Investigating the impact of treading damage on the plantain (*Plantago lanceolata* L.) content and performance of a plantain+perennial ryegrass (*Lolium perenne* L.) pasture over two years

Samuel S. WILSON[1*], Daniel J. DONAGHY[1], David J. HORNE[1],
Sole NAVARRETE[1,2] and Peter D. KEMP[1]
[1]*School of Agriculture and Environment,*
Massey University, Tennent Drive, Palmerston North 4410, New Zealand.
[2]*Facultad de Agronomía,*
Departamento de Producción Animal, Universidad de Concepción, Chillan, Chile.
*Corresponding author: s.s.wilson@massey.ac.nz

Abstract

There is industry concern over the difficulty of maintaining a satisfactory plantain (*Plantago lanceolata* L.) content within plantain+perennial ryegrass (*Lolium perenne* L.) mixed dairy pastures. One cause of the sharp decline in plantain content may be treading damage from grazing dairy cows during early spring. In an experiment at Massey University, Palmerston North, the impact of cow treading damage on the plantain content of a plantain+perennial ryegrass pasture was investigated over two production years. Measurements of pasture yield, canopy development, botanical composition and growing point density captured the response of the pasture to the treading damage. Early spring treading damage reduced pasture growth by 50% and 75% during the early spring periods of year one (2022) and two (2023), respectively. Plantain content and shoot density tended to be lower in damaged plots during early spring, before recovering throughout summer, although this effect was more pronounced during year one. These results re-iterate the importance of avoiding treading damage in early spring to avoid reductions in pasture production and plantain content throughout spring. The reduction in plantain content in all plots during the second year of the experiment reflected industry observations, suggesting that treading damage likely provides only a part of the explanation for declines in plantain content observed on-farm. An alternative cause of the decline in plantain content in year two may have been shading from ryegrass during late spring. Future research should consider the effect of grazing management and other companion species on plantain content.

Keywords: dairy production, nitrate, pasture management, persistence, pugging

Introduction

The incorporation of plantain (*Plantago lanceolata* L., PL) into high-performing perennial ryegrass (*Lolium perenne* L., RG) based pastures is one potential low-cost tool for reducing nitrogen (N) losses from New Zealand dairy farm systems (Doole et al. 2021). However, there is growing evidence that PL content within these pastures is variable (Nguyen et al. 2022) and persistence is usually poor (Dodd et al. 2019). One study on New Zealand farms has shown that PL contents rarely exceed more than 30% of the sward dry matter (DM) in grass-based pastures after two years following sowing (Dodd et al. 2019), while another study of a dairy pasture showed that the PL content peaked at 47% during the first 15 months after sowing, then declined to 20% after 23 months (Nguyen et al. 2022). This decline is a significant issue as the efficacy of PL for reducing N losses from pastures is strongly associated with the proportion of PL in the diet of cows (Minnée et al. 2020; Navarrete et al. 2022).

While PL has been labelled a 2 to 3 year forage species in grazed pastures (Kuiper and Bos 1992), it has been described by ecologists as having potential life-span greater than 12 years (Grime et al. 1989). This implies that grazed pastures introduce additional stresses for PL, suggesting some potential for improving PL persistence in pastures by alleviating these stresses. Potential causes of the shortened lifespan and corresponding rapid decline in PL content in RG-based pastures include competition from other pasture species (Bryant et al. 2019), sub-optimal grazing management (Ayala et al. 2011; Dodd et al. 2019), waterlogging (Wilson et al. 2023b), and treading damage and compaction (Blom 1979).

One recent study (Wilson et al. 2023a) showed that cow treading damage during early spring caused an immediate reduction in the PL content within a four month old PL+RG pasture. However, in that study PL content recovered to pre-damage levels by autumn, and it appeared that there was no permanent effect of the damage on PL persistence. However, it was unknown

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how the recovered PL population would perform following damage in the second year. It is possible that treading damage events might have a larger impact in the second year after sowing than in year one, which could account for the typically observed rapid decline in PL content in year two (Nguyen et al. 2022). One potential reason for this could be the lasting effects from the damage in year one, such as plant injury and burial (Brown and Evans 1973), and soil compaction (Blom 1979) and their perpetuation following any further treading damage events in year two. Further to this, a reduced ability for growth following successive treading damage events might adversely impact the ability of PL to compete with companion species for light, specifically the somewhat treading-tolerant RG (Brown and Evans 1973; Wilson et al. 2023a). Dense RG-based pastures may also inhibit the emergence of new PL seedlings (Bryant et al. 2019), and thus limit the recovery of the PL population through seed. Additionally, given that declines in PL content normally occur during the second year after sowing, older PL populations might also have a reduced capacity for recovery via asexual shoot propagation. A better understanding of these dynamics could lead to improved management strategies for maintaining high PL contents in RG-based dairy pastures at risk of repeated treading damage.

By definition, the PL content of a pasture (on a DM basis) is derived from the ratio of PL DM to all other pasture DM, and thus is driven by: 1. the DM yield of PL, and 2. the DM yield of all other pasture species. Since the benefits of PL for reducing environmental impacts are driven by the proportion of PL in a sward or cows' diet (Minnée et al. 2020; Navarrete et al. 2022), studies have concentrated on PL content when discussing the fitness of PL in a particular climate+soil type+system combination (Dodd et al. 2019; Nguyen et al. 2022). However, this approach fails to account for the important contribution of companion species DM in the determination of PL content. The current work attempted to separate PL and companion DM growth to explain the effects of treading damage stress on PL independently.

The current study is an extension of an earlier experiment (Wilson et al. 2023a) and aimed to 1. investigate the impact of treading damage, in two successive years, on the productivity of a PL+RG pasture; and 2. investigate the impact of treading damage, in two successive years, on the content and density of PL within a PL+RG pasture.

Materials and Methods

Experimental site and climate

The experiment site was established in autumn 2022 on a Manawatu silt loam. Plantain cv. *Agritonic* and perennial ryegrass cv. *Maxsyn* were direct drilled at 10 kg/ha and 5 kg/ha, respectively, on April 8 with the seeding rate designed to achieve an equal proportion of PL and RG in the pasture at the start of the experiment. In year one of the experiment (August 2022 - July 2023) there was 958 mm of rainfall, and during the measurement period of year two (August 2023 - February 2024) there was 470 mm of rainfall. The long-term average annual rainfall (1991 - 2020) for the site is 984 mm. Mean daily temperature ranged between 8°C in August 2023 to 20°C in January 2024. During the treatment period in August 2022, total thermal time was 182.2°C d, while during the treatment period in August 2023 total thermal time was 98°C d. The thermal time base temperature was 5°C. Meteorological data were sourced from a NIWA weather station, Palmerston North, 200m from the study site.

Experimental layout and treatments

The experiment consisted of two treading treatments, damaged (DD) and undamaged (ND) with four replicates of each treatment, in a randomised complete block design. Each plot was 182 m^2. The soil at the site is a Manawatu fine sandy loam which is described as a well-drained, fluvial recent soil with a high soil water holding capacity and high structural vulnerability (Manaaki Whenua - Landcare Research 2019). Dairy cows were used to implement treading damage, which was based on a difference in soil volumetric water content (VWC) between treatments at the time of grazing. Procedures were approved by the Massey University Animal Ethics Committee (AEC 22/34). Based on previous studies, it was decided that grazing at a soil water deficit of 5 - 10 mm, or 37 - 33% soil VWC, would ensure that ND plots were not damaged by the cows. On 17th August 2022, ND plots were grazed with 6 pregnant dairy cows (representing a stocking density of 330 cows/ha). In the 48 hours following this grazing there was 25 mm of rainfall, which increased soil VWC sufficiently and so DD plots were grazed (and damaged) on August 19th with the same cows.

Subsequent grazings on both treatments were carried out with lactating dairy cows for the remainder of the production year, and once with dry cows during winter. All grazing events were carried out with 6 cows per plot. Grazing occurred whenever the estimated mean pasture mass across the site reached approximately 2800 kg DM/ha, and the target residual was 1500 kg DM/ha. However, soil conditions were closely monitored throughout the year, and plots were only grazed when soil VWC was less than 37% to ensure that plots were not damaged further by cows.

On 7th August 2023, ND plots were grazed with 6 lactating dairy cows per plot. On 8th August, 15 mm of irrigation water was applied to the site, which sufficiently increased soil VWC and so DD plots were grazed and damaged on 9th August with the same cows. Later grazing events in the second year were then carried out as described above, until the last grazing on 21st February 2024. All grazing events during the experiment lasted an average of 2.5 hours.

Measurements

Soil measurements for treading damage severity included pug mark depth, which was measured with a ruler, and pug mark density, which was determined by counting the number of pug marks within a defined area. Soil VWC was measured with a portable TDR system (Time Domain Reflectometry – HandiTRASE® TDR, Soilmoisture Equipment Corp, USA) in each plot during each treading event. Soil measurements are detailed further in (Wilson et al. 2023a).

Pasture DM yield pre- and post-grazing was measured by hand-clipping herbage to ground level in three 0.1 m^2 quadrats per plot and drying the herbage at 60°C for 48 hours. Pasture growth rate was calculated by subtracting the pre-grazing DM yield from the post-grazing DM yield of the previous grazing and dividing by the number of days in the regrowth period. Herbage was cut from a 10×50 cm strip adjacent to each pre-grazing DM quadrat and separated into PL leaf, PL seed head, RG, dead matter and 'other' which comprised annual poa (*Poa annua* L.), broadleaf weeds (e.g., broadleaf dock, *Rumex obtusifolius* L. and volunteer chicory, *Cichorium intybus* L.), and white clover (*Trifolium repens* L.). Samples were dried at 60°C for 48 hours to determine pasture botanical composition on a DM basis. The growth rates of PL and RG were calculated by multiplying the pasture DM growth rate during a given season by the proportion of PL and RG in the pasture during that same period.

Light interception (LI) measurements were made using a Spectrosense2$^{+®}$ device by measuring photosynthetically active radiation (PAR) above and below the canopy three times in three fixed quadrats within each plot. Leaf area index (LAI) was measured using a LICOR LAI-2000® portable light meter by scanning once above the canopy and three times below the canopy at three fixed quadrats within each plot. Measurements of normalised difference vegetation index (NDVI) were also made with a RapidScan® CS-45 canopy analyser by scanning a pre-determined and consistent path through each third of every plot. Measurements of LI, LAI and NDVI were consistently conducted 14 days after each grazing event so that measurements could be made before canopy closure. Due to unforeseen circumstances, these measurements were made 21 days after the treading event in year two. The relationship between LI and LAI between late spring and early summer in year two was explored using the scatter plot function in Microsoft Excel.

The density of PL growing points was measured by counting the number of shoots (PL) in four fixed 0.1 m^2 quadrats per plot. The density of RG growing points was measured by counting the number of tillers (RG) in four fixed 0.05 m^2 quadrats per plot.

Statistical analysis

Statistical analyses were conducted using the MIXED procedure for an ANOVA in SAS (version 9.4, SAS institute 2018). Pair-wise t-tests were used for mean comparisons and significance was declared at $P<0.05$. All results were analysed within each sampling date with treatment as the fixed effect. All data were also analysed for repeated measures. Results for pasture growth rate, botanical composition, and PL and RG density were analysed for repeated measures with treatment, climatic season, and their interactions as fixed effects. Results for soil VWC and treading damage, were analysed for repeated measures with treatment, study year and their interactions as fixed effects. Results for pasture growth rate, botanical composition, and PL and RG density from the period between early spring to late summer, were also analysed for repeated measures in a separate analysis with treatment, study year and their interactions as fixed effects. Results for LI, LAI and NDVI were analysed for repeated measures with treatment, season, and their interaction as fixed effects. Results for PL and RG growth rates were analysed for repeated measures with species, treatment, season and their interactions as fixed effects. Interactions between fixed effects were presented only when they were statistically significant.

Results

Treading damage

During the treading events in both years, soil VWC was significantly higher ($P>0.01$) on the day that DD plots were treaded than when the ND plots were treaded two days earlier (Table 1). Both the mean pug depth ($P<0.01$) and pug density ($P<0.01$) were significantly greater in DD plots than ND plots following the treading treatments in both years. The soil VWC in ND plots at the time of treading tended to be higher in year two than in year one ($P=0.06$).

Pasture growth rate, light interception, leaf area index and normalised difference vegetation index

Pasture growth was reduced by 50% and 75% following treading damage in the early spring periods of year one and two respectively ($P<0.05$; Table 2). However, treading treatment did not significantly affect pasture growth during any other seasons (Table 2). When averaged over each year and over the entirety of the experiment, pasture growth rate was not significantly different between treading treatments.

Table 1 Mean soil volumetric water content (VWC) during treading by dairy cows in early spring 2022 (year 1) and early spring 2023 (year 2) and the resulting mean pug mark density and depth

Year	Treatment	Soil VWC (%)	Pug depth (mm)	Pug density (pugs/m^2)
1	Damaged	43	34	46
	Undamaged	35	13	37
2	Damaged	42	31	48
	Undamaged	38	18	39
SEM[1]		0.5	1.8	2.2
ANOVA p-values				
Treatment		<0.01	<0.01	0.047
Year		0.246	0.602	0.202

[1]SEM = Standard Error of the Mean

Table 2 Pasture growth rate (kg DM/ha/day) of a plantain-perennial ryegrass pasture sown in autumn 2022, following treading damage (DD) or no treading damage (ND) from dairy cows during early spring 2022 (year 1) and early spring 2023 (year 2)

			Pasture growth rate (kg DM/ha/day)		
Year	Season		DD	ND	SEM[1]
1	Early spring		24^b	48^a	8.85
	Late spring		82	83	12.57
	Early summer		52	41	6.02
	Late summer		38	47	5.49
	Autumn		26	36	3.95
	Winter		31	33	2.88
2	Early spring		7^b	27^a	5.53
	Late spring		75	77	5.27
	Early summer		86	76	10.10
	Late summer		48	36	6.09
	Mean		47	50	2.49
ANOVA p-values					
Treatment		0.371			
Season		<0.01			
Year		0.679			

Means within rows with different letters are significantly different (P<0.05)

1SEM = Standard Error of the Mean

Pasture growth varied significantly between climatic seasons (P<0.01). In year one, the mean pasture growth rate across treatments increased from 36 kg DM/ha/day in early spring to a peak of 82 kg DM/ha/day during late spring before decreasing over summer to 31 kg DM/ha/day in autumn and winter. Mean pasture growth decreased significantly in the early spring of year two, to 17 kg DM/ha/day, before increasing to 76 kg DM/ha/day in late spring (P<0.01). The mean pasture growth rate was similar in early summer, before decreasing to 42 kg DM/ha/day in late summer (P<0.01). The mean pasture growth rate between early spring and late summer was similar between the two years of the experiment.

Canopy light interception was significantly lower in DD plots than ND plots during early spring in both years (P<0.05). However, it was not significantly affected by treatment during any other season (Table

Table 3 Pasture light interception (LI), leaf area index (LAI) and normalised difference vegetation index (NDVI), measured 14 days after each grazing event, in a plantain-perennial ryegrass pasture sown in autumn 2022, following treading damage (DD) or no treading damage (ND) from dairy cows during early spring 2022 (year 1) and early spring 2023 (year 2)

		LI (%)		LAI (cm^2 leaf/ cm^2 ground)		NDVI	
Year	Season	DD	ND	DD	ND	DD	ND
1	Early spring	84^b	95^a	-	-	0.79^b	0.83^a
	Late spring	88	90	-	-	0.79	0.79
	Early summer	91	93	-	-	0.69	0.68
	Late summer	93	94	-	-	0.70	0.71
	Autumn	93	92	-	-	0.71	0.72
2	Early spring*	83^b	89^a	0.66^b	1.33^a	0.67	0.70
	Late spring	86	87	2.66	2.91	0.83	0.84
	Early summer	88	89	3.19	3.29	0.76	0.76
	Late summer	79	75	1.70	1.53	0.51	0.50
	Mean	89	87	2.05	2.27	0.72	0.72
ANOVA p-values							
Treatment		0.188		0.342		0.591	
Season		<0.01		<0.01		<0.01	

Means within rows with different letters are significantly different (P<0.05)
*Early spring measurement taken 21 days after the treading damage event.

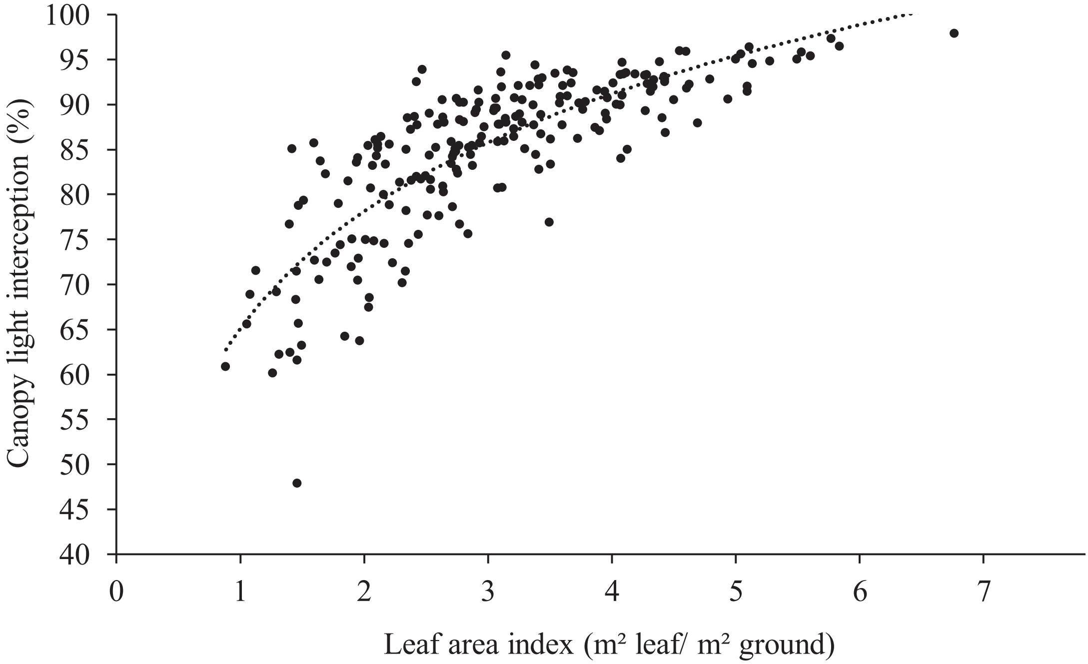

Figure 1 Relationship between leaf area index and light interception during several regrowth cycles between late spring and early summer for a two-year-old plantain+perennial ryegrass pasture. Fitted line (dashed) equation: $y = 18.866\ln(x) + 65.051$

3). Mean canopy LI was greatest during the summer of year one, and lowest during late summer in year two (season effect P<0.01).

In year two, the mean LAI of the DD pasture was 50% lower than the LAI of ND pasture during early spring (P<0.05) but was not significantly different between treading treatments during any other season. The mean LAI was greatest during late spring and early summer and lowest during early spring (P<0.01). There was a strong logarithmic regression relationship between canopy LI and LAI between late spring and early summer ($R^2 = 0.66$), with LI reaching 95% at an LAI of 4.9 (Figure 1).

During early spring in year one of the experiment, NDVI was significantly lower in DD plots than ND plots 14 days after the treading damage (P<0.05). There was no significant difference between the NDVI of treading treatments during any other season. Mean NDVI was greatest during late spring in both years and was lowest during late summer in year two (P<0.01).

Pasture botanical composition

During early spring in year one, following the treading event, PL content tended to be lower (P=0.097) in DD plots than in ND plots while RG content was 28% higher in DD plots than in ND plots during the same period (P<0.05, Figure 2). During late spring, PL content was 26% lower in DD plots than in ND plots (P<0.05), while RG content was significantly greater in DD plots than in ND plots (P< 0.05). There was no significant effect of treading treatment on PL and RG content during the remainder of year one. During early spring in year two, following treading damage, PL content appeared to be lower in DD plots than in ND plots (P=0.19), but RG content was similar in both DD and ND plots. There was no significant effect of treatment on pasture PL or RG content during the remainder of the study. When averaged over the entire experimental period, treading treatment had no significant effect on the PL content (DD = 27%, ND = 29%) or RG content (DD = 53%, ND = 51%) of plots.

The mean pasture PL and RG content varied significantly between seasons (P<0.01) In general, PL content peaked during autumn and winter, where it exceeded 40% of DM, and was lowest during late spring and early summer, where it made up ~20% of sward DM in year one and ~10% of sward DM in year two. In year one, RG content was greatest during early spring and late summer (63%) and lowest in autumn (40%), while in year two, RG content was greatest in late spring (70%) and lowest in late summer (42%). The mean pasture PL content decreased from 35% in year one to 17% in year two (P<0.01), while the mean RG content was similar between years.

The portion of pasture DM not comprising RG or PL was largely made up of annual poa, which appeared throughout spring in both years, and dead matter, which comprised 28% and 34% of sward DM during early and late summer in year two, respectively. Additionally, PL seed head content was significantly higher during the second year of the experiment, than the first year (P<0.05), while the broadleaf weed content increased gradually over the course of the experiment.

Plantain and perennial ryegrass growth rates

The growth rate of RG was significantly higher than that of PL during late spring and early summer in year one (P<0.01), and during late spring, early and late summer in year two (P<0.01) but similar to that of PL in all other seasons (Figure 3). There was a tendency for a higher growth rate for RG than for PL during early spring in both year one (P=0.09) and year two (P=0.07). The mean RG growth rate (26 kg DM/ha/day) was 138% greater than that of PL (11 kg DM/ha/day) on average over the entire experiment (P<0.01).

The mean growth rate across PL and RG was reduced by treading damage during early spring in both year one (P<0.05) and year two (P<0.01), and during autumn in year one (P<0.05). When averaged over the entire experiment, the mean growth rate across PL and RG was not significantly different between treading treatments.

The growth rate of both PL and RG varied significantly between seasons, regardless of treatment (P<0.01). In early spring of year one, the PL growth rate was 12 kg DM/ ha/ day. The mean PL growth rate then peaked during late spring and late summer (17 kg DM/ ha/day) and was similar throughout autumn and winter. In early spring of year two, the mean PL growth rate decreased to 5 kg DM/ha/day, before increasing again in late spring and then trending down for the remainder of year two. In early spring of year one, the growth rate for RG was 18 kg DM/ha/day. This increased during late spring to 51 kg DM/ha/day, but then decreased from early summer onward and was around 18 kg DM/ ha/day throughout autumn and winter. The mean RG growth rate was not significantly different between winter and the early spring of year two but increased to 53 kg DM/ha/day during late spring. The growth rate of RG then decreased gradually between early and late summer.

Plantain shoot density and perennial ryegrass tiller density

In year one, the PL shoot density in DD plots was 21% and 29% lower than in ND plots during early and late spring, respectively (P<0.05) (Figure 4). During late summer, PL shoot density was 20% lower in DD plots than in ND plots, but from autumn until late summer in year two, PL shoot density was similar between

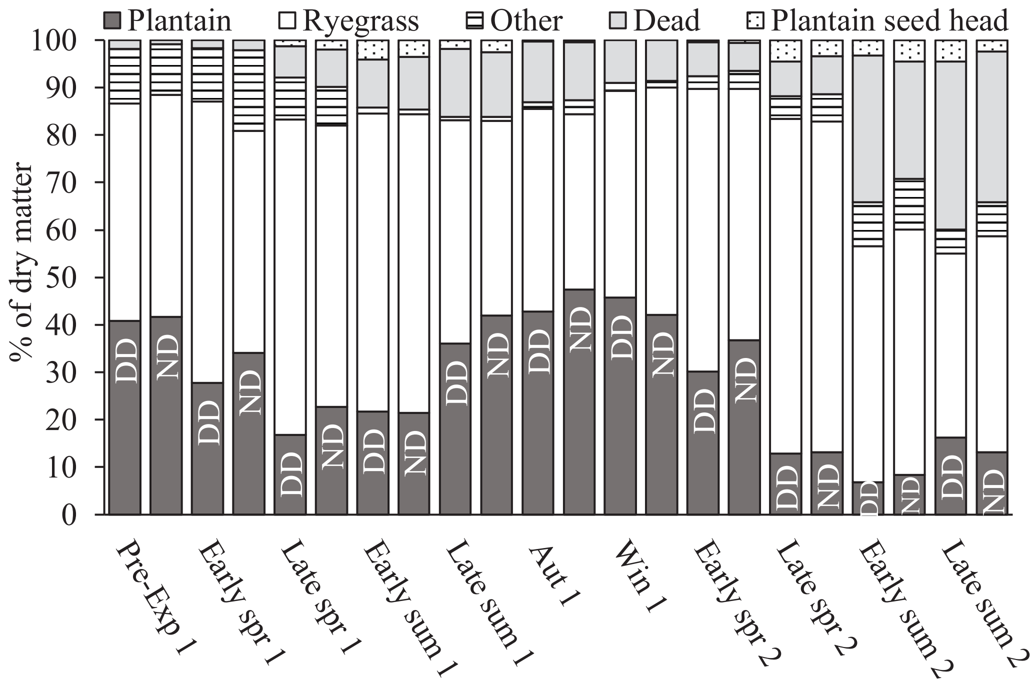

Figure 2 Botanical composition of a plantain+perennial ryegrass pasture sown in autumn 2022 over two years, following treading by dairy cows in early spring 2022 (year 1) and early spring 2023 (year 2). DD= Damaged, ND= Undamaged

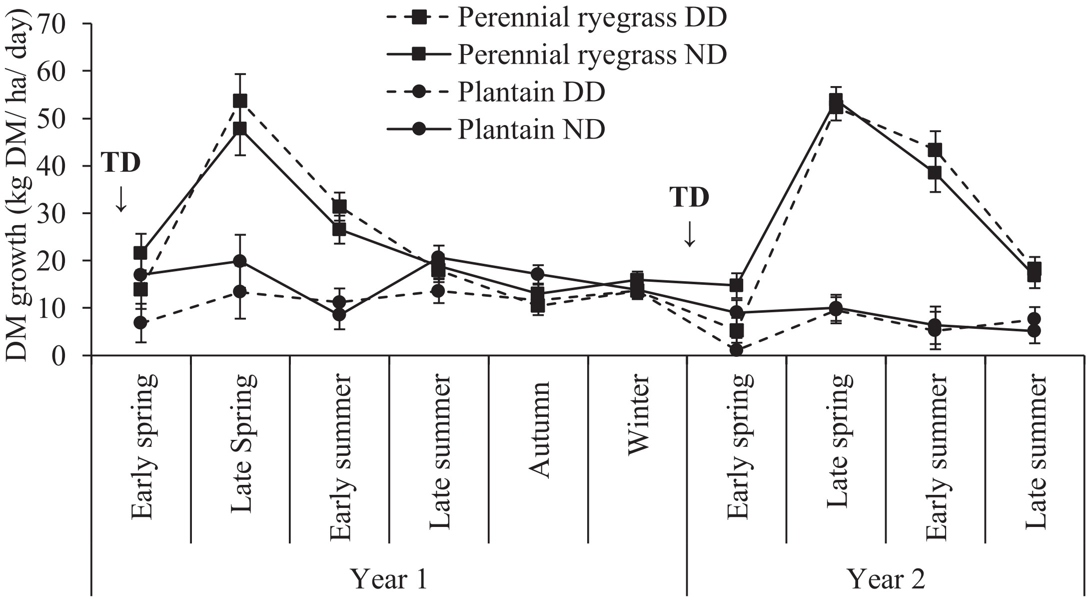

Figure 3 Daily growth rates of the plantain and perennial ryegrass components of a plantain+perennial ryegrass pasture sown in autumn 2022, following treading damage (DD) or no treading damage (ND) by dairy cows in early spring 2022 (year 1) and early spring 2023 (year 2). TD = Treading damage event. Bars show standard error of the mean.

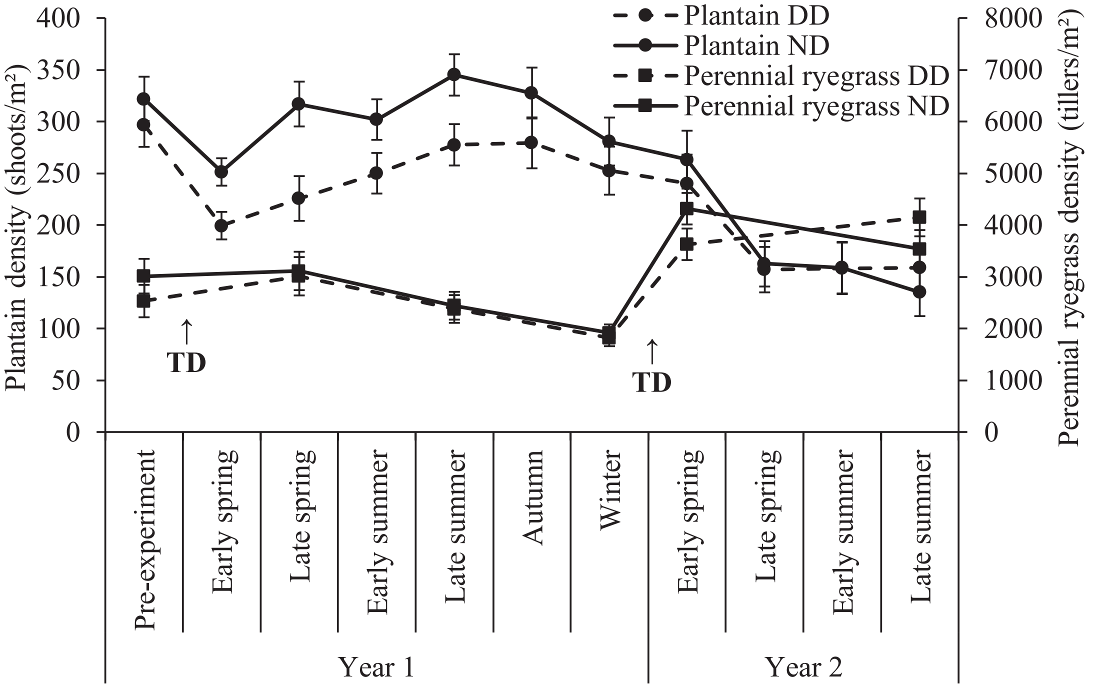

Figure 4 Density (number/m^2) of plantain shoots and perennial ryegrass tillers in a second-year plantain+perennial ryegrass pasture sown in autumn 2022, following treading damage (DD) or no treading damage (ND) by dairy cows in early spring 2022 (year 1) and early spring 2023 (year 2). TD = Treading damage event. Bars show standard error of the mean.

treatments. When averaged over the whole experimental period, PL shoot density was not significantly different between treading treatments.

Treading damage had no significant effect on RG tiller density during any season in the study.

Following the first grazing (and treading) in August 2022, mean PL shoot density across the site decreased from 309 to 225 shoots/m^2 ($P<0.01$). The mean PL shoot density then increased gradually over year one, to reach 311 shoots/m^2 in autumn. Mean PL shoot density decreased from autumn into winter ($P<0.05$). In year two, following the treading event, PL shoot density remained steady across the site and was 252 shoots/m^2 in early spring, before decreasing by 37% between early and late spring ($P<0.01$) to 160 PL shoots/m^2, and then remained constant into late summer. The mean PL shoot density decreased by 53% on average over the experiment and was significantly lower in year two than in year one ($P<0.01$).

There was also an effect of a significant interaction between treading treatment and climatic season on PL shoot density ($P<0.05$). After decreasing significantly following the treading event in year one, PL shoot density in DD plots recovered steadily and was similar to pre-experiment levels by late summer. In contrast, following a reduction in early spring, the PL shoot density of ND plots had recovered to pre-experiment levels by late spring, and then increased gradually until autumn. Between autumn in year one and the end of the experiment in year two, the shoot density of DD plots and ND plots followed a similar downward trend, with the largest reduction occurring in late spring in year two.

In year one, the mean RG tiller density was similar between the pre-experimental measurement and the late spring measurement, although it decreased significantly between late spring and late summer ($P<0.05$). The mean RG tiller density was similar between late summer and winter (1869 tillers/m^2). The mean RG tiller density increased significantly during early spring in year two, to 3971 tillers/m^2 ($P<0.01$) and then remained constant into late summer. In contrast to PL, the mean RG tiller density was significantly greater in year two than in year one ($P<0.01$).

Discussion

Treading damage

As expected during both years, mean pug depth increased with an increase in soil VWC at the time of grazing (Climo and Richardson 1984) and led to the significantly greater damage severity observed in DD plots than in ND plots after each treading event. The mean pug depths observed in DD plots across the two years are comparable to those previously observed by

Betteridge et al. (2003) in a cattle treading experiment on a silt loam soil. The greater mean pug density in DD plots than ND plots was unexpected and may have resulted from deep pug marks being more easily identified than shallow pug marks, rather than an effect of animal behaviour.

Pasture growth rate, light interception, Leaf Area Index and Normalised Difference Vegetation Index

In agreement with previous pasture treading studies (Brown and Evans 1973; Pande et al. 2000), treading damage had an immediate, negative impact on the growth of the PL+RG pasture, with a reduction in pasture growth rate of 50% and 75% in the first regrowth period following treading in years one and two respectively. Additionally, since the reduction in growth rate following treading damage was similar to that observed for RG-dominant pastures in other studies (Pande et al. 2000), it didn't appear that inclusion of PL increased the sensitivity of the mixed pasture to treading damage in the current study. Pasture growth rates recovered in DD plots during late spring in both years, suggesting that the damage caused no permanent limitations to pasture growth. Pasture growth rates followed a typical trend for RG-based swards, peaking between late spring and early summer, and declining during winter (Kemp et al. 1999). The low pasture growth rates and larger reduction in growth following treading damage in the early spring of year two than in year one probably reflected cooler temperatures during that time (Baars and Waller 1979).

Pasture growth rate is strongly associated with a pasture's ability to capture incident light through leaves (Smetham 1973). Treading damage has been shown to reduce pasture LI (Wilson et al. 2023a), LAI and thus growth rate (Pande et al. 2000) in the initial regrowth period following the damage event. In the current study, treading damage initially reduced canopy LI in both years and LAI in year two, most likely driving the reduction in growth rate during that period (Smetham 1973). The use of NDVI for capturing the negative effects of treading damage on canopy growth proved useful in early spring in year one of the study, where DD plots had a lower NDVI value than ND plots, reflecting a reduction in green leaf material following damage. However, following the treading event in year two, NDVI measurement failed to capture the severity of treading damage on pasture in DD plots. This may have been a result of the NDVI scanner receiving reflectance from dying residual herbage trampled into the soil surface in DD plots, below the height at which LI and LAI measurements were made. Therefore, the measurement of NDVI was useful for detecting damaged pasture, particularly where there was a high proportion of bare soil, although more work needs to be done to determine the limitations of its use.

Plantain content and density

Treading damage by dairy cows caused a notable reduction in PL content within the PL+RG pasture in early and late spring in year one, likely via the destruction and burial of PL growing points (Brown and Evans 1973), along with the impairment of leaf regrowth. However, the effects of the treading damage on PL content in year two were less obvious. In contrast with PL, treading damage appeared to cause an increase in RG content in both years, reaffirming its status as a more treading-tolerant pasture species (Brown and Evans 1973). Pasture PL content was lower than expected during the experiment, given that similar sowing rates of both PL and RG resulted in a peak PL content of 64% in another study in the same region (Nguyen et al. 2022). Low emergence rates, along with the rapid decline in PL content during year two, represent some of the challenges frequently observed following the incorporation of PL with RG (Bryant et al. 2019; Nguyen et al. 2022).

The pasture PL and RG contents appeared to be negatively correlated throughout the current study. As anticipated, RG growth rates peaked during late spring in both years (Kemp et al. 1999) and made up a large proportion of sward DM. However, despite also reaching a peak growth rate in late spring in both years, PL content was generally very low during this period. In contrast, during late summer and autumn in year one of the study, there was a peak in PL content, coinciding with significantly lower RG growth rates. Taken together, these results suggest that PL content was largely driven by RG growth and illustrate the impact that companion species growth has on the determination of PL content.

Pasture PL content and DM yield are also likely to be driven somewhat by PL shoot density (Ayala et al. 2011). The reduction in PL shoot density in DD plots following treading in year one appeared to account for the reduction in PL content in the pasture during that time. However, in year two, treading damage didn't appear to have any major effect on PL shoot density, which might have been due to larger, better established PL plants providing greater protection to individual shoots from the treading damage imposed. For PL to persist, it is necessary for PL populations to replace dead shoots with new shoots, either asexually through secondary shoot development, or via seedling recruitment (Grime et al. 1989). While the PL shoot population proved to be sensitive to treading in early spring in year one (Ayala et al. 2011), in year two the population largely survived this early treading, possibly also due to shoots being bunched together on larger PL plants. However, the continual reduction in PL shoot density during late spring and summer in year two is in stark contrast with the gradual increase in PL shoot density during those seasons in year one. That could indicate that older PL populations have a reduced capacity for recovery via new shoot production or seedling recruitment.

In year two, the largest reduction in PL shoot density, regardless of treading treatment, occurred between early and late spring, at a time when both the tiller density and growth rate of RG increased considerably. This result might suggest that a significant driver of reduced PL shoot density was increased competition from RG, which agrees with previous findings (Bryant et al. 2019; Dodd et al. 2019), and, in the context of PL persistence, could signify that RG is an unsuitable companion for PL. In a study by Mook et al. (1989), PL mortality in dense vegetation was concentrated in the late spring period, coinciding with a period of low light transmission through the canopy. Studies have suggested that PL growth and development are particularly sensitive to shading (van der Toorn and Pons 1988; Kuiper and Bos 1992), which has been shown to reduce PL leaf photosynthesis rates (Kuiper and Bos 1992), and is associated with suppressed secondary shoot development (Van Tienderen and van der Toorn 1991). Furthermore, low-light conditions in dense grass-based swards may inhibit the successful establishment of new PL seedlings (van der Toorn and Pons 1988; Bryant et al. 2019), thus limiting the potential for PL population maintenance or increase via seedling recruitment.

If the main driver of PL shoot survival through late spring and early summer is light captured by shoots, one potential mitigation could be to defoliate the pasture at an earlier regrowth stage than what is recommended for a RG-based pasture. Since RG pastures usually consist of thin, erect leaves, canopies may reach 95% LI, and thus their maximum growth rate (critical LAI), at a LAI of 7 in summer (Brougham 1957). However, it appears that the PL+RG pasture in the current study achieved 95% LI at a LAI of 4.9, which is closer to the critical LAI for pastures containing flat-leaved plants such as white clover (Brougham 1957). Since pasture growth rate declines gradually after a pasture reaches its critical LAI (Smetham 1973), it may be in the best interest of both PL shoot survival and pasture growth to defoliate PL+RG pastures at this lower LAI. However, more work is required to determine how an earlier defoliation would affect RG productivity, the allocation of pasture to cows, and influence feed budgeting on farm.

Conclusions

While results from the current study suggest that livestock treading damage might provide only part of the explanation for low PL contents in dairy pastures, it remains important to avoid treading damage in early spring to avoid reductions in PL content and pasture growth throughout spring.

The decline in PL content within the PL+RG pasture over the two-year experiment seemed to be largely driven by high DM yields of RG in late spring and early summer in both years, and the reduction in PL shoot density during the second year of the study. These results suggest that PL shoot survival is negatively impacted by shading in RG-based swards. By grazing PL+RG pastures at an earlier regrowth stage during late spring, it may be possible to optimise pasture productivity as well as PL shoot survival and thus improve PL persistence.

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