Pasture formulation for optimised yield and weed suppression under sheep grazing and irrigation in Canterbury

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Abstract

Farmers need evidence to make informed decisions about which species to sow when renewing a pasture. This study aimed to formulate a pasture from a diverse pool of six species. At Lincoln University, 69 monocultures and mixtures varying widely in sown number and proportions of perennial ryegrass, cocksfoot, plantain, white clover, red clover and subterranean clover were examined under sheep grazing and irrigation for 4 years. On average annual total dry matter (DM) yield increased and weed DM yield decreased with increases in number of species, but species' proportions determined the optimal pasture that maximised yield and weed suppression. For example, on average six-species pastures had 1.6 t/ha more total yield and 1.8 t/ha less weed yield than two-species pastures (12.1 and 3.1 t/ha) in Year 1. However, several pastures of equal number of species had both above-average total and below-average weed yields in each year, emphasising the importance of species identity. A diversity-interaction model predicted that sown proportions of 50% ryegrass and 25% each of white and red clovers maximised annual yield and weed suppression (14.1 and 0.3 t/ha). These seed ratios were equivalent to 9.7, 1.3 and 9.0 kg/ha respectively for a total sowing rate of 20 kg/ha.

Keywords: diversity, functional group, mixture, multispecies, simplex design

Introduction

Farmers wanting to renew their pastures need evidence that gives them the confidence to select different pasture species, or mixtures of species, adaptable to different farm systems and environments. This includes data from field experiments with mixtures, designed to inform decisions about which forage species and how much of each species to include in a new pasture.

The published evidence from species mixture experiments shows that the performance of a pasture (e.g., yield, digestibility, weed suppression) is directly related to the proportions of plant species in the pasture (e.g., Harris 1968; Black et al. 2017; Myint et al. 2021). A linear relationship occurs when two or more species perform differently (they have different identity effects) and do not interact with each other. In this case, we might only want to use the species with the largest identity effect. A nonlinear relationship occurs when two or more species interact, such as when clover enhances grass growth by increasing total nitrogen input. The difference between the nonlinear response and the linear response expected from the identity effects is the diversity effect. In a case when the pool of species differs in both identity effects and interactions, we might decide to use the species with the largest identity effect and two other species with the strongest positive pairwise interaction. In any case, the contributions of identity effects and interactions to a pasture function depend on the relative abundances of the species in the pasture. Our previous work has shown that pastures formed from three or more species seldom yield a greater quantity of higher-quality feed than pastures with two species, such as one grass with one clover (Black et al. 2021).

Our aim for this paper was to formulate a pasture under sheep grazing and irrigation from a wider pool of plant species (six) than we have tested in mixture experiments previously (three or four). To achieve this goal, our objectives were to: 1) quantify the dependence of pasture yield and its weed content on the relative sown proportions of perennial ryegrass (*Lolium perenne* L.), cocksfoot (*Dactylis glomerata* L.), plantain (*Plantago lanceolata* L.), white clover (*Trifolium repens* L.), red clover (*T. pratense* L.) and subterranean (sub) clover (*T. subterraneum* L.), 2) predict the yield and weed responses to any combination of the species' proportions and 3) identify a formulation from the six-species pool that optimises pasture yield and weed suppression.

Materials and Methods

The six species were the constituents of a 4-year mixture experiment at Lincoln University, New Zealand (43°38'52.15"S, 172°28'3.63"E and 9 m above sea level). The site was flat agricultural land. The previous crop was a mixture of mainly perennial ryegrass and white clover managed under sheep grazing with irrigation and no nitrogen fertiliser input for 8 years. The soil type was a Wakanui silt loam with a plant-available water capacity of 150 mm to 50 cm depth. Daily climate data were obtained from a station at Broadfield, about 2 km north of the site, in the NIWA

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climate database (https://cliflo.niwa.co.nz). Annual (1 July–30 June) rainfall was 514, 475, 518 and 547 mm and maximum soil water deficit (0–50 cm) was 132, 131, 111 and 121 mm in Years 1–4 respectively.

The six species, and one cultivar of each species, were selected for their suitability to sheep pastures in Canterbury (Stewart et al. 2022). The cultivars were: 'Rely' perennial ryegrass with AR1 endophyte (*Epichloë festucae* var. *lolii*), 'Aurus' cocksfoot, 'Agritonic' plantain, 'Quartz' white clover, 'Relish' red clover and 'Bindoon' sub clover. The species were categorised according to three functional groups: Species 1 and 2 (ryegrass and cocksfoot) came from Functional Group 1 (grass), Species 3 (plantain) came from Functional Group 2 (herb) and Species 4–6 (white, red and sub clovers) came from Functional Group 3 (legume).

Sixty-nine combinations of six species proportions (p_1–p_6) were identified as test points in a simplex centroid design (Cornell 2002). The design space was left unrestricted to allow monocultures and mixtures of the species, such that $0 \leq p_i \leq 1$ and $\sum_{i=1}^{S} p_i = 1$ where S is the number of species and p_i is the initial proportion of species i. There were six monocultures, 57 equal-proportion mixtures including 15 two-species mixtures, 20 three-species mixtures, 15 four-species mixtures, six five-species mixtures and a centroid six-species mixture, and six uneven mixtures dominated in turn by each species (58.3% of one species and 8.3% of each other species).

The 69 combinations were randomly allocated to plots within each of four replicate blocks. The individual plot size was 6 m × 2.1 m (the width of our plot drill). The plot layout was 12 rows of 23 plots side by side with 2 m buffers of 'Arrow' perennial ryegrass between and around rows and three rows in each block.

The site was sprayed with WeedMaster TS540 on 1 March 2018 (glyphosate, 540 g/L at 2 L/ha in 200 L/ha water), cut at 5 cm height on 12 March 2018 to remove the dead herbage, cultivated to 5 cm depth on 21 March 2018 to hasten breakdown of the turf (Amazone KE 2500 Special rotary harrow/wedge ring roller combination), cultivated to 25 cm depth on 13 April 2018 (Kverneland plough), cultivated to 10 cm depth with a rotary harrow and reconsolidated with a Flexiseeder roller on 18–19 April 2018, and sown on 23 April 2018 with a Flexiseeder drill (with 14 coulters set 150 mm apart and 10–15 mm deep). The thousand seed weights were 2.47, 0.92, 2.00, 0.68, 3.91 and 11.65 g and germination percentages were 98, 96, 93, 99, 84 and 89% for ryegrass, cocksfoot, plantain, white, red (coated) and sub (coated) clovers respectively. Sowing rate was held constant at 2,000 viable seeds/m^2 to avoid confounding effects of number of seed with effects of species' proportions.

Soil fertility was measured at 0–7.5 cm on 23 August 2018, showing pH 6.1, Olsen P 15 mg/L, K 0.6 mEq/100 g, Ca 6.4 mEq/100 g, Mg 1.13 mEq/100 g, Na 0.14 mEq/100 g and SO_4-S 2 mg/kg. Sulphur Super 30 (7% P and 30% S) was applied at 320 kg/ha on 27 September 2018.

The experiment was grazed by 70–150 ewes seven times in the first year (14 September 2018–31 May 2019) and then eight times annually in the subsequent 3 years (28 July–13 June). Pre-grazing pasture mass was 1,000–3,600 kg of dry matter (DM)/ha, depending on season. At each defoliation, sheep were allowed to graze two adjacent blocks at a time, moved when minimum sward height was 3–4 cm (after 2–10 days depending on number of sheep and pasture mass) and then all plots were trimmed at 3–4 cm height. The resulting regrowth intervals were between 22–60 days.

Irrigation was applied at 20–40 mm every 3–5 weeks, between October and April each year. The sum of irrigation was 145, 480, 760 and 220 mm in Years 1–4 respectively.

The sub clover monocultures were sprayed with Buster on 19 March 2019 (glufosinate-ammonium, 200 g/L at 5 L/ha in 200 L/ha water), hand-sown with 20 kg/ha of 'Bindoon' sub clover at grazing on 28 March 2019 and re-sprayed with Buster on 19 March 2020 (3 L/ha in 200 L/ha water). Dock (*Rumex obtusifolius*) plants were spot-sprayed across the experiment in March 2020 with Harmony 50SG (thifensulfuron-methyl, 500 g/kg at 1.5 g/10 L water). T-Max was sprayed on plots not sown with white or red clover on 19 March 2020 to suppress voluntary plants of white clover (aminopyralid, 30 g/L at 1 L/ha in 200 L/ha water).

Pasture yield and botanical composition were measured at each grazing using one of two methods.

Method 1: Before grazing, herbage in a 6 m × 0.54 m strip was cut at 3–4 cm height using a lawn mower and weighed. A 100 g subsample was dried at 65°C for 48 hours and weighed. Herbage at several unmown points was cut at 3–4 cm height, mixed and divided into quarters. Diagonally opposite quarters were discarded. The remaining quarters were mixed and quartered again until the subsample was about 400 pieces. This subsample was separated into each sown species and weed, dried at 65°C and weighed. The yield of total herbage and each fraction were then calculated. Sheep tracking along the cut strips at Defoliations 1 and 2 required the second method for all subsequent defoliations.

Method 2: Before grazing, herbage in a representative 0.2 m^2 quadrat was cut at 1 cm height, mixed and divided into quarters. Diagonally opposite quarters were put aside. The remaining quarters were mixed and quartered again until the subsample was about 400 pieces. The subsample was separated into each sown species and weed. Each fraction and the rest of

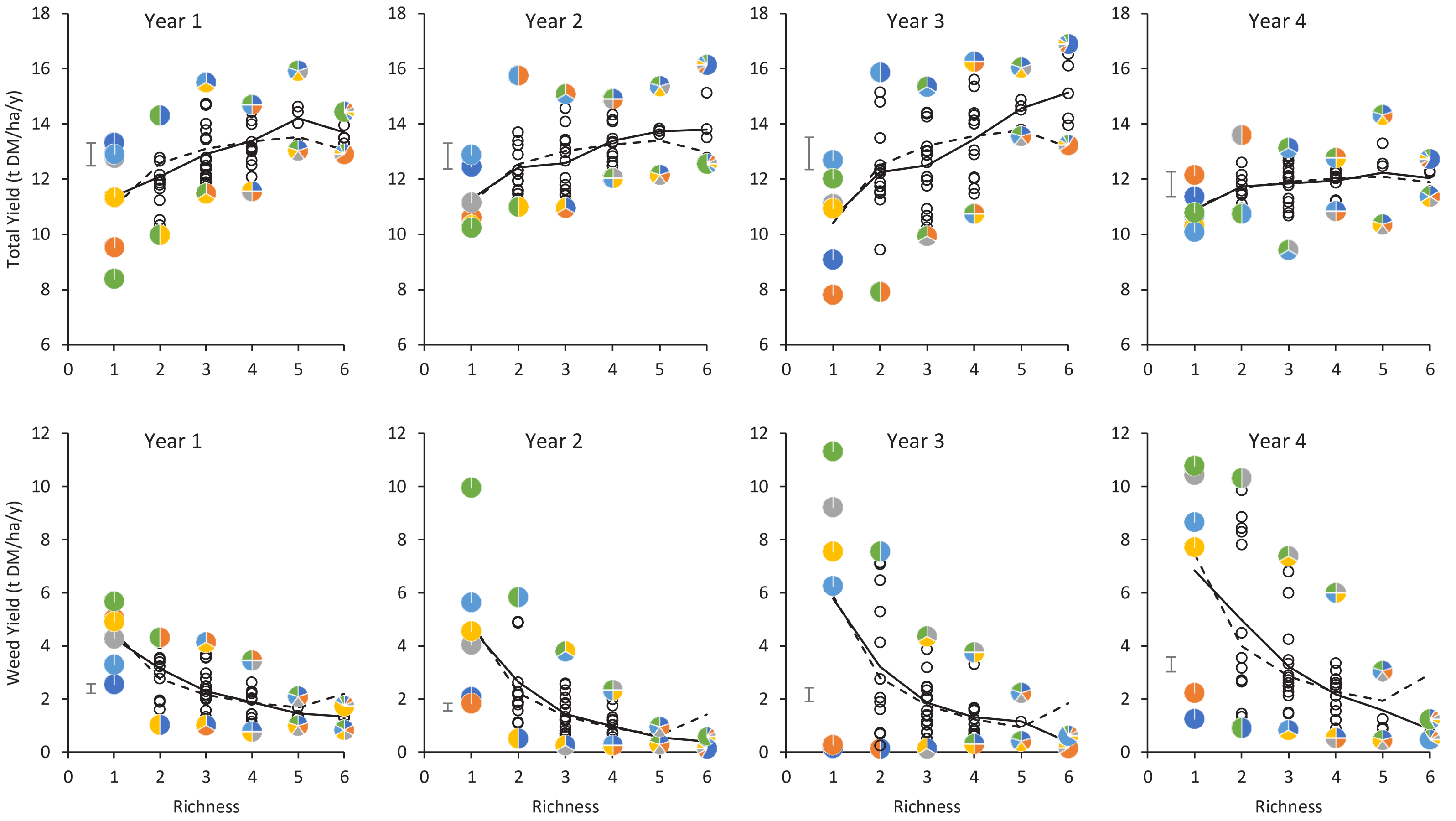

Figure 1 Total and weed dry matter yield responses (DM/ha/y) to sown species number (richness) and proportions of perennial ryegrass (blue), cocksfoot (orange), plantain (grey), white clover (yellow), red clover (light blue) and subterranean clover (green) over 4 years (Year 1, 2018–19). Data points are means of four replicate blocks. Pie-glyphs depict sown species' proportions for each point at one species (monocultures) and for extreme points at two–six species. Lines depict the average observed (solid) and modelled (dash) response. Error bars are the average standard error of the mean.

the sample were dried at 65°C and weighed. Mass of total herbage and each fraction were calculated. After trimming, for monoculture and centroid plots, herbage in a 0.2 m^2 quadrat was cut at 1 cm height using sheep shears, dried at 65°C and weighed to determine the residual pasture mass. Then the residual mass of all plots was calculated as the average residual mass of monoculture plots within a block, weighted by sown species' proportions in the pre-grazing pasture mass. The observed and calculated values of residual mass for centroid plots were used to check agreement. The yield of total herbage and each fraction were then calculated.

The DM yields were summed across defoliation events within each year, where Year 1 was from sowing to the end of Defoliation 7 (31 May 2019). The response variables of interest as key pasture functions are the annual total and weed herbage DM yields.

Multivariate diversity-interactions models (Kirwan et al. 2009) were fitted to the dataset using maximum likelihood. Both pasture functions, total yield and weed yield, were assumed to have equal importance. Models were compared using the second order version of Akaike information criterion (AICc). The model with the lowest AICc value was selected as the best fit. The selected model was refitted using restricted maximum likelihood, with the block term removed to obtain the desired fixed effects coefficients. The fixed effects coefficients and variance covariance matrix were examined. Models were fitted using package DImodelsMulti in statistical software R (Byrne 2024).

Results

The total and weed DM yield responses are plotted against the number of sown species (richness) in Figure 1. The figure shows the average observed and modelled responses of pastures, and the variation in observed responses across the different species' proportions, at each number of species.

On average there were increases in total yield and decreases in weed yield with an increasing number of species, but species' identity and proportions determined the optimal pasture. For example, comparing two species with six species at Year 1, on average the six-species pastures had 1.6 t/ha more total yield and 1.8 t/ha less weed yield than the two-species pastures at 12.1 and 3.1 (26% of total yield) t/ha. However, the 50-50 ryegrass-sub clover pasture was not different in total yield (14.3 t/ha) to the uneven six-species pasture dominated by sub clover. But if the 50-50 white clover-sub clover pasture is examined, the uneven sub clover-dominant pasture yielded 4.5 t/ha more. Similarly, the 50-50 ryegrass-white clover pasture had as much weed (1.0 t/ha; 9%) as the even six-species pasture, and the even six-species pasture had less weed than the 50-50 cocksfoot-sub clover pasture (4.3 t/ha; 42%). The differences among pastures with an equal number of species included several monocultures and mixtures with both above-average total yield and below-average weed yield (Figure 1).

The responses to species' proportions changed over time. For example, comparing the best two- and six-species mixtures at Year 2, the 50-50 cocksfoot-red clover pasture was not different in total yield (15.8 t/ha), and the 50-50 ryegrass-white clover pasture was not different in weed yield (0.5 t/ha; 4%), to the uneven pasture dominated by ryegrass. At Year 3, the 50-50 ryegrass-red clover pasture was not different in total yield (15.9 t/ha) to the uneven ryegrass-dominant pasture. Also, in Year 3, the 50-50 ryegrass-cocksfoot pasture had as much weed (0.1 t/ha; 1%) as the uneven cocksfoot-dominant pasture. In Year 4, the 50-50 cocksfoot-plantain pasture yielded as much (13.6 t/ha) as the uneven ryegrass-dominant mixture, and the 50-50 ryegrass-sub clover pasture had as much weed (0.9 t/ha; 8%) as the uneven red clover-dominant pasture.

The model selected by the maximum likelihood procedure as having the lowest AICc was a functional group model. This model assumes that species interactions can be grouped based on their functional group. The interaction terms are structured as 'between' and 'within' functional group interactions. The model equation is:

$$
\begin{aligned}
y_{kmt} &= \sum_{i=1}^{S=6} \beta_{ikt} p_{im} \\
&+ \sum_{\substack{q,r=1 \\ q<r}}^{T=3} \omega_{qrkt} \sum_{i \in FG_q} \sum_{j \in FG_r} p_{im} p_{im} \\
&+ \sum_{q=1}^{T=3} \omega_{qqkt} \sum_{i,j \in FG_q} p_{im} p_{im} \\
&+ \alpha_{kt} A + \epsilon_{kmt}
\end{aligned}
$$

where y_{kmt} is the response of pasture function k of plot m at year t, $S = 6$ is the number of species, β_{ikt} is the identity effect of species i on function k at year t and p_{im} is the initial proportion of species i for plot m. $T = 3$ is the number of functional groups (FG_1–FG_3), ω_{qrkt} is the interaction between species from functional groups q and r and ω_{qqkt} is the within functional group interaction among species from functional group q, for q, r = 1, 2, 3. For example, for a function k at year t, ω_{12} is the interaction term for any pair of species with one in FG_1 and one in FG_2, so either of ryegrass or cocksfoot with plantain, and ω_{11} is the interaction term for the pair of species in FG_1, ryegrass and cocksfoot. α is the effect of block (A) and ϵ_{kmt} is the error term.

Table 1 Model coefficient estimates (Coef.), standard errors (SE) and significance levels (Sig.) over 4 years (Year 1, 2018–19).

		Total Yield			**Weed Yield**		
Year	**Term**	**Coef.**	**SE**	**Sig.**	**Coef.**	**SE**	**Sig.**
1	β_1	**12.654**	0.67	***	**2.075**	0.67	**
2	β_1	**12.176**	0.67	***	**1.582**	0.67	*
3	β_1	**10.928**	0.67	***	**0.28**	0.67	
4	β_1	**11.889**	0.67	***	**1.428**	0.67	*
1	β_2	9.384	0.67	***	6.069	0.67	***
2	β_2	11.043	0.67	***	**2.778**	0.67	***
3	β_2	5.77	0.67	***	**0.344**	0.67	
4	β_2	**11.787**	0.67	***	**3.488**	0.67	***
1	β_3	**12.509**	0.821	***	**4.498**	0.821	***
2	β_3	10.962	0.821	***	**4.166**	0.821	***
3	β_3	**11.07**	0.821	***	9.07	0.821	***
4	β_3	**11.141**	0.821	***	11.071	0.821	***
1	β_4	9.682	0.612	***	**4.359**	0.612	***
2	β_4	9.936	0.612	***	5.451	0.612	***
3	β_4	**11.409**	0.612	***	7.21	0.612	***
4	β_4	9.958	0.612	***	7.766	0.612	***
1	β_5	**12.782**	0.612	***	4.761	0.612	***
2	β_5	**13.067**	0.612	***	6.542	0.612	***
3	β_5	**13.845**	0.612	***	8.233	0.612	***
4	β_5	10.624	0.612	***	10.096	0.612	***
1	β_6	8.93	0.612	***	5.447	0.612	***
2	β_6	9.624	0.612	***	8.668	0.612	***
3	β_6	9.397	0.612	***	10.246	0.612	***
4	β_6	10.453	0.612	***	10.928	0.612	***
1	ω_{12}	1.432	2.315		-5.872	2.315	*
2	ω_{12}	6.15	2.315	**	-6.588	2.315	**
3	ω_{12}	10.953	2.315	***	-8.517	2.315	***
4	ω_{12}	5.099	2.315	*	-18.058	2.315	***
1	ω_{13}	10.069	1.409	***	-8.38	1.409	***
2	ω_{13}	7.447	1.409	***	-13.316	1.409	***
3	ω_{13}	12.354	1.409	***	-14.559	1.409	***
4	ω_{13}	3.916	1.409	**	-17.755	1.409	***
1	ω_{23}	3.381	1.955	+	-8.707	1.955	***
2	ω_{23}	2.984	1.955		-11.055	1.955	***
3	ω_{23}	1.575	1.955		-17.485	1.955	***
4	ω_{23}	-0.078	1.955		-12.122	1.955	***
1	ω_{11}	0.075	3.159		-5.408	3.159	+
2	ω_{11}	3.17	3.159		-0.602	3.159	
3	ω_{11}	14.378	3.159	***	6.189	3.159	+
4	ω_{11}	-4.912	3.159		1.739	3.159	
1	ω_{33}	7.191	1.955	***	-4.477	1.955	*
2	ω_{33}	5.226	1.955	**	-10.515	1.955	***
3	ω_{33}	3.699	1.955	+	-11.85	1.955	***
4	ω_{33}	4.397	1.955	*	-10.081	1.955	***

β_1–β_6 are the identity effects of perennial ryegrass, cocksfoot, plantain, white clover, red clover and subterranean clover respectively. Bolded identity effects are above-average across species for total yield and below-average for weed yield. ω_{12}, ω_{13} and ω_{23} are the 'between' functional group (FG) interaction terms for pairs of species from different FGs, and ω_{11} and ω_{33} are the within FG interactions for pairs of species from within each FG, for 1, 2, 3 = grass, herb, legume. Significance codes: *** $P<0.001$; ** $0.001<P<0.01$; * $0.01<P<0.05$; + $0.05<P<0.1$.

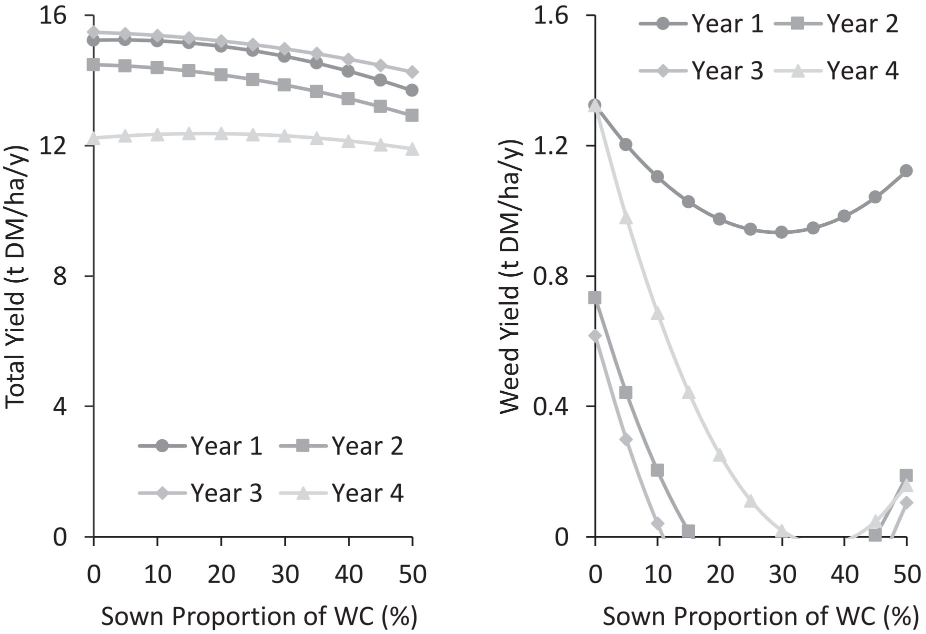

Figure 2 Modelled total and weed dry matter yield (t DM/ha/y) against sown proportion of white clover (WC) over 4 years (Year 1, 2018–19). The proportion of perennial ryegrass was fixed at 50% and the proportion of red clover was changed between 0% and 50% whilst ensuring that the sum of the three species' proportions was 100%.

Table 1 shows the model coefficients, their significance and direction. For example, the identity effect of ryegrass had a significant ($P<0.05$), positive effect on total yield at Years 1–4 and on weed yield at Years 1, 2 and 4. The identity effect of ryegrass was also above-average for total yield, i.e., larger than the average predicted total yield in monoculture (Figure 1), and below-average for weed yield, at each year. The grass-herb interaction had a positive effect on total yield at Years 2–4 and a negative effect on weed yield each year. The grass-legume interaction was also positive for total yield in all years. Both the grass-legume interaction and the herb-legume interaction were negative for weed yield each year. The grass-grass interaction affected total yield at Year 3, while the legume-legume interaction had a positive effect on total yield at Years 1, 2 and 4 and a negative effect on weed yield each year. On average, the strongest interaction estimate was the grass-legume interaction on both total and weed yields.

According to the model, to maximise yield and weed suppression simultaneously, ryegrass should be included in the pasture formulation for its strong and persistent identity effects. Combining species from Functional Groups 1 (grass) and 3 (legume) would also be important. It would be beneficial to include both white and red clovers, despite white clover having a weaker identity effect on total yield. The presence of red clover would make up for this trait. The ryegrass would compensate for the weaker effects of both clovers on weed suppression. The other three species were not necessary ingredients, given that our goal was to maximise total yield and weed suppression.

To identify the optimal formulation, the pasture functions were predicted from the model across the wide gradient of sown proportions of ryegrass, white clover and red clover in the experiment design. The formulation that maximised yield whilst minimising weed content on average across the 4 years was a mixture with sown proportions of 50% ryegrass, 25% white clover and 25% red clover. To illustrate this, the predicted responses are plotted against the proportion of white clover for each year in Figure 2. The proportion of ryegrass was fixed at 50% and the proportion of red clover was changed between 0% and 50% whilst ensuring that the sum of the three species' proportions was 100%. A range of combinations surrounding the optimal mixture also gave high predictions for total yield and low predictions for weed yield.

Discussion

The aim of this study was to formulate a pasture under sheep grazing and irrigation from a wider pool of plant species (six) than we tested in mixture experiments previously (three or four). The results confirmed that sowing two or three species from different functional groups of grass, legume and herb on average provided increased yield and weed suppression compared with monocultures (Figure 1). Any further increases in the number of species resulted in average increases in yield and weed suppression, but it was the composition and proportions of sown species that determined the optimal pasture formulation (Figures 1 and 2).

The optimal formulation of 50% ryegrass, 25% white clover and 25% red clover, identified by the diversity-interaction model (Kirwan et al. 2009), provided the most desirable balance of yield and weed suppression (average 14.1 and 0.3 t/ha per annum) because those three species had strong identity effects and interactions on the two pasture functions of total and weed yields (Table 1). The different identity effects of all species reflected their different abilities to capture sunlight energy, water and nutrients and transform them to biologically useful compounds in plant tissues (Hay and Porter 2006). The grass-legume interactions were probably the result of one or more clover species facilitating the growth of one or both grass species through the clovers' abilities to fix nitrogen. The identity effects of ryegrass and its inclusion in our pasture formulation were expected and in line with local farmer experience (Black et al. 2021). Similarly, the grass-legume interactions support the local practice of forming pastures with at least one clover and one grass species in systems with low nitrogen fertiliser input. Our decision to include both white and red clovers was also based on knowledge about the declining persistence of red clover after 4 years at the study site (Brown and Moot 2004; Black et al. 2021).

The optimal mixture also provided the most desirable outcome because ryegrass, white clover and red clover were included at relative proportions that expressed the grass-legume interactions the most. The functional group model assumes that the degree of expression of interactions for pairs of species from within and between functional groups depends on the relative abundances of the species involved (Kirwan et al. 2009). For example, both white clover and red clover had the ability to interact positively with ryegrass (Table 1), but if they were not present in large enough abundances, the expression of these interactions would not have been strong enough to affect total yield and weed content (Figure 2). The range of combinations surrounding the optimal mixture that gave high predictions for total yield and low predictions for weed yield show the robustness of the pasture functions across changing species proportions near the optimum.

The pasture yield and weed content responses of the optimal mixture (Figure 2) will generally be stable across total sowing rates. This is because the response of a pasture mixture depends on the relative proportions of species in the mixture, not the total amount of seed in the mixture (e.g., Connolly et al. 2009; Ryan-Salter and Black 2012; Myint et al. 2021). Therefore, if the sowing rate of the optimal mixture is 20 kg/ha, the sowing rates of its species will be 9.7 kg ryegrass, 1.3 kg white clover and 9.0 kg red clover/ha, accounting for differences in seed weight and germination %. If the sowing rate is 30 kg/ha, the sowing rate of each species will be 1.5 times higher. In our study, the total sowing rate was measured in number of viable seeds per unit area (2,000/m^2) to avoid any confounding effects of number of seeds with species' proportions. It was also higher than standard local practice to compensate for the delayed autumn sowing date.

The data provided in this study build on the wide body of pasture mixture research and development in New Zealand (e.g., Cockayne 1914; Levy 1923; Brougham 1954; Harris 1968; Charlton 1991; Woodward et al. 2013). The selection of test mixtures was often based on arbitrary or convenient mixtures, and the statistical analysis only identified the best entry in the experiment. This method offered limited predictive ability beyond the entries tested. In Europe, the diversity-interaction models (Kirwan et al. 2009) were developed to predict the impacts of multi-species grasslands on multiple ecosystem functions (e.g., Connolly et al. 2009; Finn et al. 2013; Kirwan et al. 2014). In New Zealand, we applied the same modelling approach to provide the scientific basis for pasture formulations, from pools of three or four species (Ryan-Salter and Black 2012; Black et al. 2017; Black et al. 2018; Black and Lucas 2018; Black et al. 2021; Myint et al. 2021) and now six species.

The next steps for future study include three points not addressed in this paper. One is forage quality. The parameters of this pasture function (e.g., metabolisable energy and crude protein) can be included in a multivariate analysis, as in Black et al. (2021) and Myint et al. (2021). These papers provided evidence of identity effects and no interaction effects of species on nutritive value. Another point is the seasonal distribution of yield and other pasture functions in each year. These data may enter the diversity-interaction models as repeated measures. The third point is the likelihood that the species' relative abundances changed substantially over time. Such changes may explain the higher predicted than observed values of the average responses at six species (Figure 1). To test whether these shifts had an impact on pasture functions, the initial species' proportions can be redefined at time points after sowing, e.g., species' proportions in the total yield at Year 1 can be used as initial conditions for an analysis of response functions in Year 2.

Conclusions

Pasture yield and weed suppression are influenced by sown species richness. But they are more strongly related to the sown species' proportions, due to species identity effects and functional group-level interactions. This determined the optimal pasture formulation in our experiment with six species (three functional groups) under sheep grazing and irrigation on the Canterbury plains. Modelled mean annual total yield was greatest and mean annual weed yield least for a pasture with sown proportions of 50% perennial ryegrass, 25% white clover and 25% red clover. This three-species mixture was equal to sowing rates of 9.7 kg perennial ryegrass, 1.3 kg white clover and 9.0 kg red clover/ha for a total sowing rate of 20 kg/ha.

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