. At the beginning of the study, NFP comprised low nutritional value species; however, grazing management and fertilisation facilitated the growth of fast-growing species of higher forage value [74]. We believe that cows in a diverse pasture spend more time walking, looking for the most palatable plant species, combined with a greater herbage mass per bite of high nutritive value [14,98]. In BM and MSM, LC spent more time walking; probably, smaller and lighter animals graze more intensely, leaving a more uniform sward residual.

The NFP had a higher density of tillers than sown pastures, in that this non-tillage pasture kept a high density of species, especially *A. capillaris* (80% of the botanical composition). The sown pastures were relatively new (one-year old), and the soil surface was not fully covered, in that seeding/planting rows were still visible. In addition, NFP grazed with LC generated a greater number of tillers. In that, LC grazed the pasture more intensively, leaving a lower ReHM, a situation that stimulated tillering [95,119].

The soil from NFP had a higher amount of wCP; as it was not disturbed with seedbed preparation, it maintained its structure [84]. However, the MP did not differ between the three pastures. In LC pastures, the number of wCP increased, which may reflect greater tillering dynamics. Furthermore, root abundance and earthworm presence contributed to the maintenance and generation of macro-porosity [31]. At the same time, the soil of the sown treatments grazed with LC presented a higher Pc (Figure 5). In that, the soil could resist greater pressure before deformation, which is directly related to the weight of the animal, and with less loss of porosity. The roots increase the pre-compression stress and the aggregate strength of the soil [120] and are thus less susceptible to compaction.

The soil of MSM was more stable and presented a lower PRa. These pastures had greater plant diversity and were composed of plant species with different rooting characteristics (superficial and deep), thereby exploring more of the soil profile (greater depth) [82,121], which allowed for further exploration of the soil profile, making it possible to access water in the deeper soil layers, which was used to support summer growth during periods of soil water restriction [74,122], plant species asynchronous growth, and overyielding [13]. In addition, plant roots help to limit compaction by generating macropores, which confer soil stability [123,124].

5. Conclusions

Heavier dairy cows had greater hoof area than the lighter cows; thus, the static pressure exerted by the hooves of cows of contrasting weights on the soil per unit of area is similar, independent of the weight range of the dairy cows. However, animals with contrasting live weights have different feeding behaviour, which causes changes in the attributes of the pasture and soil. In that, grazing with LC does not significantly alter the soil structure, and it promotes pastures with competitive species with a higher density of tillers. The magnitude of the changes caused by tillage and pasture seeding, both in the resulting pastures and the original structural and functional soil attributes, is greater than that generated by trampling and grazing during the first years of a pasture's life. Cows with contrasting live weight generate changes in soil penetration resistance, pre-compression stress, and soil porosity and functionality. Grazing with HC does not produce a negative impact on soil structure, as restrictive values were not reached.

This study provides a valuable baseline for assessing grazing systems under climate variability across time. In our study, the resilience of Andosol soils buffers the impact of grazing and pasture management, and demonstrates the value of naturalised or multispecies pastures as tools for sustainable and resilient farming. In addition, this study demonstrates that tiller density is increased by grazing with LC livestock. This indicates that cows of lower body mass are an important tool in pasture renovation improvement strategies, i.e., lighter cows promote denser pasture swards in these grazing systems. Furthermore, we suggest that pasture species composition plays a key role in soil structure development, function, and health.

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