Dry matter yield, botanical composition and nutritive value of diverse and standard pastures under contemporary and regenerative dairy management systems

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Abstract

This study investigated the potential of diverse pastures within regenerative dairy systems that aim to emulate the structure and function of grassland ecosystems through increased species diversity and adaptive grazing dynamics, compared with contemporary temperate dairy systems. Over three consecutive production years, three farmlet systems were compared: standard contemporary, diverse contemporary, and diverse regenerative. Annual pasture production differed significantly ($P < 0.01$), with diverse regenerative systems achieving the highest mean yield [dry mass] (~11 t). Seasonal growth was broadly consistent across systems, with the highest growth rates in spring (53-55 kg DM/ha/day) and minimal growth in winter. Diverse pastures in both systems demonstrated enhanced yield and greater resilience under variable climatic conditions. Botanical composition analysis indicated that diverse pastures maintained more balanced proportions relative to simpler pastures. However, the proportion of legumes and herbs declined over time across all systems. Nutritive values were largely comparable among systems, although diverse pasture systems exhibited significantly lower fibre concentration and elevated mineral content. Overall, diverse pasture systems, particularly under regenerative management, enhanced both pasture productivity and mineral composition without compromising feed quality over a three-year period. These findings highlight the potential of diversified pastures and altered management to improve the resilience and sustainability of low-nitrogen pasture-based dairy systems.

Keywords: Dairy systems, grazing management, herbage production, multiple species, nutritive analysis, pasture diversity, resilience, temperate grasslands

Introduction

Pasture-based livestock systems underpin global food security by supplying agricultural products and a wide range of ecosystem services across temperate regions. In New Zealand (NZ) and other temperate regions, perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) pastures are the predominant source of feed for grazing ruminant livestock (Caradus et al. 2023). Within these systems, seasonal and interannual variability in pasture growth strongly influences productivity, feed management, and environmental outcomes. This challenge is particularly evident in dryland (non-irrigated) systems, where large fluctuations in pasture production increase management uncertainty, reduce system resilience and constrain the long-term sustainability of pastoral farming (Chapman et al. 2009; Tait-Jamieson et al. 2025).

Pasture growth is tightly regulated by environmental conditions. During summer and early autumn, moisture deficits and elevated temperatures can constrain dry matter (DM) production and nutritive value, while in winter, pasture growth may decline to near zero due to low temperatures, frosts, and in some regions, waterlogging (Hendriks et al. 2016). In contrast, favourable conditions in spring and autumn support peak growth rates (Pembleton et al. 2015). These seasonal dynamics create recurring periods of pasture surplus and deficit, requiring careful management to align pasture supply with animal demand and maintain system performance (Pembleton et al. 2015).

In addition, the intensification of dairy systems has contributed to environmental issues, including nutrient losses, greenhouse gas emissions, and declining soil and water quality (Caradus et al. 2023). Consequently, there is increasing interest in alternative pasture management strategies that improve both productivity and environmental sustainability.

Regenerative dairy management approaches, often incorporating diverse multispecies pastures, have emerged as a potential alternative to contemporary ryegrass-clover swards. These systems aim to enhance ecosystem function, improve resilience, and support more sustainable dairy production (Cranston et al. 2015a; Baker et al. 2023b). However, robust system-level comparisons of DM production, botanical composition, and nutritive values between diverse pastures and standard pastures under contrasting

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Table 1 Grazing targets (rotation, and post-grazing residual herbage mass), conservation thresholds for silage harvesting, nitrogen fertiliser (N) application, weed management plans and stocking rates for the three dairy farmlets systems.

[1]System	Std-Con	Div-Reg	Div-Con
[2]Rotation			
Spring	20-30	40-50	30-40
Summer	30-40	50-60	30-60
Autumn	40-60	60-80	40-80
[3]Targeted residuals			
Spring and Autumn	1500-1600	2000-2200	1700-1800
Summer	1700-1800	2000-2400	1700-1800
Winter	1300	1300	1300
[3]Forage conservation during spring	>3000	>4700	>3600
[4]Targeted fertiliser N application	Up to four applications of 30	Gradual yearly restriction (1/2, ¼ and 1/8 of the contemporary baselines)	Up to four applications of 30
Weed management	Suitable herbicides (e.g. asulam, glyphosate, & MCPA) may be used on targeted species	Mechanical methods (chipping and mowing) and spot spraying were used if necessary	A mixture of mechanical methods (chipping and mowing) and spot spraying was used
[5]Stocking rate			
2022-2023	2	2	2
2023-2024	2.5	2.5	2.5
2024-2025	2.5	2	2

[1]System (Std-Con = standard pasture under contemporary management; Div-Reg = diverse pasture under regenerative management and Div-Con = diverse pasture under contemporary management); [2]Days; [3]kg DM/ha; [4]kg N/ha; [5]cows/ha; Season (spring = September 1 to November 30; summer = December 1 to February 28; autumn = March 1 to May 31; winter = June 1 to August 31).

management regimes remain limited. Therefore, the present study compared pasture production, botanical composition, and functional group stability across three dairy farmlet systems (standard contemporary, diverse contemporary, and diverse regenerative) in New Zealand.

Materials and Methods

Experimental site and establishment

The study was conducted on the Whenua Haumanu dairy farmlets, located at Dairy Farm 1, Massey University (40°22 ′ S, 175°36 ′ E), New Zealand. Experimental systems were established in April 2022. In each year, three pastures were evaluated, comprising two pasture types (Standard and Diverse) and two management approaches (Contemporary and Regenerative): standard pasture under contemporary management (Std-Con), diverse pasture under regenerative management (Div-Reg), and diverse pasture under contemporary management (Div-Con). A fourth treatment, standard pasture under regenerative management, was considered but ultimately not adopted for two reasons: (1) prioritising the investigation of hyper-diverse sward performance under intensive grazing management, which represents a critical knowledge gap; (2) due to the constraints, the scope of the study was limited to ensure adequate replication and statistical power for the remaining treatments.

Each treatment was implemented as a separate farmlet consisting of 13 paddocks (ranging from 0.6 to 1.2 ha), with a total experimental area of 36.3 ha (~12 ha/ farmlet). Farmlets were spatially balanced to account for walking distance from the milking parlour and edaphic variation, including soil type and fertility. Climatic conditions over the study period (June 2022 to May 2025), including total rainfall and mean temperature, are presented in Figure 1 alongside the 10-year climatic average.

Pasture measurements were collected between 1 June 2022 and 31 May 2025. All systems operated under rotational grazing with compact spring-calving, once-a-day milking regime, consistent with the DairyNZ System 1 classification (DairyNZ 2021). Further details of management practices, pasture composition and seed rate, soil fertility and nitrogen fertiliser application are provided in Tables 1, 2, and 3. While both the

Table 2 Systems, common name, binomial nomenclature and authority, cultivar, and seed rate of grasses, legumes, and herbs.

Systems	[1]Functional group	Common name	*Binomial nomenclature*	Cultivar	Seed rate (kg/ha)
Standard pastures under contemporary management (Std-Con)	Grasses	Diploid perennial ryegrass	*Lolium perenne* L.	[2]Platform AR37 or Maxsyn NEA4	10
		Tetraploid perennial ryegrass	*Lolium perenne* L.	4 Front NEA24	15
	Legumes	Red clover	*Trifolium pratense* L.	Relish	4
		White clover large-leaved	*Trifolium repens* L.	Kotuku	2
		White clover medium/ large-leaved	*Trifolium repens* L.	[3]Weka or Ruru	2
Diverse pastures under regenerative management (Div-Reg), and Diverse pastures under contemporary management (Div-Con)	Grasses	Diploid perennial ryegrass	*Lolium perenne* L.	[2]Platform AR37 or Maxsyn NEA4	4
		Tetraploid perennial ryegrass	*Lolium perenne* L.	4 Front NEA24	4
		Tall fescue	*Schedonorus arundinaceus* (Schreb.) Dumort	Quantica MaxP	4
		Meadow fescue	*Festuca pratensis* (Huds.) P. Beauv	Oakdon MaxR	4
		Cocksfoot	*Dactylis glomerata* L.	[2]Savvy or Safin	2
		Timothy	*Phleum pratense* L.	Kahu	2
		Phalaris	*Phalaris aquatica* L.	[4]-	1
		Prairie grass	*Bromus catharticus* Vahl.	Atom	4
	Legumes	Red clover	*Trifolium pratense* L.	Relish	4
		White clover large-leaved	*Trifolium repens* L.	Kotuku	2
		White clover medium/ large-leaved	*Trifolium repens* L.	[3]Weka or Ruru	2
		Balansa clover	*Trifolium michelianum* Savi.	Viper	2
		Persian clover	*Trifolium resupinatum* L.	Laser	2
		Crimson clover	*Trifolium incarnatum* L.	[4]-	3
		Vetch	*Vicia sativa* L.	[4]-	2
		Lucerne	*Medicago sativa* L.	Torlesse	4
	Herbs	Chicory	*Cichorium intybus* L.	Choice	1
		Plantain	*Plantago lanceolata* L.	Ecotain	2

[1]Plants are classified into grasses, legumes, and herbs based on their overall morphological characteristics and agricultural importance; [2]cultivars randomly distributed between paddocks to incorporate contributions from both major seed-industry trial partners; [3]farmlets were established with Weka, this was replaced by Ruru for subsequent regrassing due to seed availability constraints; [4]uncertified seed.

Div-Reg and Div-Con systems utilise identical multi-species seed mixes, potential differences between the two systems may arise from the interaction between management inputs and grazing regimes. Each year, 8-17% of each farmlet was regrassed, either pasture-to-pasture or following a summer forage crop, so that a more representative distribution of sward ages could be developed.

Fertiliser application

Soil from all paddocks was sampled annually as part of the broader trial monitoring program. Nitrogen allocation for Div-Reg was reduced stepwise across the 2022-2023, 2023-2024, and 2024-2025 production years, respectively (Table 3). Mineral fertilisers and lime were applied each year, as required to maintain soil fertility (pH, Phosphorus, Potassium, and Sulphur) within optimal ranges defined by Roberts et al. (2020). Under contemporary management, N and Sulphur were applied using granular urea, urease-inhibited-treated urea, granular ammonium sulphate, urea-ammonium sulphate blends, and elemental sulphur. The regeneratively managed farmlet received reduced rates of synthetic N inputs while incorporating bio-

Table 3 Soil fertility and applied Nitrogen (N) across systems over three consecutive production years

[1]Py	[2]Sy	pH	[3]P	[4]S	[5]K	[5]Mg	[6]N
	Std-Con	5.5±0.3	46±16	10±3	14±5	27±6	76±6
2022-2023	Div-Reg	5.6±0.3	57±13	11±3	16±6	31±6	19±10
	Div-Con	5.6±0.2	50±14	9±2	15±5	32±7	76±9
	Std-Con	5.9±0.2	42±20	6±2	9±4	24±6	63±19
2023-2024	Div-Reg	6.0±0.1	51±14	6±2	13±4	28±5	23±5
	Div-Con	5.9±0.1	43±16	8±2	12±3	29±6	80±18
	Std-Con	6.1±0.2	40±20	8±5	11±5	28±5	40±19
2024-2025	Div-Reg	6.2±0.2	47±14	10±3	17±6	31±6	13±13
	Div-Con	6.1±0.2	46±16	18±10	13±4	32±7	61±12

[1]P_y = production years; [2]Sy = systems (standard pasture under contemporary management (Std-Con); diverse pasture under regenerative management (Div-Reg); and diverse pasture under contemporary management (Div-Con)); [3]Olsen Phosphorus (mg/L); [4]Sulphate-sulphur (mg/kg); [5]MAF units; [6]applied Nitrogen (kg/ha); all other chemical notations adhere to standard of International Union of Pure and Applied Chemistry (IUPAC) guidelines. Data are mean ± Standard deviation.

Table 4 Seasonal calibration equations (kg DM/ha) for each system

	Std-Con	Div-Reg	Div-Con
Spring and winter	92 × CSH + 827	89 × CSH + 855	86 × CSH + 828
Summer	92 × CSH + 1780	89 × CSH + 1950	86 × CSH + 1999
Autumn	92 × CSH + 1238	89 × CSH + 1556	86 × CSH + 1543
Model accuracy	R^2 = 0.47, CCC = 0.72	R^2 = 0.51, CCC = 0.68	R^2 = 0.54, CCC = 0.73

CSH = compressed sward height in 5 mm increments; R^2= coefficient of determination; CCC = Lin's concordance correlation for external validation; standard pasture under contemporary management (Std-Con); diverse pasture under regenerative management (Div-Reg); and diverse pasture under contemporary management (Div-Con).

Botanical composition and pasture nutritive value

stimulant amendments, including humates, fulvic acid, fish hydrolysate, and seaweed extract. The Nitrogen supplied by these amendments was practically zero (< 1 kg N/ha) compared to the synthetic fertiliser inputs. Analysis of fertiliser inputs and responses is outside the scope of the current study.

Pasture measurements

Rising plate meter calibration and weekly whole-farm herbage monitoring

Weekly whole-farm pasture cover was estimated using an electronic rising plate meter (RPM) (Jenquip, EC20 Bluetooth Electronic Counter, Feilding, New Zealand). Between 80 and 120 readings were recorded per hectare within each paddock to determine average pasture cover. Annual pasture yield for each system was calculated using pasture growth rates for individual paddocks based on the consecutive weekly measurements. The RPM was calibrated concurrently through a dedicated study for more than two years using the cut-and-weigh method (Earle and McGowan 1979). Compressed sward height (CSH, 5 mm increments) and herbage DM from quadrats were collected for calibration (n = 683, 657, and 651 for Std-Con, Div-Reg, and Div-Con, respectively). Sampling was distributed across all seasons, systems, and pre- and post-grazing swards to ground level, ensuring the resulting linear regression models robustly accommodated the full gradient of sward heights and densities. Seasonal calibration equations for each system were developed using linear regression (Table 4; Susruthan et al. 2026).

Pre-grazing herbage samples (200g to 300g fresh mass) were collected during monitoring months (Feb, April, July, September and November) by hand-plucking to simulate cow grazing height from paddocks that were determined to be ready for grazing at each interval and manually separated into functional groups (grass, legume, and herb). Unsown weed species were classified separately, and dead material from any plants was also recorded as a percentage of dry weight. Volunteer species were defined as agronomically functional components not included in the original seed mix for a given system that established themselves laterally over time. The botanical composition was

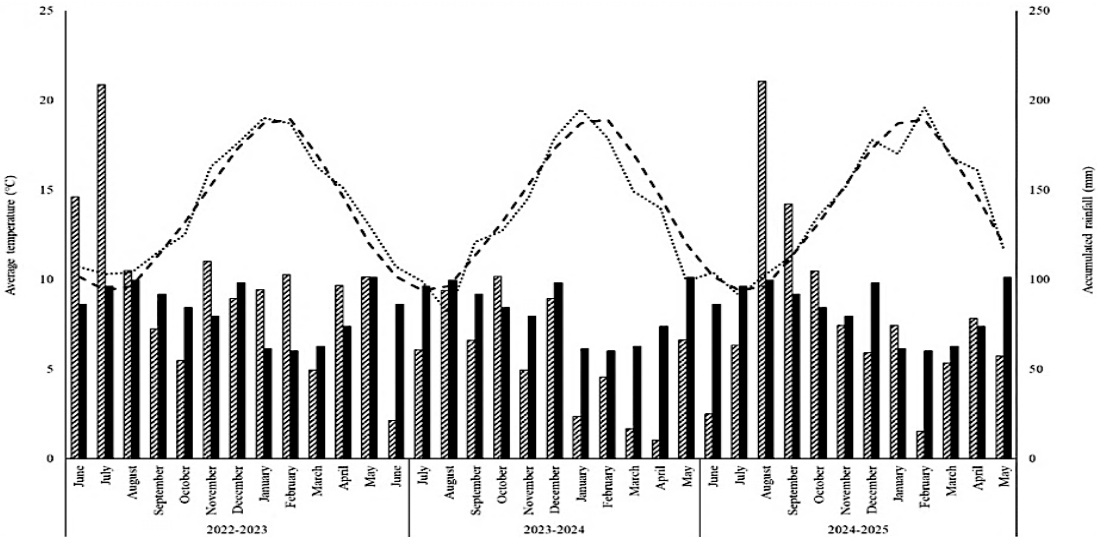


Figure 1 Ten-year (2015-2025) and experimental years (2022-2025) monthly accumulated rainfall (mm), and monthly averaged air temperatures (°C), distinguished by bar and line patterns (solid bar = ten-year average rainfall, wide upward bar = experimental years average rainfall, round dotted line = experimental years average air temperature; dashed line = ten-year average air temperature)

determined by the hand-sorting method (Cayley & Bird February 1996). Additional hand-harvested herbage samples were collected for nutritive analysis. Samples were oven-dried (Unitherm Drier, Birmingham, England) at 60 °C to a constant weight and then ground using a 1 mm screen prior to chemical analysis. Chemical analysis was carried out at an accredited commercial laboratory (RJ Hills Laboratories Ltd., Hamilton, New Zealand).

Data preparation and analysis

Average pasture cover was initially measured using the standard equation provided by DairyNZ (CSH x 140 + 500, DairyNZ 2021) and subsequently recalculated using a site-specific equation derived from the RPM calibration study. By transitioning to a site-specific calibration model, the systematic bias and localised noise embedded in the raw RPM data were effectively nullified (Susruthan et al. 2025). Data preparation and preprocessing were conducted using Microsoft Excel (Microsoft® Excel® for Microsoft 365 MSO (Version 2508 Build 16.0.19127.20314) and Python 3.10.7 (Python Software Foundation, 2022). Paddocks that were grazed, harvested for silage or hay, or renewed during measurement periods were excluded from pasture growth rate calculations to avoid disruption of natural growth patterns in the data. Statistical analyses were performed using SAS® 9.4 (SAS Institute Inc, USA, 2012). Pasture growth dynamics were modelled using a mixed model, with fourth-order polynomial functions fitted to the growth data. The production year was defined from 1 June 2022 to align with the NZ spring-calving dairy season and the Southern Hemisphere pasture growth cycle. Sward botanical composition and nutritive value were analysed using a general linear model. Systems and production year were treated as fixed effects, while paddock was treated as a random effect to account for repeated measures and inherent spatial variability. Season was included as an additional fixed effect for botanical composition and nutritive value analysis. Statistical significance was declared at $P < 0.05$.

Climate data

Monthly and 10-year average climate data (Figure 1) showed typical temperate seasons: peak temperatures occurring from December to February and minimum temperatures from June to August. In contrast, rainfall exhibited high inter-month variability and lacked consistent seasonal distribution. The second production year began with an exceptionally dry June 2023 (~21 mm), though rainfall recovered to ten-year averages during July and August (~95 mm). This was followed by a moderate, consistent rainfall from September to November. The most severe climate anomalies occurred in the late summer/autumn, with a major rainfall deficit from March to April 2024, with April receiving near-zero accumulation. Beyond these seasonal variations, a long-term trend toward regular severe droughts and frequent extreme weather has been observed in the Manawatu region (Tait-Jamieson et al. 2025).

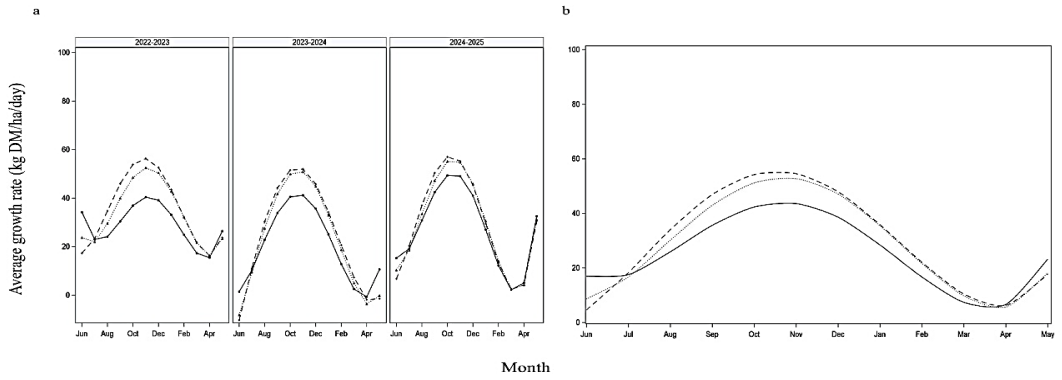


Figure 2 Monthly pasture growth rate (kg DM/ha/day) by systems over three consecutive production years (2022-2023, 2023-2024, and 2024-2025) (a) and average pasture growth rate (kg DM/ha/day) by systems (b). Data are presented for three different systems (Std-Con, Div-Reg, and Div-Con). Individual system curves are distinguished by line patterns: Std-Con (solid), Div-Reg (dashed), and Div-Con (dotted), with 95% confidence intervals

Table 5 Pasture yield under three different systems over three consecutive production years.

	Production year	Std-Con	Div-Reg	Div-Con	S. E	Significance		
						[1]Sy	[2]Py	$S_y \times P_y$
Pasture yield[3]	2022-2023	10.5^{bx}	12.8^{ax}	12.3^{ax}	0.4	***	***	N.S.
	2023-2024	7.2^{by}	8.7^{az}	8.2^{abz}	0.4			
	2024-2025	10.0^{x}	10.8^{y}	10.6^{y}	0.4			
	Average	9.2^{b}	10.7^{a}	10.4^{a}	0.4			

[1]Sy = systems (standard pasture under contemporary management (Std-Con); diverse pasture under regenerative management (Div-Reg); and diverse pasture under contemporary management (Div-Con)); [2]Py = production year; [3](t DM/ha). Data are mean ± Standard error. Mean values in the same row that are followed by different alphabetical letters (a, b) are different between systems, and column means with different letters (x, y, z) indicate differences between production years within a single system ($P < 0.05$); ***$P < 0.0001$.

Results

Herbage daily growth rates

Seasonal pasture growth rates (kg DM/ha/day) displayed a classic temperate curve across all three experimental systems (Std-Con, Div-Reg, and Div-Con), with monthly average peaking in mid-spring (October) before steadily declining through summer and autumn to reach winter minimums in June (Figure 2a and 2b). All three experimental systems rapidly accelerated in growth from late winter (August) into early spring, peaking between October and November before steadily declining through summer and autumn to winter minimums. The diverse systems achieved significantly higher peak growth rates compared to the Std-Con framework. In the 2022-2023 and 2023-2024, both diverse systems (Div-Reg and Div-Con) tracked closely together, peaking between 53 and 55 kg DM/ha/day, whereas Std-Con reached a lower peak of ~44 kg DM/ha/day in November. In the 2024-2025 season, peak productivity increased across all systems; the diverse systems peaked at roughly 55 to 57 kg DM/ha/day, while Std-Con reached a maximum of 49 kg DM/ha/day in October. In early winter (May and June), Std-Con maintained a higher growth rate than diverse systems. Interannual variations were most pronounced during production years. The 2022-2023 featured the mildest autumn decline, with April growth rates staying above 15 kg DM/ha/day across all the systems. In contrast, the other two years experienced a sharper autumn decline.

Pasture yield

Pasture production per hectare was significantly affected by systems and production years ($P < 0.001$), with no significant interaction between systems and production year ($P > 0.05$; Table 5). Averaged across the years, diverse systems produced the highest mean yield (~11 t DM/ha), while Std-Con had the lowest production (~9 t DM/ha). Climatic and seasonal fluctuations caused variations in yield between dairy production years within each system, particularly in Std-Con.

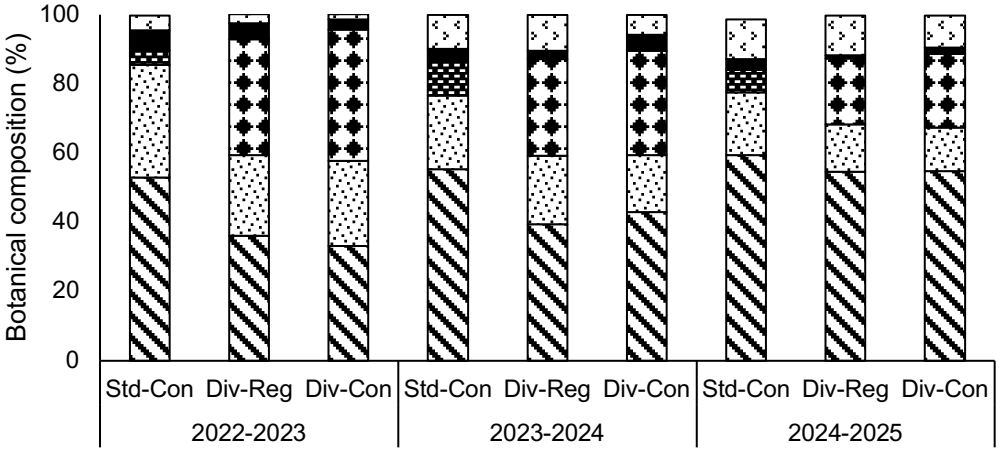


Figure 3 Botanical composition percentages of swards under three different systems (Std-Con, Div-Reg, and Div-Con), over three consecutive production years. Values are expressed as the percentage contribution of grass (▨), legume (▩), herb (▦), volunteer species (▩), unsown species (■), and dead materials (▩) to total yield. Unsown species denote non-pastoral weeds; volunteer species denote non-sown, functional forage components.

Botanical composition

Botanical composition differed significantly among treatments, production years, and seasons ($P < 0.05$; Figure 3). Grasses were the dominant component across all systems and years, ranging from 33% to 60%. Grass proportion was consistently higher under Std-Con (53-60%), than in Div-Reg (36-55%) and Div-Con (33-55%), and increased over time in all systems, with the highest values observed in 2024-2025.

Legume proportion declined across all systems over the study period. In 2022-2023, legumes were highest in Std-Con (33%) and lower in Div-Reg (23%) and Div-Con (25%), decreasing to 18%, 14%, and 13%, respectively, by 2024-2025. Notably, Div-Reg maintained its legume population over three years ($P < 0.05$), whereas the contemporary systems initiated a steady decline from the second production year ($P < 0.05$). Further, Std-Con experienced a further significant drop by the third year ($P < 0.05$).

In both diverse systems, herb proportion declined over time in the diverse pasture systems, from 33% to 19% in Div-Reg and from 38% to 21% in Div-Con in year 3. However, both diverse systems maintained their diversity in the first two years and declined in the third year. Volunteer species, particularly plantain, increased in Std-Con from 4% to 10% in 2023-2024, before declining to 6% in 2024-2025. Unsown species contributed a small proportion across all systems (< 6%) and did not differ significantly among systems or seasons. Dead material did not significantly differ with systems, but varied with production years and seasons, increasing during the summer and over time, with the highest proportions recorded in 2024-2025 (9-12%).

Seasonal patterns further differentiated systems ($P < 0.05$; Table 6). In Std-Con, pastures were strongly grass-dominated, with peak grass proportions in spring (70%) and winter (66%), declining significantly in summer (35%) before partially recovering in autumn (52%). Legumes peaked in summer (33%) and were lowest in winter (17%), while dead material increased substantially in summer (16%) and remained high through autumn (12%). In contrast, diverse pasture systems exhibited more balanced functional composition. Grass proportions followed a similar seasonal trend, but were lower overall, reaching a minimum in summer (31% and 33% for Div-Reg and Div-Con, respectively). Legumes also peaked in summer, particularly in Div-Con (28%), but declined in winter. Herb content increased from spring (21-25%) to peak in autumn (33-35%) and remained relatively high in winter. Unsown species remained a minor component (< 10%), while dead material accumulation was highest in summer, particularly in Div-Reg (17%), but consistently lower in Div-Con.

Sward nutritive quality

Pasture nutritive value varied with system, production year, and season, with several significant main effects ($P < 0.05$; Table 7). Crude protein (CP) did not differ among systems but varied significantly with production year ($P < 0.0001$), averaging ~21%. Crude fat (CF) was significantly ($P < 0.01$) influenced by systems, in first two years production year, and season, with the highest values (3.85%) observed in Std-Con in 2022-2023.

Digestibility (DOMD) and metabolisable energy (ME) were also affected by systems, production year, and season ($P < 0.01$), ranging from 69% to 74% and 11

Table 6 Seasonal botanical composition percentages of systems across four seasons

Systems	Spring	Summer	Autumn	Winter
Std-Con				
Grass	70.4±3.2^{a}	34.6±3.9^{c}	51.5±3.6^{b}	66.3±4.0^{a}
Legume	20.2±2.8^{b}	32.8±3.5^{a}	27.7±3.2^{ab}	16.5±3.5^{b}
Volunteer species	5.3±1.7	9.9±2.1	7.0±1.9	5.3±2.1
Unsown species	3.5±1.3	6.8±1.7	2.3±1.5	5.3±1.7
Dead material	0.6±2.1^{b}	15.9±2.2^{a}	11.6±2.6^{a}	6.6±2.7^{ab}
Div-Reg				
Grass	53.4±3.3^{a}	31.4±4.1^{c}	38.6±3.6^{bc}	51.2±4.1^{ab}
Legume	20.1±2.2^{ab}	25.1±2.7^{a}	16.8±2.4^{ab}	13.2±2.7^{b}
Herbs	21.0±2.7^{b}	23.5±3.4^{ab}	32.9±3.0^{a}	30.1±3.4^{ab}
Unsown species	2.9±0.7	2.7±0.9	2.7±0.8	2.0±0.9
Dead material	2.6±1.8^{b}	17.4±2.2^{a}	9.0±1.9^{b}	3.4±2.2^{b}
Div-Con				
Grass	53.9±2.7^{a}	33.1±3.5^{c}	39.8±3.1^{bc}	48.3±3.4^{ab}
Legume	16.8±1.7^{b}	27.6±2.1^{a}	16.6±1.9^{b}	10.5±2.1^{b}
Herbs	25.0±2.6	27.1±3.6	34.5±2.9	33.2±3.2
Unsown species	3.1±0.8	3.2±1.1	2.4±0.9	3.5±1.1
Dead material	1.2±1.0^{b}	9.1±1.3^{a}	6.7±1.1^{a}	4.5±1.3^{ab}

Standard pasture under contemporary management (Std-Con); diverse pasture under regenerative management (Div-Reg); and diverse pasture under contemporary management (Div-Con). Season (spring = September 1 to November 30; summer = December 1 to February 28; autumn = March 1 to May 31; winter = June 1 to August 31). Unsown species denote non-pastoral weeds; volunteer species denote non-sown, functional forage components. Data are mean ± standard error. Mean values in the same row that are followed by different alphabetical letters (a,b,c) are significantly different ($P < 0.05$).

MJ/kg to 11.8 MJ/kg, respectively. The Std-Con system recorded the highest DOMD (74%) and ME (11.8 MJ/kg) in the year 2022-2023, with values declining across all systems in subsequent years. The Div-Reg showed the greatest decline, reaching the lowest value in year 3 (DOMD = 68.6%; ME = 10.98 MJ/kg).

Water-soluble carbohydrates (WSC) were unaffected by system or production year but varied with season ($P < 0.0001$), with slightly higher values in the diverse pasture systems. Fibre fractions were influenced by system, production year, and season ($P < 0.05$). Neutral detergent fibre (NDF) was highest in Std-Con (40%) and lower in the diverse pasture systems (36-38%), while acid detergent fibre (ADF) showed a smaller, but significant difference. Ash and lignin content were also affected by system and temporal factors ($P < 0.05$). Ash concentrations were higher in the diverse pasture systems, whereas lignin accumulation was greater in Div-Reg and increased over time, reaching 5.5% in 2024-2025. Mineral composition showed clear systems effects ($P < 0.05$), except for N and potassium content. Calcium, zinc, and copper concentrations were consistently higher in diverse pasture systems compared to Std-Con ($P < 0.05$).

Discussion

In rotational grazing systems, optimising pasture production, nutritive value, and persistence are key objectives (Donaghy et al. 2021). The present study provides a systems-level comparison of dairy pasture yield, seasonal growth dynamics, botanical composition, and nutritive values from standard and diverse pastures under contemporary and regenerative management. The results demonstrate clear advantages of diverse pastures in terms of seasonal yield stability and annual DM production, particularly under regenerative management, while also highlighting important trade-offs in pasture composition over time.

Across all years, seasonal patterns of pasture production remained consistent, with peak pasture growth occurring during spring and the lowest production during winter. However, both diverse systems (Div-Reg and Div-Con) consistently achieved greater peak growth rates and a more even seasonal

Table 7 Chemical composition of pasture under three different systems over three consecutive production years.

[1]Py	[2]System	[3]CP	[3]CF	[3]DOMD	[5]ME	[3]WSC	[3]NSC	[3]NDF	[3]ADF	[3]Ash	[3]Lignin	[3]N	[3]P	[3]K	[3]Ca	[4]Zn	[4]Cu	[4]Mg
2022-2023	Std-Con	21.3	3.5^{a}	73.5	11.8	9.3	26.7^{b}	38.1	22.0	10.3^{b}	3.8^{b}	3.4	0.39^{b}	3.3	0.7^{b}	35.3^{b}	11.1^{b}	0.23
	Div-Reg	20.6	3.2^{b}	71.4	11.5	10.0	30.3^{a}	34.6	21.8	11.3^{a}	5.3^{a}	3.3	0.44^{a}	3.6	1.0^{a}	46.8^{a}	15.8^{a}	0.21
	Div-Con	20.6	3.2^{b}	71.7	11.5	10.1	29.9^{ab}	35.0	21.6	11.2^{a}	5.2^{a}	3.3	0.45^{a}	3.6	1.0^{a}	45.9^{ab}	14.5^{a}	0.22
	S.E.	0.8	0.1	1.0	0.2	0.6	1.1	1.2	0.6	0.3	0.5	0.1	0.01	0.1	0.1	3.8	1.0	0.01
2023-2024	Std-Con	22.0	3.5	70.4	11.3	8.6	22.5^{b}	41.7^{a}	23.3^{a}	10.3^{b}	4.6^{b}	3.5	0.36^{b}	3.1	0.9^{b}	40.0^{b}	9.6	0.24
	Div-Reg	20.8	3.3	69.8	11.2	9.7	28.4^{a}	36.5^{b}	22.1^{ab}	11.1^{a}	5.6^{a}	3.3	0.39^{a}	3.3	1.1^{a}	49.0^{a}	10.8	0.23
	Div-Con	20.9	3.3	70.6	11.3	9.7	28.6^{a}	35.9^{b}	21.8^{b}	11.4^{a}	5.5^{a}	3.3	0.39^{a}	3.3	1.2^{a}	51.5^{a}	11.6	0.23
	S.E.	0.6	0.1	0.7	0.1	0.5	0.8	0.9	0.5	0.2	0.3	0.1	0.00	0.1	0.0	2.5	0.7	0.01
2024-2025	Std-Con	22.2^{a}	3.9^{a}	71.0^{a}	11.3^{a}	9.7	22.5^{b}	40.0	22.6	10.5	5.4	3.6^{a}	0.38	3.3	0.8	36.9	9.2	0.23
	Div-Reg	19.8^{b}	3.6^{b}	68.3^{b}	10.9^{b}	9.3	24.6^{ab}	41.8	23.7	10.2	5.5	3.2^{b}	0.40	3.2	0.9	37.8	9.8	0.23
	Div-Con	20.1^{b}	3.6^{b}	69.8^{ab}	11.2^{ab}	9.8	26.2^{a}	40.0	22.5	10.1	5.2	3.2^{ab}	0.39	3.2	0.9	39.0	10.0	0.23
	S.E.	0.5	0.1	0.7	0.1	0.4	0.9	0.9	0.5	0.2	0.3	0.1	0.00	0.1	0.0	2.4	0.7	0.01
Overall mean	Std-Con	21.9^{a}	3.7^{a}	71.6^{a}	11.5^{a}	9.2	23.9^{b}	40.2^{a}	22.6	10.4^{b}	4.6^{b}	3.5^{a}	0.38^{b}	3.3	0.8^{b}	37.4^{b}	10.0^{b}	0.23
	Div-Reg	20.4^{b}	3.4^{b}	69.8^{b}	11.2^{b}	9.7	27.8^{a}	37.6^{b}	22.5	10.9^{a}	5.6^{a}	3.3^{b}	0.41^{a}	3.4	1.0^{a}	44.1^{a}	12.1^{a}	0.22
	Div-Con	20.6^{b}	3.4^{b}	70.7^{ab}	11.3^{ab}	9.9	28.2^{a}	37.0^{b}	22.0	10.9^{a}	5.3^{a}	3.3^{b}	0.41^{a}	3.4	1.0^{a}	45.5^{a}	12.1^{a}	0.23
	S.E.	0.4	0.1	0.6	0.1	0.3	0.6	0.7	0.4	0.2	0.2	0.1	0.00	0.1	0.03	2.0	0.6	0.01

[1]P_y = dairy production years ([1](2022-2023), [2](2023-2024) and [3](2024-2025); [2]Systems (Std-Con = standard pasture under contemporary management, Div-Reg = diverse pasture under regenerative management and Div-Con = diverse pasture under contemporary management); [3](% DM);[4](mg/kg); [5](MJ/kg DM); [6](spring = September 1 to November 30; summer = December 1 to February 28; autumn = March 1 to May 31; winter = June 1 to August 31); CP = crude protein; CF = crude fat; DOMD = digestible organic matter in DM; ME = metabolisable energy; WSC = water soluble carbohydrate; NSC = non-structural carbohydrate; NDF = neutral detergent fibre; ADF = acid detergent fibre; L = lignin; all other chemical notations adhere to IUPAC guidelines. Data are mean ± standard error. Mean values in the column that are followed by different alphabetical letters (a, b) are significantly different ($P < 0.05$).

distribution of herbage production than the ryegrass-clover system (Std-Con). This more stable seasonal production indicates improved synchrony between pasture supply and livestock demand and likely reflects complementary functional traits among species. Differences in rooting depth, seasonal growth phenology, and resource acquisition strategies enable multispecies communities to maintain productivity under fluctuating environmental conditions, particularly during periods of soil moisture limitation (Hoekstra et al. 2014; Shackleton et al. 2024).

The greater annual herbage DM production observed in the diverse systems (Div-Reg approximately 16% and Div-Con approximately 13% greater than Std-Con) further demonstrates the productivity advantages of functionally diverse pasture communities. The particularly high production during the establishment year (2022–2023), together with the relatively small autumn decline, was likely driven by vigorous seedling establishment, rapid vegetative growth, the high abundance of legumes (approximately 43%) and herbs (approximately 6%) and high summer rainfall within the hyper-diverse mixtures. These components likely enhanced canopy development, biological nitrogen fixation, and resource capture during early pasture establishment.

Stocking rates were adjusted annually according to the previous year's pasture production and target post-grazing residuals. Despite these management differences, stocking rate had no detectable effect on annual pasture production. This agrees with Macdonald et al. (2008), who reported that pasture production generally remains unchanged across moderate stocking rates (2.2–2.7 cows/ha), with increases in herbage production becoming apparent only at substantially higher stocking rates.

A consistent reduction in pasture production of approximately 20% from year one to year two occurred across all systems, potentially reflecting the transition from establishment-related juvenile vigour to mature sward dynamics, compounded by increasingly warm and dry climatic conditions. In the diverse systems, this decline was further influenced by the loss of annual species. Although climatic conditions strongly influenced pasture production across all treatments, the relative decline in production was consistently smaller in the diverse systems than in Std-Con, suggesting that the ryegrass-dominated conventional pasture was more susceptible to heat and moisture stress, whereas the diverse systems exhibited greater resilience to climatic variability.

By the third year, the diverse systems had reached a relatively stable level of production, suggesting that the perennial species had successfully established and the community had undergone functional reorganisation. Complementary resource use among species, together with drought- and heat-tolerant components such as plantain, chicory, and lucerne, likely sustained productivity during periods when ryegrass growth was constrained (Pembleton et al. 2015; Nguyen et al. 2022). Herb abundance also increased during autumn and remained relatively high throughout winter, helping to buffer seasonal feed deficits. These findings support previous studies demonstrating that greater plant diversity enhances the temporal stability, seasonal distribution, and climatic resilience of pasture production (Pembleton et al. 2015; Jing et al. 2017; Baker et al. 2023a; Shackleton et al. 2024; Thomson et al. 2025).

The greater productivity and stability of the diverse systems are consistent with ecological theory: whereby increased functional diversity improves the efficiency with which resources are captured and utilised (Sanderson et al. 2004; Soder et al. 2007; Baker et al. 2023c). Several complementary mechanisms are likely responsible, including biological nitrogen fixation by legumes, complementary rooting architectures that enhance water and nutrient acquisition, temporal partitioning of growth, and reduced interspecific competition through spatial and temporal niche differentiation (Sanderson et al. 2004; Pembleton et al. 2015; Vibart et al. 2016; McCahon et al. 2021). Collectively, these processes improve resource-use efficiency, increase resilience to environmental variability, and sustain pasture production across seasons. However, species-specific functional traits, root dynamics, and physiological responses were not directly measured; the relative contribution of each mechanism requires further investigation.

A key finding of our study was the ability of the regenerative system (Div-Reg) to maintain greater pasture production despite progressively lower fertiliser nitrogen inputs and declining legume abundance during later years, albeit over a three-year period. This suggests that improved nutrient-use efficiency and enhanced system-level resource capture compensated for reduced external nitrogen inputs. These responses were likely reinforced by regenerative grazing management, particularly longer grazing rotations and higher post-grazing residuals, which promoted recovery between grazing events. Previous studies have similarly demonstrated that multispecies swards can maintain herbage production comparable to ryegrass-based pastures while receiving substantially lower nitrogen inputs (Grace et al. 2018; Baker et al. 2023c).

These findings align with ecological niche theory, whereby greater plant diversity increases whole-system resource capture and reduces competitive overlap (Hoekstra et al. 2014; Pembleton et al. 2015; Jing et al. 2017; Grace et al. 2018). Although fertiliser responses

are influenced by multiple interacting factors, including soil nitrogen availability, species-specific nitrogen-use efficiency, biological nitrogen fixation, and climatic conditions, our study demonstrates that regenerative multispecies systems can substantially reduce fertiliser nitrogen requirements without compromising annual pasture production. Consequently, these systems offer considerable opportunities to improve both farm profitability through reduced input costs and environmental sustainability through lower fertiliser dependence.

Post-grazing residual height did not affect annual herbage DM production in the current study, a similar finding was observed in Baker et al. (2023b) defoliation study. However, Cranston et al. (2015b) reported that multispecies swards comprising legumes and herbs produced greater annual herbage dry matter (DM) when managed to a lower post-grazing residual height (4 cm) than a higher residual (8 cm), highlighting that responses to grazing intensity may vary depending on sward composition and management. Management practices, however, likely drive these ecological processes. For example, extending grazing rotation length increased annual herbage production by allowing greater post-defoliation recovery (Lee et al. 2015; Baker et al. 2023b), as longer recovery periods replenish non-structural carbohydrate reserves, protect basal growing points, and promote rapid regrowth following grazing (Donaghy and Fulkerson 2002; Cranston et al. 2015b; Baker et al. 2023b). In addition, higher post-grazing residuals may enhance resilience by maintaining a protective vegetative canopy that reduces soil temperature, limits evaporative water loss, and moderates the soil microclimate during periods of moisture stress (Blanco-Canqui et al. 2023). This suggests that responses in the Div-Reg treatment were not from plant diversity alone, but from the interaction between plant functional diversity and regenerative grazing management.

Despite yield benefits, maintaining botanical composition remains a significant management challenge. Notably, Div-Reg stabilised the legume proportion across all production years, whereas contemporary systems exhibited a progressive decline. In Div-Con, the initial presence of annual legumes may also have contributed to higher first-year legume proportions that were not sustained, though the remaining perennial legume population stabilised during dairy production years two and three. Conversely, the herb fraction declined severely in both diverse systems by year three. These findings are consistent with previous studies where the legumes and herb populations were decreased after two years (Sanderson et al. 2005; Nguyen et al. 2022; Shackleton et al. 2024), potentially due to higher post-grazing residuals that protect growing points, especially on higher-crowned species, a longer recovery period, reduced N input and reduced competitive suppression (Cranston et al. 2015b; Jing et al. 2017; Grace et al. 2018; Baker et al. 2023b; Schon et al. 2024; Shackleton et al. 2024). The Std-Con experienced a progressive multi-year decline of legume proportion; this trend likely reflects a combination of the dominant nature of ryegrass, grazing pressure, the nature of plant species, animal selectivity, N application and environmental conditions (Sanderson et al. 2005; Cartmill and Donaghy 2024; Schon et al. 2024; Shackleton et al. 2024; Wilson et al. 2024).

Interestingly, dead material did not differ significantly among systems despite longer grazing intervals in Div-Reg. This likely reflects the sampling methodology, which focused on the actively grazed horizon where senescent material remains limited. This reflects a trade-off between maintaining plant persistence and managing pasture quality. The presence of volunteer plants in the Std-Con may be due to spreading mechanisms, such as wind dispersal, and a legacy soil seed bank. However, further study is required to investigate the mechanisms behind this volunteer establishment.

The overall forage nutritive value remained comparable among systems, indicating that increasing pasture diversity did not compromise feed quality. Lower neutral detergent fibre concentrations and higher mineral concentrations within the diverse systems further suggest nutritional advantages associated with the inclusion of herbs and legumes (Brink et al. 2001; Pirhofer-Walzl et al. 2011), while metabolizable energy and digestibility remained within ranges suitable for dairy production (NRC 2001; Lean et al. 2014). However, declines in ME and DOMD over time likely reflect increasing plant maturity, seasonal management effects, and increasing grass dominance (Shackleton et al. 2024). Lower NDF in diverse pasture systems was consistent with reduced grass composition (Fulkerson et al. 2007) and may have positive implications for intake, rumen function, and N use efficiency (Shi et al. 2023). Although lignin content increased over time in Div-Reg, reflecting greater structural material and senescence, this did not substantially reduce overall digestibility.

Two distinct functional pathways emerged to achieve comparatively high yields in diverse pastures. Div-Con sustained its productivity through a high-turnover system driven by moderate N applications. Conversely, Div-Reg achieved identical productivity through structural longevity and ecological buffering, despite low N input, by allowing a longer recovery period and higher residuals. The Div-Reg system exploited the biological and physical potential of hyper-diverse pastures, proving that both diverse systems can decouple

total DM production from synthetic and biological inputs once sward equilibrium is achieved. This has implications not only for pasture growth but also for nutrient losses to the ecosystem. However, maintaining species diversity remains a key management challenge. These systems require adaptive management to balance productivity, persistence, and composition. While the present study provided valuable insights, the three-year duration may not fully capture longer-term dynamics. Longer-term studies are therefore required to determine whether these productivity, resilience, and compositional trajectories persist beyond the initial establishment phase and to better understand the underlying soil, plant, and rhizosphere processes driving system resilience.

Conclusions

This study demonstrates that over the three years, contemporary diverse systems-maintained production through relatively high nutrient inputs and rapid nutrient turnover, whereas the regenerative system achieved comparable or greater productivity through enhanced ecological buffering, greater resource-use efficiency, and reduced reliance on external nitrogen inputs. Illustrating that high pasture productivity can be maintained through alternative system designs that increasingly depend on ecological processes rather than input intensity alone. Over the three-year period, diverse pastures supported more balanced botanical composition and improved mineral availability without compromising overall nutritive value. Importantly, diverse pasture systems also showed greater resilience to climatic variability, maintaining more stable yield under moisture stress. However, the gradual shift towards grass dominance observed across all systems indicates that maintaining functional diversity remains a key challenge requiring ongoing adaptive management. Longer-term studies are therefore required to determine whether these productivity, resilience, and compositional trajectories persist beyond the initial establishment phase and to better understand the underlying soil, plant, and rhizosphere processes driving system resilience.

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