

Crops and Soils Research Paper

Cite this article: Al-Marashdeh O, Herath HMGP, Thomas C, McMillan N, Tanner J, Woods RR, and Bryant RH (2026). Calibration of a rising plate metre for herbage mass estimation in ryegrass-white clover mixed swards containing different proportions of plantain (*Plantago lanceolata* L.). *The Journal of Agricultural Science* **164**(e32), 1–10. <https://doi.org/10.1017/S0021859626100690>

Received: 7 December 2025

Revised: 13 April 2026

Accepted: 22 April 2026

Keywords:

compressed height; dairy cows; dairy systems; grazing; herbs; plantain-incorporated swards

Corresponding author:

Omar Al-Marashdeh;

Email: omar.al-marashdeh@lincoln.ac.nz

Calibration of a rising plate metre for herbage mass estimation in ryegrass-white clover mixed swards containing different proportions of plantain (*Plantago lanceolata* L.)

Omar Al-Marashdeh¹ , H.M.G.P. Herath¹, Charissa Thomas², Natalie McMillan², Jasmine Tanner¹, Roshean R. Woods² and Racheal H. Bryant¹

¹Faculty of Agriculture and Life Sciences, Lincoln University, Canterbury, New Zealand and ²DairyNZ Ltd, PO Box 85066, Lincoln 7608, New Zealand

Abstract

The objective of this study was to develop calibration equations for a rising plate metre (RPM) to estimate herbage mass in irrigated ryegrass/white clover (RGWC) swards with varying proportions of plantain. A 32-ha area, divided into 0.3-ha paddocks, was randomly allocated to three treatments sown with increasing plantain seeding rates: (i) RGWC with no plantain, (ii) RGWC + 3 kg/ha and (iii) RGWC + 6 kg/ha. Over two production years (2021/22 and 2022/23), 1138 quadrat cuts and 228 botanical samples were collected. Data were grouped by season (late-winter, spring, summer and autumn) across treatments and years. A multivariate linear regression model incorporating compressed sward height, plantain % in sward DM and season explained 73.5% of the variation in herbage mass ($R^2 = 0.735$; $P < 0.001$). Compressed sward height was positively associated with herbage mass (estimate $\pm$ SE; 145 ± 6.2 kg DM/ha per RPM unit; $P < 0.001$), while plantain % was negatively associated (-0.45 ± 0.12 kg DM/ha per 1% increase; $P < 0.001$). Season significantly affected the intercept ($P < 0.001$), being -128 ± 135.0 (late-winter), 82 ± 104.0 (spring), 251 ± 106.0 (summer) and -81 ± 111.0 (autumn) kg DM/ha. Validation using an independent dataset from the 2023/24 production year showed the model predicted herbage mass with a root mean square error (RMSE) of 350 kg DM/ha. These equations can be integrated into RPM devices to estimate herbage mass in rotationally grazed, irrigated RGWC swards containing plantain, accounting for both plantain content and seasonal variation.

Introduction

In pasture-based livestock production systems, accurate estimation of available herbage mass is important to feed animals according to their nutritional requirements while optimising herbage utilisation. Inaccuracy in predicting herbage mass can negatively impact on-farm feed budgeting, potentially leading to over- or under-feeding animals, which compromises overall farm performance and profitability. In rotational grazing dairy systems, where the pasture area is subdivided into multiple paddocks and grazed sequentially, the rising plate metre (RPM) device is used to estimate herbage mass (Cho *et al.*, 2019; Michell, 1982; Murphy *et al.*, 2021a; Rennie *et al.*, 2009). The RPM measures the compressed height of the sward to estimate herbage mass using calibrated equations (Thomson *et al.*, 2001). In New Zealand, calibrated equations for mixed swards of perennial ryegrass and white clover (RGWC) have been well established across different seasons and geographical regions (L'Huillier and Thomson 1988; Lile *et al.*, 2001; Thomson *et al.*, 2001). However, with growing interest in multispecies swards, limited data exist for using the RPM to estimate herbage mass in mixed swards other than RGWC, which may differ in morphology and dry matter (DM) content.

The narrow-leaved herb plantain (*Plantago lanceolata* L.) has been promoted for its reduced environmental impact, particularly reducing nitrogen loss from dairy systems (Pinxterhuis *et al.*, 2024). Compared to RGWC, feeding plantain-containing herbage to dairy cows has been shown to reduce their urinary nitrogen concentration (Box *et al.*, 2017; Minnée *et al.*, 2020; Nguyen *et al.*, 2022a), resulting in a lower nitrogen load per urine patch. This can lead to a reduction in nitrate leaching (Carlton *et al.*, 2019; Woods *et al.*, 2018) and nitrous oxide emissions (Gardiner *et al.*, 2016; Simon *et al.*, 2019). However, integration of such herbs into farming systems requires information about managing plantain-based swards, including an accurate, inexpensive and easy-to-use tool for herbage mass estimation. Such a management tool would help farmers make real-time grazing decisions, thereby facilitating the rate and extent of adoption.

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The RPM is an inexpensive and simple tool for herbage mass estimation, but the accuracy of calibrated equations is sensitive to factors such as sward type (Baker *et al.*, 2025; Harmony *et al.*, 1997), content of dead material (L'Huillier and Thomson 1988), season of the year (Ferraro *et al.*, 2012) and presence of herbs (Haultain *et al.*, 2014). Further, estimated herbage mass has been reported to be affected by the moisture content of herbage (Hanna *et al.*, 1999; Serrano *et al.*, 2011). Inclusion of plantain into a mixed RGWC sward reduces the sward's DM content (Minnée *et al.*, 2019; Nguyen *et al.*, 2022b), and such a change in DM content varies across different seasons due to seasonal variation in sward content of plantain (Herath *et al.*, 2023; Nguyen *et al.*, 2022b), influencing calibration equations used for herbage mass estimation. Haultain *et al.* (2014) showed that the calibration equation for pure crops of plantain could be as accurate as those for RGWC but differed in their slope and intercept.

Farmers commonly apply equations developed for RGWC to estimate herbage mass in mixed swards containing plantain. However, this may lead to overestimation due to plantain's lower DM (Minnée *et al.*, 2019), its more erect growth habit which may reduce sward compression under the plate (Dodd *et al.*, 2025), and potentially lower bulk density resulting from its longer and more upright stems compared to perennial ryegrass. This highlights the need for calibrated RPM equations for herbage mass estimation in plantain-based swards to improve the accuracy of feed planning and allocation. This is partly supported by a recent study in Ireland, which reported that including season, sward type and their interactions with compressed sward height improved prediction accuracy compared with height alone (Baker *et al.*, 2025). However, the improvement was modest, and the authors emphasised the practical value of simpler height-based models for multispecies swards. Notably, sward composition in that study was represented as categorical sward type rather than quantified botanical proportions, leaving uncertainty around how individual species, such as plantain, influence RPM estimates, particularly at higher proportions (e.g. >20%). Therefore, the objective of this study was to develop calibration equations for RPM to estimate the herbage mass of irrigated RGWC mixed swards with varying proportions of plantain across different seasons of the year. We hypothesised that RPM could accurately estimate the herbage mass of RGWC swards containing plantain, though the slope and intercept of the calibration equation would differ from those of RGWC swards without plantain.

Materials and methods

The study was conducted at Lincoln University Research Dairy Farm, Lincoln, New Zealand, over two production years 2021/22 and 2022/23 (June to May). The data collected in this research was part of a 4-year dairy farm systems study aimed to investigate effects of different proportions of plantain in a mixed RGWC sward on dairy system productivity and nitrate leaching.

The site was located on a flat terrain with imperfectly to well-drained silt and sandy loam soil types, including Templeton and Barrhill (Manaaki Whenua Landcare Research, 2025). Weather data were measured via a weather station installed at site of study (Scott Technical Instruments Ltd., New Zealand). The daily maximum air temperature ranged from 8.1 to 29.6 °C in 2021/22 and 7.0 to 33.5 °C in 2022/23, and the minimum air temperature ranged from −4.3 to 17.8 °C in 2021/22 and −4.2 to 20.5 °C in 2022/23. The cumulative rainfall was 770 mm and 860 mm in 2021/22 and 2022/23, respectively. Total irrigation of 216 mm and

257 mm was applied in 2021/22 and 2022/23, respectively, during the dry periods from late October (mid to late spring) to March (early autumn).

Farmlet establishment and management

Details of farmlet establishment and management are described by Herath *et al.* (2023) and Hintz *et al.* (2026). Briefly, a total of 32 ha was allocated to nine farmlets (12 paddocks, approximately 0.3 ha each, per farmlet). The experimental paddocks were evaluated to ensure they were balanced among the farmlets for sowing method, soil type and distance to the milking parlour. Farmlets were then randomly allocated into one of three herbage treatments sown with an increasing plantain seed rate: (i) RGWC without plantain; (ii) RGWC + 3 kg/ha plantain (PL3) or (iii) RGWC + 6 kg/ha plantain (PL6). During the study period, each farmlet area was rotationally grazed by one of nine herds each comprised of 12 Holstein-Friesian × Jersey lactating dairy cows at a stocking density of 80 cows/ha per day for the majority of the production year. Herds were balanced by age, live weight, body condition score, previous level of milk production and breeding and production worth (production genetic index) and randomly allocated to farmlets. The grazing rotation interval was 22 to 24 days for most of the production year, when herbage growth met or exceeded animal nutritional demand, from early-mid spring (late September or early October) to early autumn (early March). It was extended to 36 ± 6.7 days (mean ± SD) in mid to late autumn and to 62 ± 22.4 days during late winter, when herbage growth rates were below animal demand. Farmlets were managed individually, and herds were grazing on their farmlet area during the lactation period from calving in late July to dry-off the following May. After dry-off, cows were shifted to graze off the farmlet area following a common management practice in the region as explained by Al-Marashdeh *et al.* (2021). Thus, no pasture measurements were conducted in June and early-July.

Pasture establishment

The mixed swards were established in March 2021. Prior to the establishment of the swards, plots received a mixed herbicide application of glyphosate (2.8 kg/ha) and either saflufenacil (17.5 g/ha) in direct-drilled paddocks or fluroxypyr (300 g/ha) in cultivated paddocks. The seed mixtures were sown via direct drilling (18 ha) or light cultivation (14 ha). The RGWC only paddocks were sown with a seed mixture of a late flowering (+13 days) diploid perennial ryegrass (*Lolium perenne* L.; cv. Legion AR37; 20 kg/ha) and white clover (*Trifolium repens* L. cv. Tribute; 2 kg/ha). The RGWC plus plantain paddocks were sown with the same cultivars of perennial ryegrass (18 kg/ha or 15 kg/ha, for PL3 and PL6, respectively) and white clover (2 kg/ha) plus plantain (*Plantago lanceolata* L; Ecotain™: a blend of cv. Agritonic and cv. Ceres Tonic) at either 3 kg/ha (PL3) or 6 kg/ha seeding rate (PL6). White clover seed was re-sown into all treatment paddocks by broadcasting at a rate of 5 kg/ha from late spring (mid-October 2021) to early summer (early December 2021). In February 2022, PL3 and PL6 paddocks with low plantain botanical composition (≤ 20% in sward DM in PL3 and ≤ 30% in PL6 treatments) were over-sown with Prillcote® plantain seed (cv. Agritonic) at a rate of 12 kg/ha (equivalent to 6 kg/ha of bare seeds), covering a total of 3.9 ha in PL3 and 3.3 ha in PL6. In addition, during February 2023, PL3 and PL6 paddocks with low plantain proportions were under-sown (i.e. directly drilled) with plantain at a rate of 6 kg/ha bare seeds (cv. Agritonic). A total of 3.6 ha in the PL3 treatment and

3.3 ha in the PL6 treatments were under-sown with plantain seed in 2023.

Measurements

Weekly (in 2021/22) or fortnightly (in 2022/23) herbage mass and compressed sward height were measured in one paddock per farmlet (total of 9 paddocks; 3 paddocks per herbage treatment). Paddocks were randomly selected to represent a range of sward heights based on days since grazing (< 7 days, 2–3 weeks and 1–3 days pre-grazing) within each herbage treatment. Four 0.259 m² quadrats were placed randomly in each paddock (equivalent to 13.3 quadrats per ha). In paddocks with uniform pasture cover, quadrat sites were selected by walking through the paddock and tossing the quadrat randomly, avoiding areas with faecal deposits. In paddocks with non-uniform pasture cover, representative areas with contrasting herbage heights were identified, and quadrat sites were selected randomly within these areas. Compressed sward height was measured at the quadrat site using an RPM (EC09; Jenquip, Feilding, New Zealand), with each measurement based on the average of two RPM readings per quadrat. All herbage within the quadrat was cut to ground level. The RPM measures compressed sward height in units (referred to as ‘clicks’), where one unit equals 5.0 mm. The cut herbage was washed and then oven-dried at 60°C for 48 hours to determine total DM in each quadrat. The herbage mass (kg DM/ha) was then calculated as dry weight (g) $\times$ (10 000 m²/ha $\div$ 0.259 m²) $\div$ 1000 g/kg. This protocol is commonly applied in farm systems research (Chapman *et al.*, 2021; Macdonald *et al.*, 2008), to generate monthly calibration equations for estimating accumulated herbage growth.

Each week (in 2021/22) or fortnight (in 2022/23), the botanical content of the herbage was measured from one paddock per farmlet (three paddocks per herbage treatment) that was due to be grazed. Botanical samples were collected by cutting a handful of herbage, using hand scissors, at estimated grazing height (approximately 5 cm above ground), every five to ten steps of walking in a zig-zag pattern across the paddock, covering at least 20 different sites within a 0.3-ha paddock. At the lab, the bulk sample (approximately 500 g fresh weight) was mixed, and a sub-sample of herbage (50 g fresh weight) was dissected into sown (perennial ryegrass, white clover, plantain), unsown monocot and dicot species and dead material. Samples were then dried at 60 °C for 48 hours to determine the dry weights. The dry weight of each component was used to determine the proportion of the respective component relative to the total dry weight of the sample (i.e. the botanical composition on a DM basis).

Statistical analysis

Data were grouped by season across herbage treatments and production years: late-winter (mid-July to August), spring (September to November), summer (December to February) and autumn (March to May). Only paddocks where quadrat cuts were collected and at least one botanical measurement was recorded within a given season were included in the analysis. The paddock was used as the observational unit. For each paddock, compressed sward height and herbage mass (kg DM/ha) were averaged across the four quadrat cuts, and botanical composition was recorded at the paddock level. If a paddock was sampled more than once within a season in a given production year, measurements were averaged to generate a single seasonal value. For summary statistics (Supplementary Table 1), data were pooled and categorised into

two groups based on the presence of plantain in the mixed sward: RGWC-only (RGWC-based sward with no plantain) and RGWC + PL (RGWC-based sward with plantain). Sward DM content and botanical composition data were analysed in R (version 4.5.0) using RStudio (version 2025.05.0 + 496). A linear mixed model was fitted using the lme4 package, with sward type, season and their interaction included as fixed effects and paddock as a random effect. White clover, dead material and unsown monocot and dicot species data were log (x + 1)-transformed prior to analysis to improve normality and homogeneity of variance. Estimated marginal means were obtained using the emmeans package.

All model development, statistical analyses and model validation were performed using Genstat (24th edition) statistical software (VSN International Ltd., Hemel Hempstead, UK). Multivariate linear and quadratic regression analyses were used to develop a final herbage mass prediction model. The full model consisted of the RPM compressed sward height, plantain % in the mixed sward DM, season of the year and their interactions as independent variables, and herbage mass (kg DM/ha) as the dependent variable. The effects of white clover, dead material and unsown monocot plus dicot species content were each tested by fitting them individually into the base model to prevent potential masking due to term order. The final model was developed using a stepwise approach, where variables were excluded based on their contribution to model fit, assessed through the accumulated analysis of variance (based on F probabilities), changes in adjusted *R*² and Root Mean Square Error (RMSE). Variables that did not improve model performance, i.e. did not meaningfully reduce RMSE or increase adjusted *R*², were removed.

The regression models were fitted with an unconstrained intercept (i.e. intercept was not forced to zero). Although a compressed sward height of zero would theoretically correspond to zero herbage mass, the dataset did not include zero observations height (minimum 5.6 RPM unit; 28.0 mm). Constraining the model through the origin would, therefore, impose a fixed point outside the observed data range and could bias parameter estimates. In addition, this constraint assumes linearity across the full range of sward heights, whereas changes in sward structure at low heights may result in non-linear relationships outside the range of measurements. The non-zero intercept should, therefore, be interpreted as a statistical artefact of fitting the model within the observed range, rather than a physically meaningful estimate at zero height.

To validate the model, data from the following year (2023/24 production year) were used. These were collected from the same site and using the same approach described above for RPM and botanical composition (Supplementary Table 2). Although the data were collected from the same location, individual paddocks contained different levels of plantain compared to the original data used in the model development. This was due to plantain's lifecycle and natural fluctuations in its abundance within the mixed sward over time (Nguyen *et al.*, 2022b). The observed values of herbage mass were compared with those predicted using the developed season-specific models. Lin's concordance correlation coefficient (CCC), Pearson's correlation coefficient and the coefficient of determination relative to the 1:1 line (1:1 *R*²) were used as measures of correspondence between observed and predicted herbage mass values. The deviation of observed values (*O_i*) from predicted values (*P_i*) was quantified using the following error metrics:

Table 1. Summary of rising plate metre (RPM) compressed sward height (measured in RPM unit¹ where 1.0 RPM unit = 5.0 mm) and herbage mass (kg DM/ha) from quadrat cuts collected in a ryegrass/white clover mixed sward with nil plantain (RGWC-only) or with plantain (RGWC + PL) and used in model development. Swards were established in Mar 2021 and quadrats collected over two production years (2021/22–2022/23) during late winter (mid-Jul to Aug), spring (Sep to Nov), summer (Dec to Feb) and autumn (Mar to May)

Treatment × season	Number of paddocks	Number of quadrats	Quadrat per ha	Rising plate metre compressed height (RPM unit ¹)				Herbage mass (kg DM/ha)			
				Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Late-Winter											
RGWC-only	3	12	13.3	17.3	4.04	9.3	23.5	2402	693.2	1205	3650
RGWC + PL	13	56	14.4	16.8	8.25	4.9	33.4	2180	1062.0	352	4603
Spring											
RGWC-only	27	152	18.8	15.2	5.36	5.6	33.6	2259	1006.8	444	4681
RGWC + PL	57	284	16.6	14.9	5.44	4.2	30.8	2156	863.3	493	4323
Summer											
RGWC-only	20	94	15.7	13.4	4.92	7.1	26.6	2075	943.9	535	5125
RGWC + PL	54	264	16.3	14.1	5.18	5.7	31.4	2215	907.0	442	5261
Autumn											
RGWC-only	18	91	16.9	14.6	5.18	5.7	27.7	1932	901.9	444	4845
RGWC + PL	36	185	17.1	15.6	6.57	4.4	33.9	2014	1040.9	275	5620
Overall											
RGWC-only	68	349	17.1	14.6	5.21	5.6	33.6	2129	961.5	444	5125
RGWC + PL	160	789	16.4	14.9	5.92	4.2	33.9	2145	937.8	275	5620

$$\text{Root mean square error, } RMSE = \sqrt{\sum_{i=1}^n (O_i - P_i)^2 / n} \quad (1)$$

$$\text{Mean absolute error, } MAE = \left(\sum_{i=1}^n |O_i - P_i| \right) / n \quad (2)$$

Mean relative absolute error,

$$MRAE = \left[\sum_{i=1}^n \left(\frac{|O_i - P_i|}{O_i} \right) \times 100\% \right] / n \quad (3)$$

Normalised root mean square error,

$$NRMES = (RMSE / \text{mean}(O_i's)) \times 100\% \quad (4)$$

Results

Compressed sward height and herbage mass

Summary of RPM compressed sward height and herbage mass (kg DM/ha) data used in model development are presented in Table 1. A wide range of compressed sward height and herbage mass values were used to derive the herbage estimation equations. Across all seasons, the compressed sward height ranged from 5.6 (28.0 mm) to 33.6 (168.0 mm) RPM unit (average 14.6 RPM unit; 73.0 mm) for RGWC-only and 4.2 (21.0 mm) to 33.9 (169.5 mm) RPM unit (average 14.9 RPM unit; 74.5 mm) for RGWC + PL. Herbage mass ranged from 444 to 5125 kg DM/ha (average 2129 kg DM/ha) in RGWC-only and 275 to 5620 kg DM/ha (average 2145 kg DM/ha) in RGWC + PL (Table 1).

Dry matter and botanical composition

Overall, plantain inclusion in the RGWC-based mixed sward reduced ($P = 0.002$) sward DM content from 18.7% (averaged across seasons) in RGWC-only to 16.8% in RGWC + PL, with no sward × season interaction effect (Table 2). Sward DM content was lower ($P < 0.001$) in autumn (15.6%) than in other seasons, but similar between late-winter (18.2%), spring (18.2%) and summer (18.9%) (Table 2).

Across all seasons, the ryegrass content (leaves plus reproductive stem) ranged from 51.1 to 99.1% in RGWC-only and from 15.4 to 93.1% in RGWC + PL sward (Supplementary Table 1). There was an interaction effect between sward and season on ryegrass content ($P = 0.027$; Table 2). Ryegrass content was higher in RGWC-Only than RGWC + PL in spring (83.7 vs 70.9%), summer (82.1 vs 67.2%) and autumn (81.3 vs 56.2%), and was similar between the two swards in winter (78.4 vs 71.2%, respectively). Plantain content (leaves plus reproductive stem) in the RGWC + PL ranged from 0.2 to 84.4% (Supplementary Table 1), averaging 13.2% in late-winter, 15.1% in spring, 22.6% in summer and 37.0% in autumn (Table 2). An interaction effect between sward and season was observed for white clover content ($P = 0.005$; Table 2), with higher values in the RGWC-only than RGWC + PL in summer (7.8 vs 4.1%) and autumn (10.6 vs 4.3%), but similar between swards in late-winter (5.1 vs 2.7%) and spring (2.3 vs 2.8%; respectively). Unsown monocots content was higher ($P < 0.001$; Table 2) in spring (4.5%) than in summer (1.7%) and autumn (0.5%), but similar between spring and late-winter (3.7%), with no significant effects of sward or sward × season interaction. There were no significant ($P > 0.05$) effects of sward or season on the content of dead material (average 4.1%) or unsown dicots (average 2.4%; Table 2).

Table 2. Estimated mean¹ dry matter content (%) and botanical composition (% in dry matter) of ryegrass/white clover-based mixed swards with nil plantain (RGWC-only) or with plantain (RGWC + PL). Swards were established in March 2021 and herbage samples collected over two production years (2021/22 and 2022/23) during late winter (mid-Jul to Aug), spring (Sep to Nov), summer (Dec to Feb) and autumn (Mar to May)

	Number of paddocks (n)	Dry matter content	Perennial ryegrass	Plantain	White clover	Dead material	Unsovn monocots	Unsovn dicots
Late-winter								
RGWC-only	3	19.0	78.4	–	5.1	5.1	3.9	4.4
RGWC + PL	13	17.4	71.2	13.2	2.7	4.8	3.5	3.3
Spring								
RGWC-only	27	19.1	83.7 ^a	–	2.3	5.5	5.0	2.1
RGWC + PL	57	17.3	70.9 ^b	15.1	2.8	4.1	3.9	2.6
Summer								
RGWC-only	20	20.2	82.1 ^a	–	7.8 ^b	4.9	1.6	1.9
RGWC + PL	54	17.7	67.2 ^b	22.7	4.1 ^a	2.6	1.8	1.5
Autumn								
RGWC-only	18	16.6	81.3 ^a	–	10.6 ^b	3.2	0.5	2.6
RGWC + PL	36	14.6	56.4 ^b	36.7	4.3 ^a	2.9	0.5	1.1
S.E.M		0.72	3.10	–	1.28	0.91	0.80	0.7
P value								
Sward		0.002	<0.001	–	0.006	0.165	0.637	0.299
Season		<0.001	0.003	–	<0.001	0.055	<0.001	0.078
Sward × season		0.870	0.027	–	0.005	0.529	0.679	0.270

¹Estimated marginal means from linear mixed model. White clover, dead material and unsown species data were analysed on a log ($x + 1$) scale; values presented are back-transformed estimated means expressed as percentages ($\times 100$). No analysis was conducted for plantain content because values in the RGWC-only sward were zero; therefore, raw means are presented. Means with different superscripts within a season differ significantly ($P < 0.05$).

RPM calibration equations

The full model, which included compressed sward height, herbage mass, plantain % in sward DM, season and their interactions, explained 74.3% of the variance in herbage mass ($R^2 = 0.743$; $P < 0.001$; Table 3). No significant quadratic effects were detected ($P > 0.05$). The inclusion of white clover, unsown monocot plus dicot species, or dead material content, or their interactions with season, did not significantly affect herbage mass ($P > 0.05$; Supplementary Table 3). Adding these variables increased model R^2 by less than 1% (from 0.743 to 0.750) and reduced the RMSE by less than 5% (from 371 to 361 kg DM/ha). Therefore, these variables were excluded from the final model to simplify the equation for practical use by farmers.

Plantain % in the sward DM significantly affected the slope of the regression line ($P = 0.001$; Table 3) but had no effect on the intercept (Table 3). Whereas the season of the year did not affect the slope of the regression line (Table 3), it did affect the intercept ($P < 0.001$; Table 3). There was no plantain % × season interaction effect on slope or intercept. Non-significant variables were excluded in the final model (Table 3), leaving three variables out of seven in the full model. The final reduced model retained three variables, the RPM sward compressed height, the effect of plantain % on slope and the effect of season on the intercept, maintaining an adjusted R^2 at 0.735 and RMSE of 377 kg DM/ha (Table 3).

The slope of the regression line decreased by 0.45 units for each 1% plantain increase in the mixed sward DM (Figure 1). Thus, herbage mass (kg DM/ha) increased by $145 - (0.45 \times \text{plantain \% in the mixed sward DM})$ per RPM unit increase (Figure 1). The intercept was highest for the summer equation (251), followed by

the spring equation (82) and autumn equation (–81), and was lowest for the winter equation (–128) (Figure 1). Accordingly, the following season-specific equations were derived:

$$\text{Late-winter : Herbage mass kg DM/ha} = [145 - (0.45 \times \text{Plantain \%})] \times \text{RPM unit} - 128 \quad (5)$$

$$\text{Spring : Herbage mass kg DM/ha} = [145 - (0.45 \times \text{Plantain \%})] \times \text{RPM unit} + 82 \quad (6)$$

$$\text{Summer : Herbage mass kg DM/ha} = [145 - (0.45 \times \text{Plantain \%})] \times \text{RPM unit} + 251 \quad (7)$$

$$\text{Autumn : Herbage mass kg DM/ha} = [145 - (0.45 \times \text{Plantain \%})] \times \text{RPM unit} - 81 \quad (8)$$

Model validation

Relationship between predicted and observed herbage mass values is presented in Figure 2, and the statistical assessment of model predictions is presented in Table 4. The overall model 1:1 R^2 was 0.719, and MAE and RMSE were 284 and 350 kg DM/ha, respectively. The model error, as measured by RMSE, was lowest for the spring equation (RMSE = 315; MAE = 258 kg DM/ha) and highest for summer equation (RMSE = 367; MAE = 290 kg DM/ha). Relative error metrics indicated that prediction accuracy was

Table 3. Comparative effect on coefficients and goodness of fit (Adj. R^2) in full vs. reduced multivariate regression models. Full model fitted with a rising plate metre (RPM) compressed sward height, herbage mass, plantain % in a ryegrass-white clover mixed sward dry matter, season of the year and their interactions. Non-significant effects were excluded in the final reduced model

Variable	Full model	Final reduced model
RPM	$P < 0.001$	$P < 0.001$
Slope		
Plantain%	$P = 0.001$	$P < 0.001$
Season ^a	NS	
Plantain% $\times$ Season	NS	
Intercept		
Plantain%	NS	
Season	$P < 0.001$	$P < 0.001$
Plantain% $\times$ Season	NS	
Adjusted R^2	0.743	0.735
Root mean square error (RMSE; kg DM/ha)	371	377
P value (Linear regression)	$P < 0.001$	$P < 0.001$

^aSeason: late-winter (mid-July–Aug), spring (Sep–Nov), summer (Dec–Feb) and autumn (Mar–May).

generally consistent across seasons (Table 4), with MRAE ranging from 0.135 (summer equation) to 0.315 (late-winter equation), and NRMSE between 0.104 (spring equation) and 0.121 (summer and autumn equations). The CCC ranged from 0.771 in autumn to 0.855 in summer. Pearson's correlation coefficient was lowest in spring (0.868) and highest in late winter (0.982). The coefficient of determination relative to the 1:1 line (1:1 R^2) was lowest in autumn (0.619) and greatest in summer (0.724).

Discussion

The aim of this study was to develop calibration equations for RPM to estimate the herbage mass of RGWC swards with varying proportions of plantain. It was hypothesised that RPM could accurately estimate the herbage mass of RGWC swards containing plantain, though the slope and intercept of the calibration equation would differ from those of RGWC-only swards. The regression model explained 73.5% of the variability in herbage mass (Adjusted $R^2 = 0.735$), comparable to values reported by Haultain *et al.* (2014) for ryegrass-based swards ($R^2 = 0.73$), pure chicory (mean $R^2 = 0.72$) and pure plantain ($R^2 = 0.70$). This supports the hypothesis that RPM can serve as a practical tool for herbage mass prediction in RGWC swards containing plantain. However, the proportion of plantain in the sward must be accounted for, as increasing plantain content reduces the slope of the regression line. These findings are also consistent with those of Baker *et al.* (2025) who reported that incorporating season and sward type alongside compressed sward height improved the accuracy of herbage mass predictions compared with height alone. However, in that study, sward composition was represented as categorical sward types rather than quantified botanical proportions. In contrast, the present study demonstrates that explicitly accounting for plantain proportion as a continuous variable refines RPM calibration within ryegrass-based swards, particularly where plantain content varies.

Table 4. Measures of deviation between observed and predicted values of herbage mass for data collected over the 2023/24 production year and not used in the model development: mean absolute error (MAE), root mean square error (RMSE), mean relative absolute error (MRAE) and normalised root mean square error (NRMSE). Relationships between observed and predicted values are illustrated using Pearson's correlation coefficient, Lin's concordance coefficient (CCC) and coefficient of determination relative to the 1:1 line (1:1 R^2)

	Model equation				
	Late-winter	Spring	Summer	Autumn	Overall
MAE	333	258	290	282	284
RMSE	359	315	367	364	350
MRAE	0.315	0.149	0.135	0.149	0.167
NRMSE	0.119	0.104	0.121	0.121	0.116
CCC	0.840	0.811	0.855	0.771	0.834
Correlation	0.982	0.868	0.910	0.861	0.849
1:1 R^2	0.648	0.651	0.724	0.619	0.719

Validation metrics indicate that the developed model predicts herbage mass with acceptable accuracy and precision. The model had an overall RMSE of 350 kg DM/ha (ranging from 315 kg DM/ha for the spring equation to 367 kg DM ha⁻¹ for the summer equation) and an MAE of 284 kg DM/ha (ranging from 258 to 333 kg DM/ha for the spring and late-winter equations, respectively). These values are comparable to those reported by Murphy *et al.*, (2021b) for simple linear regression (RMSE = 354 kg DM/ha) and multiple linear regression model incorporating management data such as nitrogen fertiliser alongside RPM values (RMSE = 330 kg DM/ha), and fall within the range of residual standard deviations reported by L'Huillier and Thomson (1988) and O'Donovan *et al.*, (2002) for herbage mass estimated by various techniques (e.g. RPM, capacitance probe and sward height). The CCC, a measure of model reproducibility, was 0.77 for the autumn equation and above 0.80 for the remaining equations and the model overall, indicating substantial agreement between observed and predicted values (McBride, 2005; Tedeschi, 2006).

The inclusion of plantain in RGWC mixed swards reduces sward DM content (Minnée *et al.*, 2019; Nguyen *et al.*, 2023; Nguyen *et al.*, 2025) and, hence, herbage DM density (unit of DM per unit of sward height). This reduction in DM density lowers the change in herbage DM yield per unit change in sward height. In this study, DM content was consistently lower in RGWC + PL swards compared to RGWC-only sward across all seasons (average 16.8 vs 18.7 %, respectively). As a result, the slope of the derived calibration equation decreased by 0.45 units per every 1 % of plantain in the mixed sward DM, and this effect was consistent across seasons. This indicates that at the same compressed sward height (i.e. RPM unit), less herbage mass is predicted with the inclusion of plantain. For example, at an RPM value of 15.0 unit (75.0 mm), predicted herbage mass is 14% lower in a RGWC sward containing 50% plantain (2089 kg DM/ha in summer) compared to a RGWC-only sward (2426 kg DM/ha). Similarly, in a study conducted in the Waikato region, New Zealand, Haultain *et al.* (2014) reported a lower RPM regression slope for pure plantain swards (95 units) compared to ryegrass-based swards (218 units). The authors attributed this difference to the lower DM content of plantain. In summary, inclusion of plantain in mixed swards lowers sward DM content and, consequently, sward DM density.

Other factors that may have contributed to the reduction in herbage mass response per unit change in sward height with the

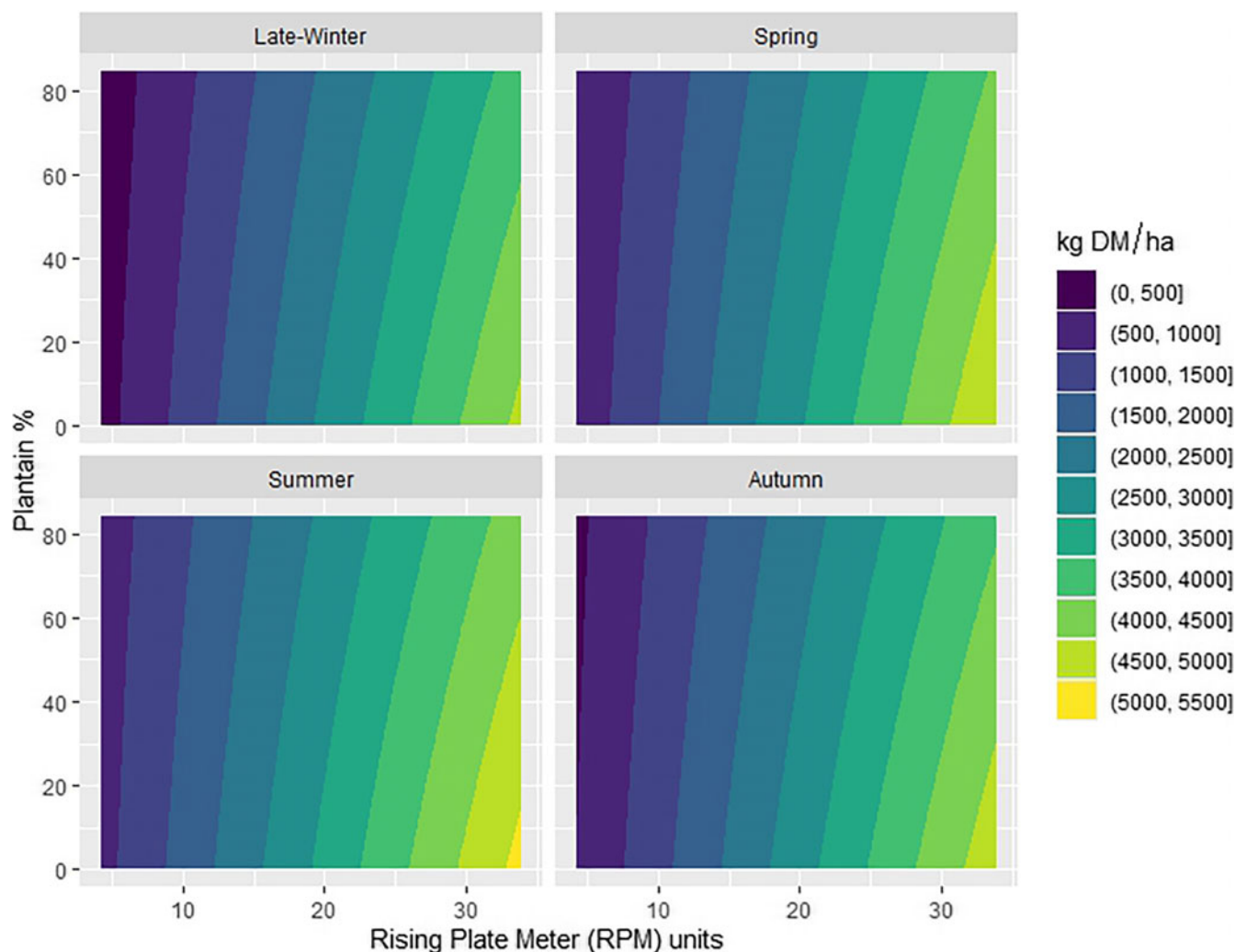


Figure 1. Three-way relationship between the compressed sward height measured by a rising plate metre (RPM; 1 RPM unit = 5.0 mm), plantain % in a ryegrass/white clover-based mixed sward dry matter and the herbage mass (kg DM/ha) in late-winter (mid-Jul to Aug), spring (Sep to Nov), summer (Dec to Feb) and autumn (Mar to May). The model equation (estimate $\pm$ SE): $\text{Herbage mass (kg DM/ha)} = [145 \pm 6.2 - (0.45 \pm 0.12 \times \text{Plantain \% in the mixed sward DM})] \times \text{RPM unit} + \text{intercept}$. The intercept was significantly affected by season ($P < 0.001$), being -128 ± 135.0 for late-winter, 82 ± 104.0 for spring, 251 ± 106.0 for summer and -81 ± 111.0 for autumn. Regression model adjusted $R^2 = 0.735$ ($P < 0.001$), and root mean square error (RMSE) = 377 kg DM/ha.

inclusion of plantain include changes in sward morphology. Plantain stems are typically taller and less dense than ryegrass stems, so a higher proportion of plantain may reduce vertical bulk density, in turn, decrease the change in herbage mass (kg DM) per unit change in sward height. Additionally, Dodd *et al.* (2025) explained that plantain's erect growth habit likely reduces compression under the measurement plate, further limiting the change in compressed sward height relative to herbage mass compared to RGWC swards. These morphological traits, along with plantain's lower DM content, may explain the reduced slope observed in the calibration equation. However, further agronomic studies focusing on how plantain alters sward structure are needed to confirm this effect.

The slope derived for RGWC with no plantain (plantain % = 0) in our study (145 units) closely aligns with the standard RPM equation (140 units; herbage mass kg DM/ha = $140 \times \text{RPM} + 500$) provided by the manufacturer and commonly used in New Zealand for estimating biomass in RGWC swards (DairyNZ, 2023b). This standard equation, also known as the 'winter equation', was developed from an extensive dataset collected over multiple years and regions across New Zealand to standardise

RGWC herbage mass estimation for dairy systems (Thomson *et al.*, 2001). The comparable slopes between the standard equation and our study support the applicability of the standard equation for estimating changes in RGWC yield per unit change in sward compressed height. However, the season-specific intercepts derived in our study (-128 , 82 , 251 and -81 for late-winter, spring, summer and autumn, respectively,) differ from that of the standard equation, indicating differences in predicted herbage mass. Seasonal variation, influenced by climatic conditions and plant morphology, has been shown to impact RPM regression equations and the accuracy of herbage mass estimation (Brock *et al.*, 1996; Haultain *et al.*, 2014; Somasiri *et al.*, 2014). The equations in this study were developed from irrigated pasture under climatic conditions in Canterbury, New Zealand, but additional data are required to confirm their applicability to swards in environments with markedly different soil and climate conditions.

Despite the seasonal effect on intercept for the prediction equation, the absence of a seasonal effect on the slope of the equations derived in this study suggests that any of these equations could be used to estimate net herbage accumulation and

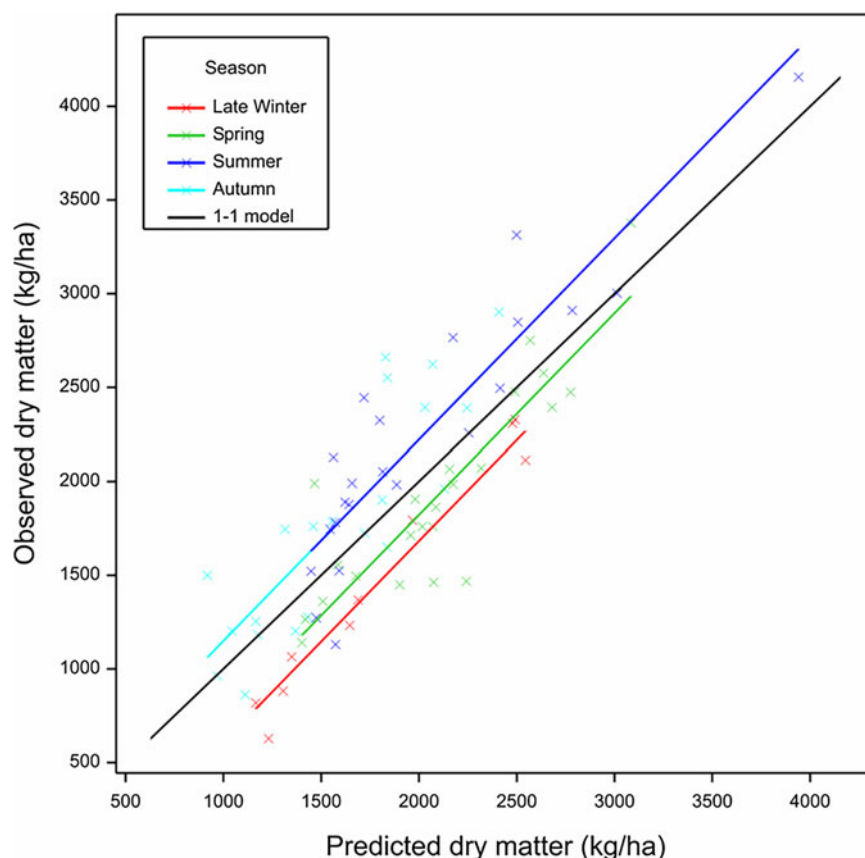


Figure 2. Relationship between predicted and observed herbage mass values by season for data collected over the 2023/24 production year and not used in the model development. The black line represents the 1:1 line (perfect agreement). The coefficient of determination relative to the 1:1 line ($1:1 R^2$) was 0.719.

subsequent herbage growth rate (kg DM per day) across seasons. This aligns with the practical use of the RPM, where farmers estimate net herbage accumulation and herbage growth rate during regular farm walks by measuring herbage mass increases across ungrazed paddocks (Lile *et al.*, 2001). Furthermore, the similar slopes of the standard equation (herbage mass kg DM/ha = $140 \times \text{RPM} + 500$) and the equation derived for RGWC without plantain (plantain % = 0) in our study suggests that either equation would yield comparable net herbage accumulation measurements. However, the inclusion of plantain affects the slope, demonstrating the need to account for plantain % in the mixed sward DM to ensure more accurate estimations, particularly in swards with plantain content greater than 20% in pre-graze herbage mass DM.

The effect of plantain content in the mixed sward DM on the slope of the RPM-derived equations in this study highlights the need for farmers to have an easy, quick and accurate method to estimate plantain proportion in their swards. This is particularly important for determining available herbage mass and net herbage accumulation in mixed swards with high plantain content (i.e. >20% in sward DM). DairyNZ (2023a) developed a visual assessment method to help farmers estimate plantain content in mixed swards DM, primarily to evaluate its impact on nitrate leaching. This method could also support more accurate herbage mass estimation. However, training is essential to ensure farmers can accurately account for variability in plantain proportions within and between paddocks. Additionally, more objective and timely methods, such as using drones or satellite imagery to assess plantain content, could provide opportunity to improve accuracy and support timely management decisions, including herbage DM allocation.

Conclusion

The regression model incorporating RPM compressed sward height, plantain % in mixed sward DM and season explained 73.5% of the variability in estimated herbage mass. Validation showed that the model predicted herbage mass with a RMSE of 350 kg DM/ha and CCC of 0.83, indicating acceptable accuracy and precision. Plantain content should be accounted for, as each 1% increase reduces slope of the regression line by 0.45 units. The prediction equations developed in this study could support integration into electronic RPM or imaging-based systems, enabling improved estimation of herbage mass across seasons.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/S0021859626100690>.

Acknowledgements. The authors acknowledge Lincoln University Research Dairy Farm staff for management of the farm systems, and DairyNZ technicians Jack Greig and Rowena Allardyce for help with sample collection, and Dr. David Baird, developer of the Genstat statistical package, for assistance with the statistical analysis.

Author contribution. Funding acquisition and conceptualisation, O.A.; validation, J.T. and O.A.; formal analysis, J.T. and O.A.; investigation, C.T. and N. M.; data curation, O.A. and H.H.; writing – original draft preparation, O.A. and H.H.; writing – review and editing, all co-authors; supervision, O.A. All authors have read and agreed to the published version of the manuscript.

Funding statement. This research was conducted as part of the DairyNZ-led Primary Sector Growth Fund Plantain Potency and Practice Programme, funded by DairyNZ, Ministry for Primary Industries, Fonterra and PGG Wrightson Seeds.

Competing interests. The authors declare no conflicts of interest.

Ethical standards. Not applicable.

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