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Tagasaste silvopastures in steep-hill country. 2. Effect of increasing proximity to tagasaste on growth and survival of companion pasture species

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ABSTRACT

Context. Tagasaste (*Cytisus proliferus*), a fast-growing leguminous tree, has potential to supplement pasture production in steep-hill country and to increase pasture resilience. **Aims.** In the companion paper, we quantified tagasaste production characteristics. Here, we determine the effect of proximity of 10-year-old tagasaste trees on productivity of eight pasture species including grasses (perennial ryegrass, *Lolium perenne*; cocksfoot, *Dactylis glomerata*; prairie grass, *Bromus willdenowii*; microlaena, *Microlaena stipoides*), perennial legumes (white clover, *Trifolium repens*; red clover, *T. pratense*; lotus, *Lotus pedunculatus*), and an annual legume (subterranean clover, *T. subterraneum*). **Methods.** A site was established in the East Coast region of the North Island of New Zealand on steep-hill country (>20° slope). Herbage production, nutritive value and survival of pasture species established as spaced transplants were measured over 3 years. **Results.** Cocksfoot had high survival, herbage production and metabolisable energy content but was negatively affected by proximity to tagasaste. Microlaena was not significantly affected by proximity to tagasaste; however, it was much less productive and had lower nutritive values than the other grasses. Only 40% of perennial ryegrass transplants survived 3 years, and survival of perennial legumes was negligible. Subterranean clover was able to set seed in the open and in shade. **Conclusions.** Cocksfoot was the most productive grass species, and microlaena was least affected by proximity to tagasaste. Given the poor persistence of perennial clovers, annual clovers may be better suited to a tagasaste silvopasture on steep, dry hillsides. **Implications.** Mixtures of cocksfoot and subterranean clover may be well suited to summer-dry hillsides, between and under trees in a tagasaste silvopasture. Microlaena may provide some forage and can maintain groundcover despite shade.

Keywords: feed value, forages, forage trees, herbage production, hill country, nutritive values, pasture productivity, tree lucerne, tree-pasture systems.

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Introduction

Tagasaste (*Cytisus proliferus* L. f. var. *palmensis* Christ) is a fast-growing, leguminous tree that can provide palatable forage of high nutritive value for grazing livestock (Snook 1986; Francisco-Ortega *et al.* 1991; Dann and Trimmer 2003). It grows in drought-prone sites in well-drained soils but does not tolerate waterlogging. Research into tagasaste establishment and production in annual- and perennial-based pastures has previously been conducted on flat or gently sloping land in Mediterranean, temperate and tropical regions (Oldham and Moore 1989; Townsend and Radcliffe 1990; Douglas *et al.* 1996; Assefa *et al.* 2012); however, no data were available on tagasaste productivity when grown on steep-hill country (>20° slope). In the first paper of this two-part series, we reported on tagasaste edible dry matter (DM) production, mineral content and nutritive value when grown in perennial pastures on steep-hill country (Tozer *et al.* 2023).

Furthermore, there is a lack of understanding of which perennial pasture species are most productive and persistent in temperate hill-country pastures where spaced tagasaste trees have been established for browse forage (hereafter referred to as a 'tagasaste silvopasture'). Previous studies have demonstrated that shading can reduce the nutritive value of hill-country pastures, although effects were often confounded with changes in botanical composition when comparing open pasture and pasture under the tree canopy (e.g. Guevara-Escobar *et al.* 2007; Benavides *et al.* 2009). Studies have also focused on sampling of whole pasture rather than individual species. Research is therefore required to understand the effects of tree shading on the nutritive value of individual pasture species.

Species selected for this study were those considered most suitable for the environment of the experimental hill-country site, based on climatic factors and published research. Where average annual rainfall exceeds 700 mm, species such as perennial ryegrass (*Lolium perenne* L.) and prairie grass (*Bromus willdenowii* Kunth), a short-lived perennial, can provide high-quality feed in temperate hill-country pastures (e.g. Suckling 1959; Fulkerson *et al.* 2000; Waller and Sale 2001). Cocksfoot (*Dactylis glomerata* L.) provides a productive alternative for drier regions (Lolicato and Rumball 1994). Microlaena (also called weeping grass or rice grass; *Microlaena stipoides* (Labill.) R.Br.) is indigenous to New Zealand, Australia and the biogeographical region of Malesia (Edgar and Connor 2000; Mitchell *et al.* 2016). It is recommended as an option for low-input pastures in Australia, although it responds well to applications of nitrogen (Chivers and Aldous 2005).

Companion legumes for these perennial pasture grasses include white clover (*Trifolium repens* L.), red clover (*T. pratense* L.) and lotus/greater lotus (*Lotus pedunculatus* Cav., syn. *L. uliginosus*) (Orr and Wedderburn 1996; Díaz *et al.* 2005). Lotus provides an alternative to white clover for acidic, low-fertility soils (Hopkins *et al.* 1996). In drier areas, the annual legume subterranean clover (*Trifolium subterraneum* L.) is also widely used (Moss *et al.* 2022).

We conducted this study to determine how the growth, nutritive value and survival of these pasture species were affected by proximity to 10-year-old tagasaste trees in hill country in the East Coast region of the North Island of New Zealand. We focused on the relative performance of the perennial grass, perennial legume and annual legume species separately, to inform the selection of species for a grass–legume mix. It was hypothesised that increasing proximity to tagasaste would increase shading and decrease productivity (growth, survival and nutritive value) of all pasture species, but that some species would be more severely affected than others by increasing proximity.

Methods

Site establishment and management

Details of location, climate, soils, micro-climatic variables (e.g. soil moisture, soil surface temperature, solar radiation), characteristics of the tagasaste trees (e.g. height, canopy spread), annual DM production and botanical composition of resident pasture, and site management are presented in Part 1 of this two-part series (Tozer *et al.* 2023). Briefly, the field site was on a typical beef and sheep hill-country farm in the Eastern Coast region of the North Island of New Zealand (39°01′11″S, 177°34′17.69″E). The area has a temperate maritime climate with average maximum temperatures (°C) in the mid-20s in summer (December–February) and average minimum temperature of ~6°C in winter (June–August), when most of the rain falls. The 10-year average annual rainfall (2005–14) is 1510 mm. Summer droughts occurred in 2019–20 and 2020–21. The soils are Orthic raw soils according to the New Zealand Soil Classification system (Hewitt 2010).

The field site was on a north-west-facing hillside, with an average slope of 30°, and comprised a 10-year-old tagasaste silvopasture with 156 trees ha^{-1}. When measured in November 2018, tagasaste trees had an average (± s.e.m., $n = 7$) height of 4.3 ± 0.2 m, canopy width of 6.1 ± 0.4 m, trunk diameter (at the first branch) of 24.3 ± 0.9 cm and root-collar diameter of 25.7 ± 4.1 cm, with an average of 7.1 ± 0.9 branches >2.5 cm diameter.

Experimental design and treatments

The experimental design has been detailed in Part 1. Briefly, the study was established as a split-plot, randomised complete block design with seven replicates of three shade treatments (heavy shade, light shade, open pasture) positioned across the hill within the tagasaste plantation. Shade treatments were the main plots. Heavy shade plots were established within 1 m of a tagasaste trunk; light shade plots 1–2 m from a tagasaste trunk; and open pasture plots were positioned between trees and not directly under the canopy of a tagasaste tree. However, the open pasture treatment could not be regarded as uninfluenced by adjacent tagasaste trees, above or below the ground.

Within each main plot, nine pasture species treatments and an unsown, bare-ground treatment were randomly allocated to subplots (30 cm by 30 cm), which were arranged in two adjacent rows of five perpendicular to the hillslope. In the first year, the nine pasture species treatments comprised three perennial grass species, three perennial legume species and three subterranean clover cultivars. In the second year, a poorly performing subterranean clover cultivar was replaced with a prairie grass treatment. The bare-ground treatment enabled us to determine the composition of the seedbank and is reported in the companion paper. Pasture species were selected based on their use in New Zealand hill country and their ability to tolerate moderate levels of shading and drought (Table 1).

On 14 March 2018, 50 bare seeds of each pasture species were sown into Hillson root trainers (3.8 cm by 3.6 cm by 12 cm) containing a commercial potting mix. The root

Table 1. Pasture species and cultivars established at the field site near Wairoa.

Common name	Cultivar(s)	Botanical name	Characteristics considered beneficial for use in hill country in a tagasaste silvopasture
Perennial ryegrass	Grasslands Samson	*Lolium perenne* L.	Widely sown species (grass control) (Waller and Sale 2001)
Cocksfoot	Savvy	*Dactylis glomerata* L.	Shade and drought tolerant (Devkota *et al.* 1998; Sanada *et al.* 2010)
Microlaena	Wakefield	*Microlaena stipoides* (Labill.) R.Br.	Shade and drought tolerant (Firth *et al.* 2002; Mitchell *et al.* 2016)
Prairie grass[A]	Atom	*Bromus willdenowii* Kunth	Shade tolerant and productive under lax grazing (Burtt-Davy 1916; Stewart 1996)
White clover	Grasslands Nomad	*Trifolium repens* L.	Widely sown species (legume control)
Red clover	Grasslands Relish	*T. pratense* L.	Shade tolerant (Van Sambeek *et al.* 2007; St. John 2008)
Subterranean clover	Antas, Denmark	*T. subterraneum* L.	Drought tolerant (Devkota *et al.* 1997; Widdup and Pennell 2000; Smetham 2003)
Lotus/greater lotus	Grasslands Trojan	*Lotus pedunculatus* Cav. (syn. *L. uliginosus*)	Shade tolerant (Devkota *et al.* 1997)

[A]Prairie grass was established in the second year.

trainers were then placed in a glasshouse with an average day temperature of 18.5°C and night temperature of 11.9°C. Seedlings were watered with Thrive All Purpose Soluble Fertiliser (1 g L^{-1} applied to 28 plants; Yates, Wyee, NSW, Australia) at 2-week intervals from April to August 2018, when they were transplanted into the field site. Because microlaena has a low germination rate (<25%), plants were purchased from a commercial retailer, subdivided to match the size of other test grass species (~3 tillers $plant^{-1}$) and transplanted into Hillson root trainers.

At the field site, branches and debris were removed from the plot locations, and Roundup (Bayer CropScience, Melbourne, Vic., Australia) was applied to existing vegetation in each plot and its surrounds (1.8 m by 1.8 m area) at a rate of 10 mL Roundup L^{-1} water, using a knapsack sprayer, in early August 2018.

On 22 and 23 August, 2 weeks after herbicide application, the soil was cultivated with a shovel to a depth of 15 cm, the seedlings were transplanted into the centre of each subplot, and the soil was firmly pressed around each plant. Each transplant was irrigated with ~700 mL water and identified with a plastic label. On 23 August after transplanting, slug bait was applied to each subplot (25 g, Eden Gardener Snail Bait containing metaldehyde at 5 g kg^{-1}).

On 26 September and 9 October 2018, any dead transplants were replaced and slug bait re-applied at the same rate. The number of tillers (or stolons) on each plant was counted on 26 September 2018. Signs of a viral disease were apparent on Campeda subterranean clover (red colouration of leaves) and became more severe over successive months. Campeda was eliminated from the dataset because there were concerns that any effects of shade treatments would be confounded with disease effects. There was no sign of disease in the other cultivars (Antas and Denmark).

In September 2018, ~5 weeks after seedlings were transplanted, the number of tillers (or stolons) per plant was similar for all three shade treatments (average across species 11 $plant^{-1}$). Of the grasses, number of tillers per plant was highest for perennial ryegrass (29 tillers), intermediate for microlaena (21 tillers) and lowest for cocksfoot (14 tillers) (± 1.3, standard error of difference; $P < 0.001$). There was no difference among white clover, red clover and lotus for number of stolons per plant (average 9 stolons), or between Antas and Denmark subterranean clover (average 6 stolons) ($P > 0.05$).

Antas and Denmark subterranean clover were re-established in 2019 to provide 2 years of consecutive data. Because it was not possible to obtain data on Campeda in the first year, the biennial species prairie grass was substituted as an alternative pasture species given its suitability for hill country (Table 1). Antas and Denmark subterranean clover and Atom prairie grass seeds were sown in seed-raising mix in Hillson root trainers on 17 April 2019 as described above. In July 2019, subterranean clover seedlings (Antas 5.8 ± 0.6 stolons $plant^{-1}$ and Denmark 5.4 ± 0.5 stolons $plant^{-1}$) were transplanted into the same subplots as in 2018, and prairie grass seedlings (2.0 ± 0.3 tillers $plant^{-1}$, $n = 8$) were transplanted into the former Campeda treatment subplots. Slug bait was applied as above.

Livestock were excluded from the tagasaste silvopasture during establishment between August and October 2018. The plantation was grazed approximately every 6 weeks between October 2018 and June 2021 with Coopworth ewes and lambs or hoggets, at an average stocking rate of 254 ± 31 stock units ha^{-1}. Within 24 h before grazing, plots were covered with a plastic mesh sheet (with 1-cm diameter cells) pinned to the ground. This prevented stock from grazing and trampling the test plants while still allowing sunlight to reach the plants and allowing stock access to the surrounding pasture. The mesh sheet was removed within 48 h after stock were removed from the plantation. Further details on grazing management are provided in the companion paper.

Measurements

Measurements were taken at intervals of 4–7 weeks from 22 August 2018 to 9 June 2021. There were four measurements of the pasture species in 2018 (August–December), seven in 2019, eight in 2020 and four in 2021 (January–June). Measurement frequency declined over summer when pasture growth was slower, and there were fewer visits than envisaged throughout autumn 2020 owing to COVID-19-related travel restrictions. Measurements were completed within 48 h.

Pasture species survival, herbage production, herbage quality, canopy cover (plant area), plant damage and soil moisture content were assessed on each measurement occasion as follows.

To measure survival, any plants with green tissue were recorded as surviving and those with no green tissue were recorded as dead. Plants classified as dead occasionally had green tissue present on subsequent measurement dates, in which case they were reclassified as surviving.

For assessment of herbage production and quality, herbage was removed at the top of the pseudostem (typically ~5 cm above ground level) by using scissors. Retaining the pseudostem is thought to enable satisfactory replenishment of carbohydrate reserves for several pasture species (e.g. perennial ryegrass, cocksfoot, prairie grass) and minimise defoliation stress (Turner *et al.* 2007). The herbage from each plant was quickly frozen in dry ice. Samples were stored at −20°C, freeze-dried (FD80 freeze dryer; Cuddon, Blenheim, NZ), weighed, and ground to a powder of particle size <1 mm (Cyclone sample mill; UDY, Fort Collins, CO, USA). Ground samples were analysed by Hill Laboratories (Hamilton, NZ) using near-infrared spectroscopy (Corson *et al.* 1999) to obtain estimates of metabolisable energy (ME), crude protein, soluble sugars, neutral detergent fibre (NDF) and ash. Dry weights were summed for each species to obtain seasonal and total annual herbage production.

Canopy cover of each plant was visually assessed in a 30 cm by 30 cm quadrat divided into 5 cm by 5cm cells. The total number of cells occupied by each plant was multiplied by the cell area. A cell was considered empty if <50% filled with vegetation, and occupied if >50% filled with vegetation (Hayes *et al.* 2021).

Plant damage was quantified visually, assigning a score of 1 to a plant that was vigorous and healthy with no disease/invertebrate damage; a score of 2 to a plant with disease/invertebrate damage and up to 50% of tillers/stolons dying; and a score of 3 to a plant with >50% of tillers/stolons dying and the whole plant with disease/invertebrate damage.

Subterranean clover seedling emergence from the seedbank was quantified in autumn 2019. All subterranean clover seedlings that emerged from the Antas and Denmark subterranean clover treatments were counted and removed. These data were collected to determine whether the Antas and Denmark transplants established in 2018 were able to produce viable seed.

Soil moisture content was measured as described in Tozer *et al.* (2023). In summary, soil moisture content was measured at a depth of 0–12 cm using a portable time domain reflectometry instrument (Hydrosense II; Campbell Scientific, Logan, UT, USA), calibrated for the field site using gravimetric soil moisture values.

Statistical analyses

All data other than survival were analysed by split-plot analysis of variance (ANOVA) using GenStat 21st edition (GenStat 2021). Treatments used in the analyses were three shade levels (heavy, light, open), species (or cultivars in the case of the annual legume), and the shade × species interaction. Pasture species were classed as perennial grasses, perennial legumes and annual legumes and were analysed separately because of high mortality rates in perennial and annual legumes and because there was no interest in comparing grass species with legume cultivars. Survival data were analysed as a generalised linear mixed model with binomial distribution, with shade and species/cultivar as fixed effects, and site and shade within site as random effects. A repeated-measures split-plot ANOVA was performed for herbage quality variables for grasses in the second and third year and damage score in the first year. In all cases, there were significant interactions between time and fixed treatments ($P < 0.001$). Other repeated-measures analyses failed to converge owing to sparse data and inconsistent sampling (e.g. some replicates were eliminated from the analyses if plants had died). Consequently, times were analysed individually. This demonstrated how differences between means changed over time without formally measuring those patterns. Residuals from the analyses were checked for normality. Herbage production was square-root transformed to equalise the variance to meet the normality assumptions of the analysis. Mean separation was assessed by Fisher's protected least significant difference.

Results

Survival

Grasses

Survival was lower in light shade than in heavy shade and open pasture in April 2021 ($P < 0.05$, Fig. 1*a*). Survival of grass transplants remained high in the first year (>90%), but by the end of the study only 20% of transplants survived in light shade and an average of 85% in the heavy shade and open pasture treatments.

In July 2020, survival was higher for microlaena and prairie grass than for perennial ryegrass and cocksfoot

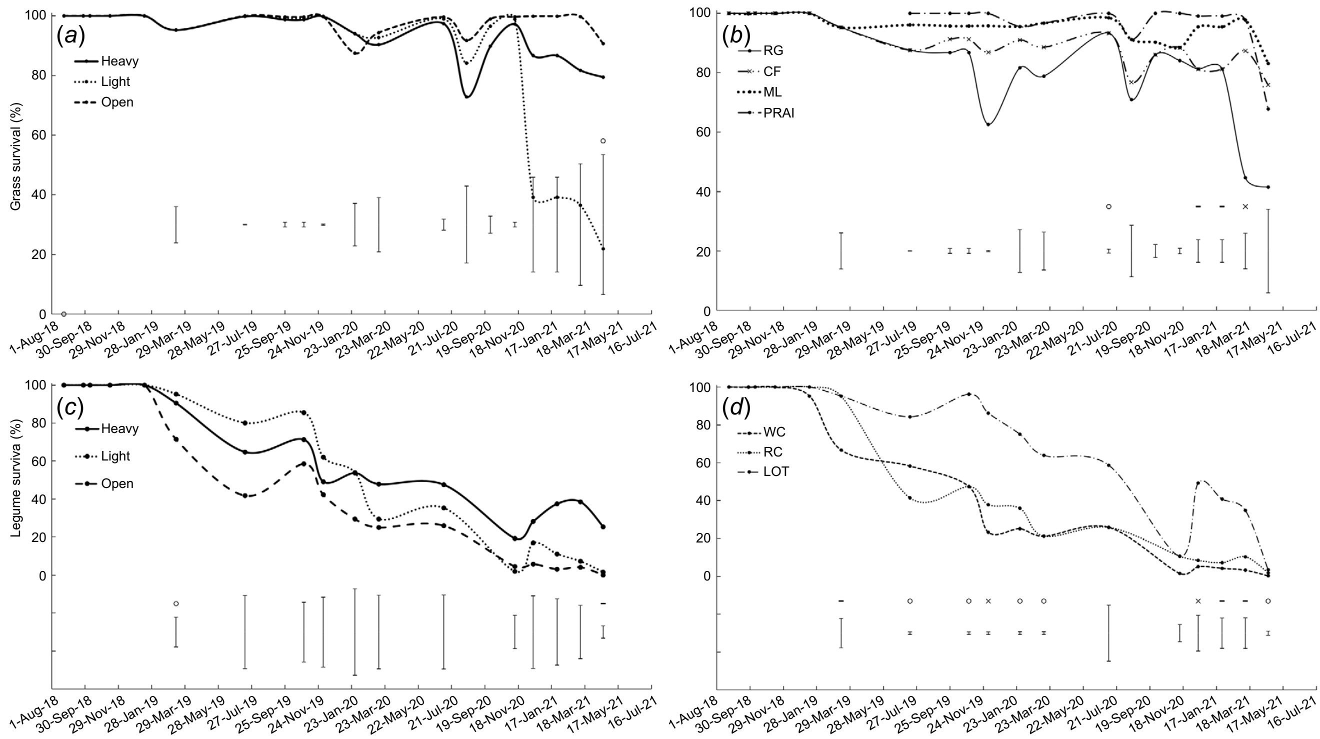

Fig. 1. Transplant survival (as evidenced by the presence of green tissue) for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. On some occasions, plants appeared to be dead (i.e. no green tissue present) but later recovered. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

($P < 0.05$, Fig. 1*b*). From midsummer 2020 onwards, survival was generally highest for microlaena and prairie grass and lowest for perennial ryegrass, with cocksfoot intermediate ($P < 0.01$ in December, January and March; $P = 0.051$ in April). Approximately 80% of microlaena but only 40% of perennial ryegrass transplants were alive in April 2021 (Fig. 1*b*).

Legumes

In March 2019, legume survival was higher in the light and heavy shade treatments than in open pasture ($P < 0.05$, Fig. 1*c*). By April 2021, survival was higher in heavy shade (25%) than in light shade (2%) and open pasture, where no legumes survived ($P < 0.01$, Fig. 1*c*).

There were significant differences among legume species in survival on 10 occasions, when survival was generally higher for lotus than for white clover and red clover (Fig. 1*d*, $P < 0.05$). By April 2021, only 4% of lotus, 2% of red clover and <1% of white clover transplants were alive.

Herbage production

Grasses

Shading (heavy and/or light shade) reduced total and seasonal herbage production of the grasses during most seasons and all years compared with open pasture ($P < 0.05$, Table 2). Herbage production in open pasture was often >3-fold greater than in heavy shade, with production in light shade intermediate but not always significantly different from either heavy shade or open pasture.

Cocksfoot had the greatest seasonal and total annual herbage production of the perennial grasses from summer 2018–19 onwards for all seasons and years (Table 3). Cocksfoot was more productive than microlaena in the first year, and its DM production was ~3-fold greater than that of perennial ryegrass and microlaena in the second year and 2-fold greater in the third year. Perennial ryegrass was also more productive than microlaena in 2018–19 ($P < 0.001$), whereas from winter 2019 onward, DM production was similar for the two species ($P > 0.05$, Table 3). Total annual herbage production of (2-year-old) prairie grass was greater than that of (3-year-old) perennial ryegrass transplants in the final year of the study ($P < 0.05$, Table 3).

There was a significant shade × grass species interaction in the first year ($P < 0.05$, Table 4) which demonstrated that herbage production of perennial ryegrass and cocksfoot was strongly suppressed by heavy shade, whereas microlaena was unaffected by shading, although as noted, it had significantly lower production than cocksfoot and ryegrass.

Table 2. Seasonal and total annual herbage production in the heavy shade, light shade and open pasture treatments.

	Season	Perennial grasses (g DM plant^{-1})					Perennial legumes (g DM plant^{-1})				
		Heavy	Light	Open	s.e.d.	*P*-value	Heavy	Light	Open	s.e.d.	*P*-value
2018–19	Spring	5.3a	11.5b	13.9b	2.55	0.016	4.1a	8.5a	16.0b	2.24	<0.001
	Summer	12.9a	35.5b	40.8b	10.68	0.049	8.7a	21.2a	42.4b	8.18	<0.001
	Autumn	2.9	6.5	6.8	1.80	0.084	0.5	0.9	2.3	1.69	n.s.
	Total annual[A]	20.9a	53.4b	61.3b	14.71	0.038[B]	13.3a	30.6b	62.4c	9.01	<0.001[B]
2019–20	Winter	0.7a	1.2a	5.9b	1.16	0.004	0.2	0.2	0.4	0.17	n.s.
	Spring	4.9a	8.4a	31.9b	6.60	0.006	7.7	7.6	8.8	1.70	n.s.
	Summer	8.8a	15.3ab	28.0b	6.33	0.041	9.5	13.8	15.5	4.03	n.s.
	Autumn	1.3a	4.6ab	11.9b	3.78	0.025	0.7	1.0	1.9	1.08	n.s.
	Total annual	15.7a	29.6a	77.7b	16.80	0.013	18.1	22.6	26.6	5.72	n.s.
2020–21	Winter	2.7a	4.8a	14.4b	3.81	0.028	0.5	1.1	1.6	0.85	n.s.
	Spring	6.4a	10.6a	25.0b	5.83	0.022	1.7	1.3	3.0	1.86	n.s.
	Summer	6.1a	7.9ab	16.2b	4.51	0.043	4.5	3.3	2.9	1.85	n.s.
	Autumn	7.2	7.0	14.2	3.87	n.s.	2.2	1.5	0.8	0.79	n.s.
	Total annual	22.3a	30.2a	69.7b	16.85	0.024	8.9	7.1	8.2	4.80	n.s.

Data were analysed separately for the grass species and legume species.
s.e.d., standard error of the difference; n.s., not significant ($P > 0.05$).
Within rows and pasture type (grasses or legumes), means followed by the same letter (or no letter) are not significantly different ($P > 0.05$). Raw means and s.e.d.s are presented, with the *P*-value and mean separation from square-root transformed data analysis.
[A]Total annual herbage production was for only three seasons in the first year.
[B]Significant shade × species treatment interaction (shade × species combination means are provided in Tables 4 and 5).

Table 3. Seasonal and total annual herbage production for perennial ryegrass (RG), cocksfoot (CF), microlaena (ML), prairie grass (PRA), white clover (WC), red clover (RC) and lotus (LOT).

	Season	Perennial grasses (g DM plant^{-1})						Perennial legumes (g DM plant^{-1})				
		RG	CF	ML	PRA	s.e.d.	*P*-value	WC	RC	LOT	s.e.d.	*P*-value
2018–19	Spring	16c	13b	2a	n/a	1.4	<0.001	5a	12b	11b	1.4	<0.001
	Summer	29b	49c	11a	n/a	6.0	<0.001	8a	31b	34b	6.5	<0.001
	Autumn	4a	9b	4a	n/a	1.2	<0.001	0a	1a	4b	0.7	<0.001
	Total annual	49b	71c	17a	n/a	7.3	<0.001[A]	14a	44b	49b	7.6	<0.001[A]
2019–20	Winter	3b	6c	1a	<1a	1.0	<0.001	<1	<1	<1	0.19	n.s.
	Spring	12a	31b	6a	12a	4.8	<0.001	4a	6a	14b	3.0	0.010
	Summer	8a	28c	13ab	21bc	4.9	<0.001	8	12	20	5.6	n.s.
	Autumn	2a	12c	4a	5ab	2.1	<0.001	1	1	2	1.2	n.s.
	Total annual	25a	78b	24a	37a	11.5	<0.001	13a	19ab	36b	8.8	0.039
2020–21	Winter	5a	12b	5a	7ab	2.3	0.033	<1	<1	2	1.0	n.s.
	Spring	9a	19b	8a	19b	3.2	<0.001	1	<1	4	1.9	n.s.
	Summer	6a	15b	8a	11ab	2.6	0.008	3	3	5	2.0	n.s.
	Autumn	6a	14b	8ab	11b	3.0	0.022	1	2	2	0.9	n.s.
	Total annual	26a	59b	30a	48b	9.3	0.002	6	6	12	5.0	n.s.

Data are averaged over shade treatments for perennial grasses and for perennial legumes.
s.e.d., standard error of the difference; n.s., not significant ($P > 0.05$); n/a, not applicable.
Within rows and pasture type (grasses or legumes), means followed by the same letter (or no letter) are not significantly different ($P > 0.05$). Raw means and s.e.d.s are presented, with the *P*-value and mean separation from square-root transformed data analysis.
[A]Significant shade × species treatment interaction (shade × species combination means are provided in Tables 4 and 5).

Table 4. Significant ($P < 0.05$) shade × grass species treatment interactions for key parameters.

Parameter	Season/year	Heavy				Light				Open				s.e.d.	Interaction *P*-value
		RG	CF	ML	PRA	RG	CF	ML	PRA	RG	CF	ML	PRA		
Herbage production (g DM plant^{-1})	2018–19 (sqrt)	4.6a	5.6a	2.6		7.3b	9.2b	3.7		7.9b	8.8b	4.8		1.16	0.035
Canopy cover (cm^2 plant^{-1})	Average 2018–19	35a	59a	20		59b	99b	26		52b	70a	31		7.4	0.011
	Average 2019–20	46	104a	44	54	75	134a	50	85	75	189b	72	70	23.1	0.037
Plant damage score (1–3)	Autumn 2021	2.2b	1.9	1.1	1.5	2.6b	1.4	1.6	1.4	1.5a	1.4	1.3	1.6	0.33	0.025
ME (MJ kg DM^{-1})	Summer 2018–19	9.3ab	9.2	9.9b		8.8a	9.6	9.3b		9.8b	9.3	8.4a		0.39	0.015
Soluble sugars (% of DM)	Winter 2019	5a	5	6	6a	6a	5	6	8ab	12b	6	7	10b	1.2	0.044
	Autumn 2021	8a	6	8	9a	10b	6	8	8a	12c	5	9	11b	0.8	0.036
	Annual average 2020–21	9a	6	7	8a	9a	6	8	9a	11b	6	8	11b	0.6	0.023
NDF (% of DM)	Average 2018–19	47b	52b	49	n/a	48b	50ab	49	n/a	43a	48a	50	n/a	1.1	0.011
	Summer 2019–20	45	52ab	50a	56	47	51a	53a	54	47	55b	57b	54	1.8	0.004

ME, metabolisable energy; NDF, neutral detergent fibre; RG, perennial ryegrass; CF, cocksfoot; ML, microlaena; PRA, prairie grass; s.e.d., standard error of difference; n/a, not applicable.
Within rows, means followed by the same letter (or no letter) are not significantly different ($P > 0.05$) when comparing the same species across the three shade treatments. Prairie grass was not present in 2018–19.

Legumes

Herbage production in spring and summer, and total annual herbage production, were greater in open pasture than in heavy and light shade in 2018–19 ($P < 0.05$, Table 2).

Herbage production in spring 2018, summer 2018–2019 and autumn 2019, and total annual herbage production in 2018–19, were greater for lotus and, often, red clover than for white clover ($P < 0.001$, Table 3). Total annual herbage production in 2019–20 was also greater for lotus than white clover, with red clover intermediate but not significantly different from either of the other species ($P < 0.05$, Table 3).

There was a significant shade × legume species interaction for total annual herbage production (Table 5). Compared with open pasture, total annual herbage production of white clover was not affected by shading, whereas herbage production of red clover and lotus was suppressed by light and heavy shade ($P < 0.01$, Table 5). From the second year onwards, legumes performed poorly in all treatments and there were no significant interactions.

Nutritive values

Metabolisable energy

Grasses. In January 2020, ME content was lower in open pasture than in heavy shade, with light shade intermediate ($P < 0.05$, Fig. 2*a*). There were differences among perennial grasses on 16 occasions ($P < 0.05$) with an overall trend of ME content being highest for perennial ryegrass, similar and sometimes lower for cocksfoot, and lowest for microlaena and prairie grass (Fig. 2*b*).

In summer 2018–19, compared with open pasture, light shading reduced the ME content of perennial ryegrass and

Table 5. Significant ($P < 0.05$) shade × legume species treatment interactions for key parameters.

Parameter	Season/year	Heavy			Light			Open			s.e.d.	Interaction *P*-value
		WC	RC	LOT	WC	RC	LOT	WC	RC	LOT		
Herbage production (g DM plant^{-1})	2018–19 (sqrt)	2.3	3.4a	3.8a	4.1	4.8a	6.0b	3.7	9.0b	8.9c	0.87	0.003
Canopy cover (cm^2 plant^{-1})	Autumn 2019	21	14	43a	30	15	61ab	<1	32	79b	14.7	0.039
Plant damage score (1–3)	Average 2018–19	1.5ab	1.5b	1.2	1.3a	1.4ab	1.2	1.7b	1.2a	1.2	0.11	0.002
ME (MJ kg DM^{-1})	Autumn 2019	11.3b	10.2	9.8a	11.1ab	11.1	10.1ab	10.2a	10.2	11.0b	0.49	0.043
Soluble sugars (% of DM)	Autumn 2019	6	7	1a	6	8	2a	5	8	6b	0.8	0.004
NDF (% of DM)	Average 2018–19	32	38	38b	34	35	37b	33	35	31a	1.7	0.031
Ash (% of DM)	Autumn 2019	15b	12a	13	13ab	12a	11	10a	17b	10	1.9	0.045

ME, metabolisable energy; NDF, neutral detergent fibre; WC, white clover; RC, red clover; LOT, lotus; s.e.d., standard error of difference.
Within rows, means followed by the same letter (or no letter) are not significantly different ($P > 0.05$) when comparing the same species across the three shade treatments.

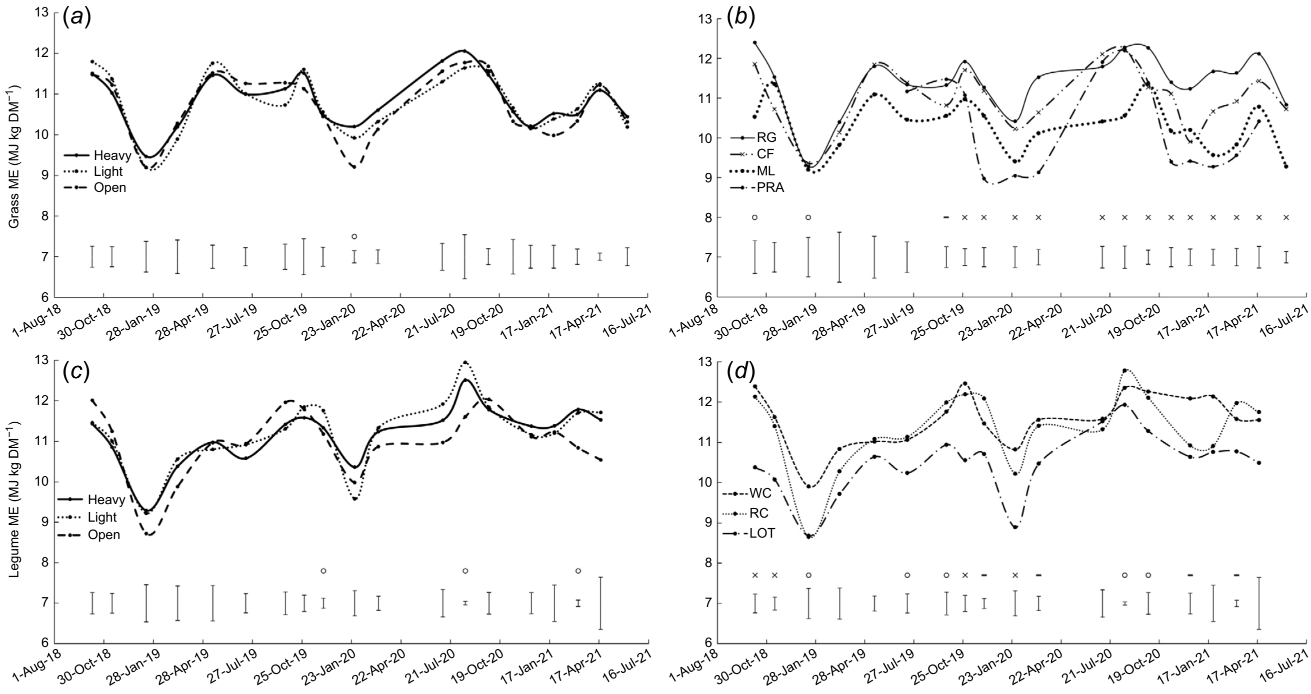

Fig. 2. Metabolisable energy (ME) content for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

increased that of microlaena, but there was no effect of shade treatment on cocksfoot ME content (shade × grass species interaction $P < 0.05$, Table 4).

Legumes. There were differences among shade treatments on three occasions ($P < 0.05$), although there was no consistent trend (Fig. 2*c*). ME content was generally higher in white clover and red clover than in lotus, with differences being significant on 13 occasions ($P < 0.05$, Fig. 2*d*).

In autumn 2019, compared with open pasture, heavy shading increased the ME content of white clover and reduced that of lotus, but there was no effect of shade treatment on red clover ME content (shade × legume species interaction $P < 0.05$, Table 5).

Crude protein

Grasses. Crude protein content was higher in heavy shade than in open pasture, and intermediate in light shade, with significant differences occurring on eight occasions ($P < 0.05$, Fig. 3*a*). There were significant differences among grass species on 12 occasions, but trends were inconsistent ($P < 0.05$, Fig. 3*b*).

Legumes. There were differences in crude protein content among the shade treatments on five occasions and among legume species on eight occasions ($P < 0.05$, Fig. 3*c*, *d*). Crude protein content was generally higher in heavy shade and/or light shade than in open pasture and higher in white clover and/or lotus than red clover.

Soluble sugars

Grasses. There were differences in soluble sugar content among shade treatments on five occasions ($P < 0.05$, Fig. 4*a*) and among grass species on 15 occasions ($P < 0.05$, Fig. 4*b*). Soluble sugar content was higher in open pasture than in heavy shade, with light shade intermediate (Fig. 4*a*). Soluble sugar content was often lowest for prairie grass and fluctuated for the other species (Fig. 4*b*).

In winter 2019 and autumn 2021, and on average for 2020–21, shading reduced the soluble sugar content in perennial ryegrass and prairie grass but there was no effect of shade treatment in cocksfoot or microlaena (shade × grass species interaction $P < 0.05$, Table 4).

Legumes. There were differences in soluble sugar content among shade treatments on 10 occasions ($P < 0.05$, Fig. 4*c*) and among legume species on 13 occasions ($P < 0.05$, Fig. 4*d*). Generally, the soluble sugar content was greater in open pasture than heavy and light shade. It was also higher in red clover than in lotus, with white clover intermediate (Fig. 4*d*).

In autumn 2019, there was no effect of shade treatment on white clover or red clover but shading severely reduced the soluble sugar content in lotus (average of 1% in heavy and

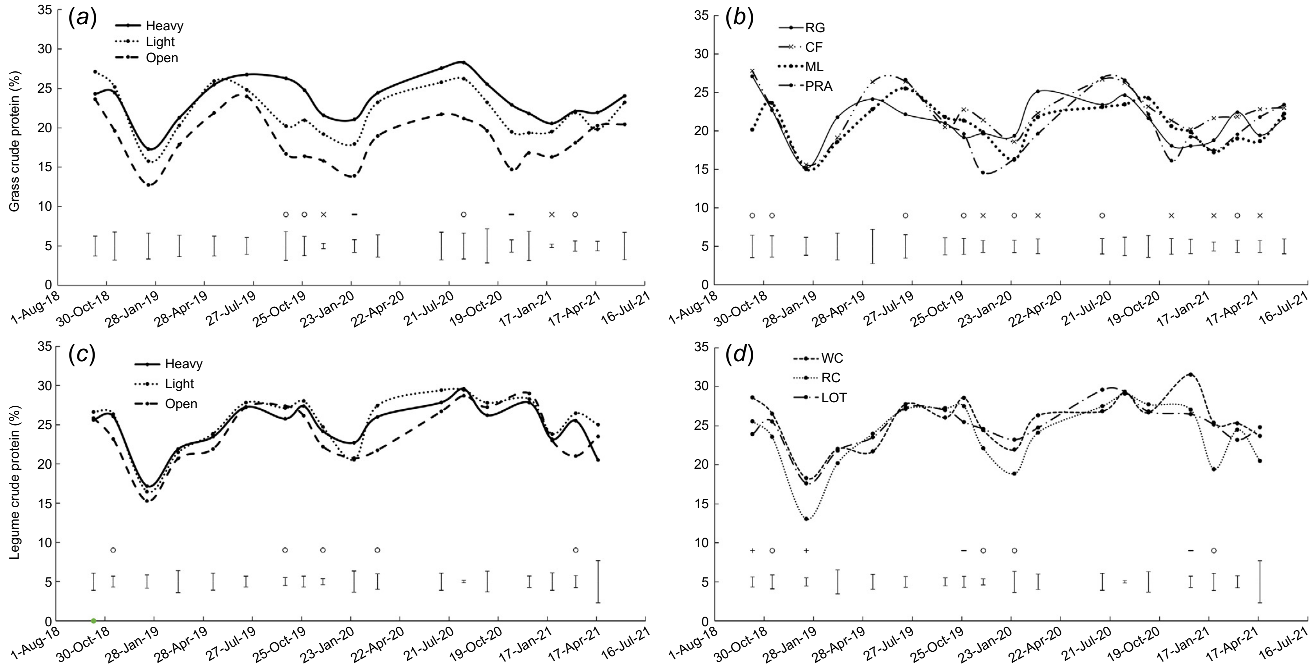

Fig. 3. Crude protein content (% of DM) for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

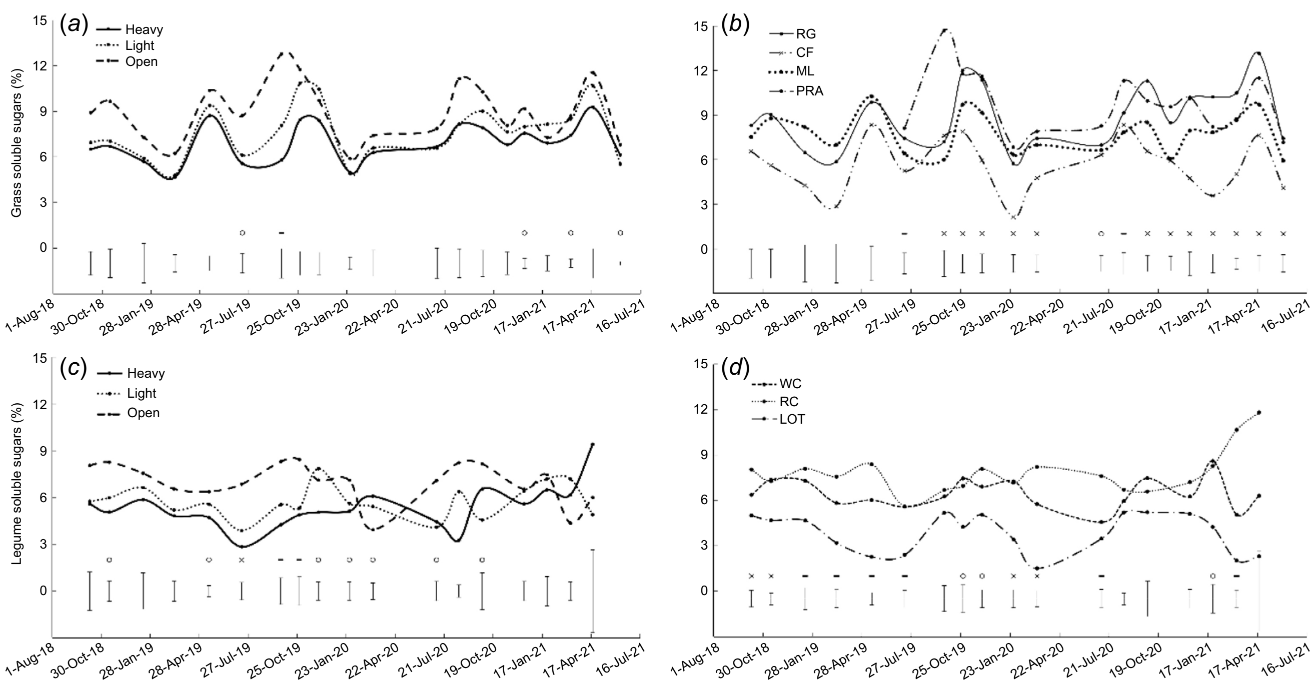

Fig. 4. Soluble sugar content (% of DM) for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

light shade vs 6% in open pasture; shade × legume species interaction $P < 0.01$, Table 5).

Neutral detergent fibre

Grasses. There was no effect of shade treatment on NDF content ($P > 0.05$, Fig. 5*a*). There were differences among grass species on 19 occasions, with perennial ryegrass generally having a lower NDF content than the other three grass species ($P < 0.05$, Fig. 5*b*).

In spring 2018 (data not shown), and for the average annual values for 2018–19 (Table 4), compared with open pasture, shading (heavy and/or light shade) increased the NDF content of perennial ryegrass and cocksfoot but there was no effect of shade treatment on microlaena (shade × grass species interaction, $P < 0.05$). In summer 2019–20, the trends were reversed: shading reduced the NDF content of cocksfoot and microlaena but there was no effect of shade treatment on perennial ryegrass or prairie grass (shade × grass species interaction, $P < 0.01$, Table 4).

Legumes. Compared with open pasture, shading increased the NDF content in winter or spring (July 2019, October 2019, September 2020; $P < 0.05$). The reverse occurred when sampled in summer or autumn, when NDF was lower in heavy and/or light shade than open pasture (December 2019, March 2020, March 2021; $P < 0.05$, Fig. 5*c*). There were differences between perennial legumes on 12 occasions, with a general trend of higher NDF content in red clover and lotus than white clover ($P < 0.05$, Fig. 5*d*).

In 2018–19, compared with open pasture, shading increased the average annual NDF content in lotus but there was no effect of shade treatment on white clover or red clover (shade × legume species interaction $P < 0.05$, Table 5).

Ash

Grasses. Ash content was greater in heavy shade than open pasture on four occasions, with the ash content in light shade often intermediate ($P < 0.05$, Fig. 6*a*). There were differences between grass species on 16 occasions, when the ash content was most often highest for microlaena, intermediate for perennial ryegrass and cocksfoot, and lowest for prairie grass ($P < 0.05$, Fig. 6*b*). There was no shade × grass species interaction for ash content ($P > 0.05$).

Legumes. Ash content of legumes generally followed a similar trend when shaded to that of the grasses, with a higher content in heavy shade than open pasture on four occasions ($P < 0.05$, Fig. 6*c*). Ash content was greater in white clover than in red clover and lotus on 10 occasions ($P < 0.05$, Fig. 6*d*).

In autumn 2019, compared with open pasture, heavy shade increased the ash content of white clover, and heavy and light shade reduced the ash content of red clover, but there was no

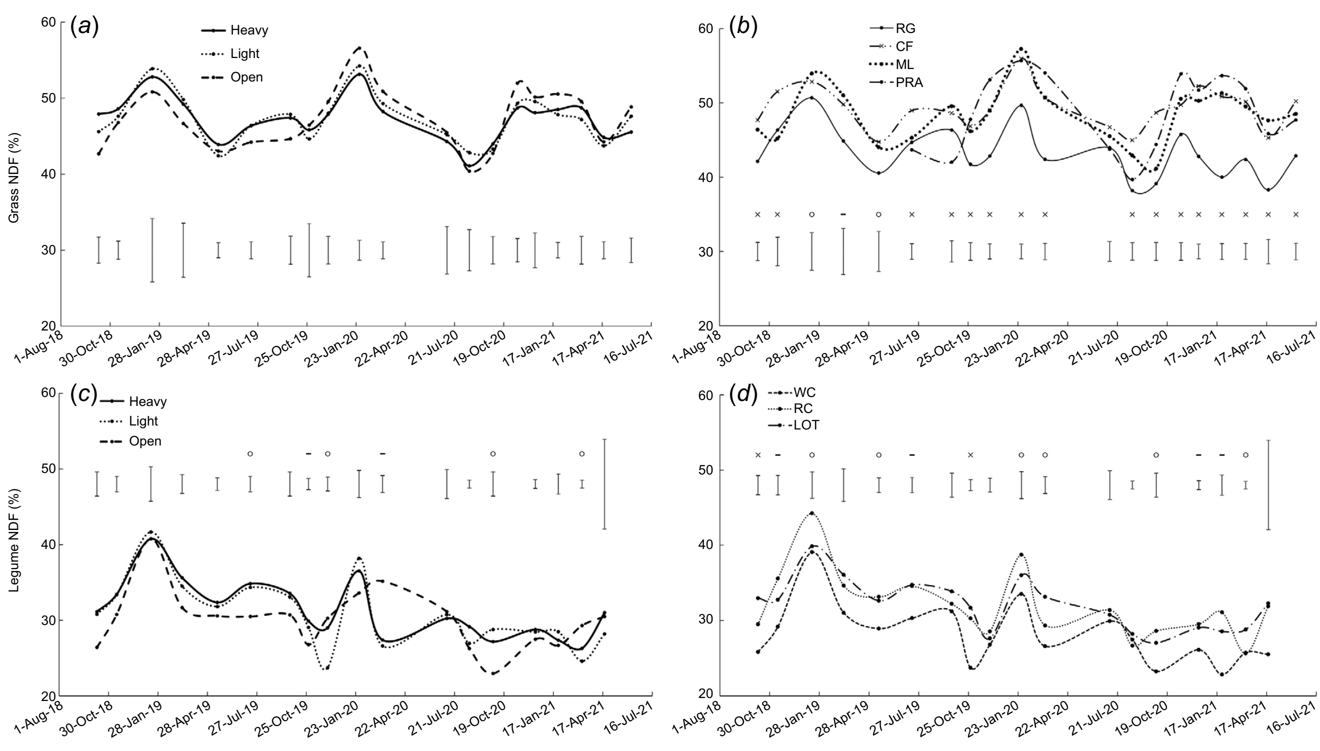

Fig. 5. Neutral detergent fibre content (NDF, % of DM) for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

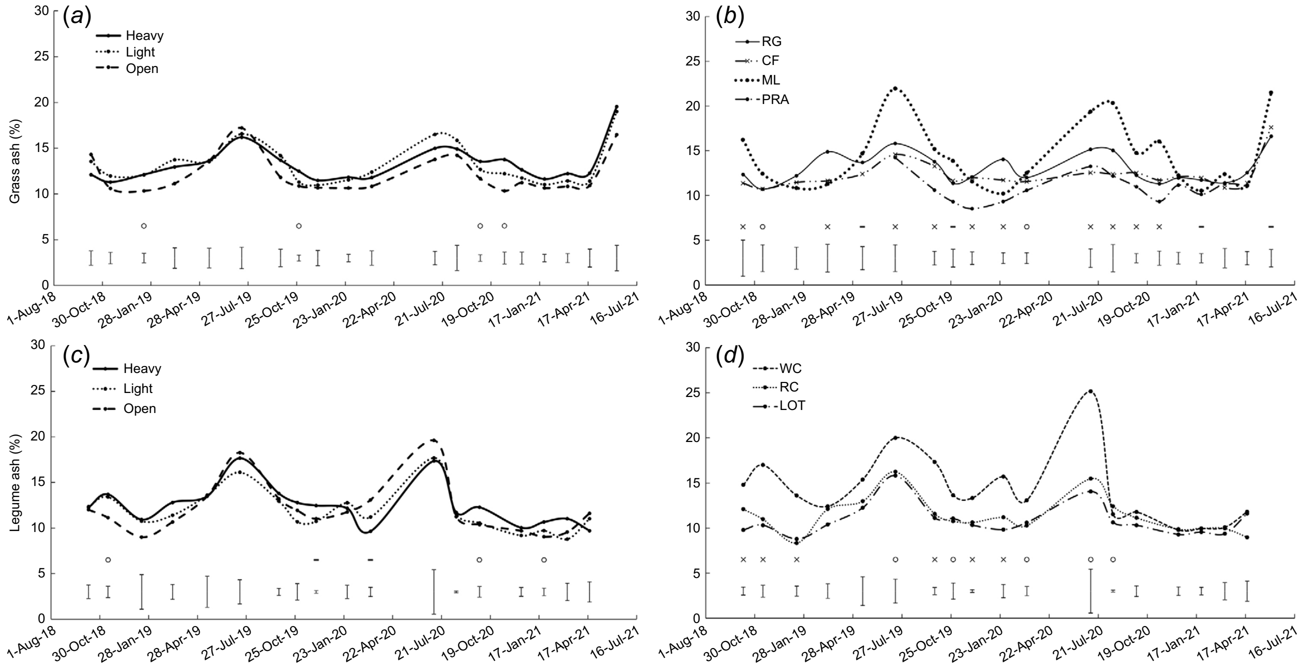

Fig. 6. Ash content (% of DM) for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

effect of shade treatment on the ash content of lotus (shade × legume species interaction $P < 0.05$, Table 5).

Canopy cover

Grasses

Canopy cover was greater in open pasture than heavy shade on four occasions and greater in open pasture than light shade on two occasions ($P < 0.05$, Fig. 7*a*).

There were significant differences in canopy cover among grass species for all measurement dates ($P < 0.05$, Fig. 7*b*). By January 2019, canopy cover was nearly always higher for cocksfoot than perennial ryegrass and microlaena, with prairie grass generally intermediate ($P < 0.01$, Fig. 7*b*).

There were shade × grass species interactions in spring 2018 ($P < 0.01$, data not shown) and summer 2018–19 ($P < 0.01$, data not shown) and on average for 2018–19 ($P < 0.05$, Table 4). There was a consistent trend of greater canopy cover for perennial ryegrass and cocksfoot in light shade than heavy shade, with open pasture being intermediate and not always significantly different from either, whereas for microlaena, canopy cover was not affected by shade treatment ($P < 0.05$, Table 4). By spring 2019, there was no longer an advantage of light shade; canopy cover of cocksfoot was greater in open pasture than in light shade and heavy shade but there was no effect of shade treatment on any other grass species ($P < 0.05$, data not shown). The same trend was observed for the average annual canopy cover in 2019–20 ($P < 0.05$, Table 4).

Legumes. Canopy cover was greater in open pasture than in one or both shade treatments on five occasions ($P < 0.05$, Fig. 7*c*). There were significant differences in canopy cover among perennial legumes on 13 occasions (Fig. 7*d*, $P < 0.05$). Canopy cover was generally greater for lotus than for white clover and red clover up to January 2020 ($P < 0.05$), after which time, trends were less consistent. In January and March 2021, canopy cover was greater for white clover than red clover and lotus ($P < 0.05$), but by June 2021, there was no difference in canopy cover among the three species (average 26 cm^2, $P > 0.05$, Fig. 7*d*).

In autumn 2019, canopy cover of lotus was lower in heavy shade than open pasture, whereas white clover and red clover were not affected by shade treatment (shade × legume interaction $P < 0.05$, Table 5).

Plant damage

Grasses

There was no effect of shade on plant damage on any occasion ($P > 0.05$, Fig. 8*a*).

There were significant differences in plant damage among grass species on 12 occasions ($P < 0.05$, Fig. 8*b*) On eight of these occasions, plant damage was greatest in ryegrass and least for microlaena, with the other two species intermediate

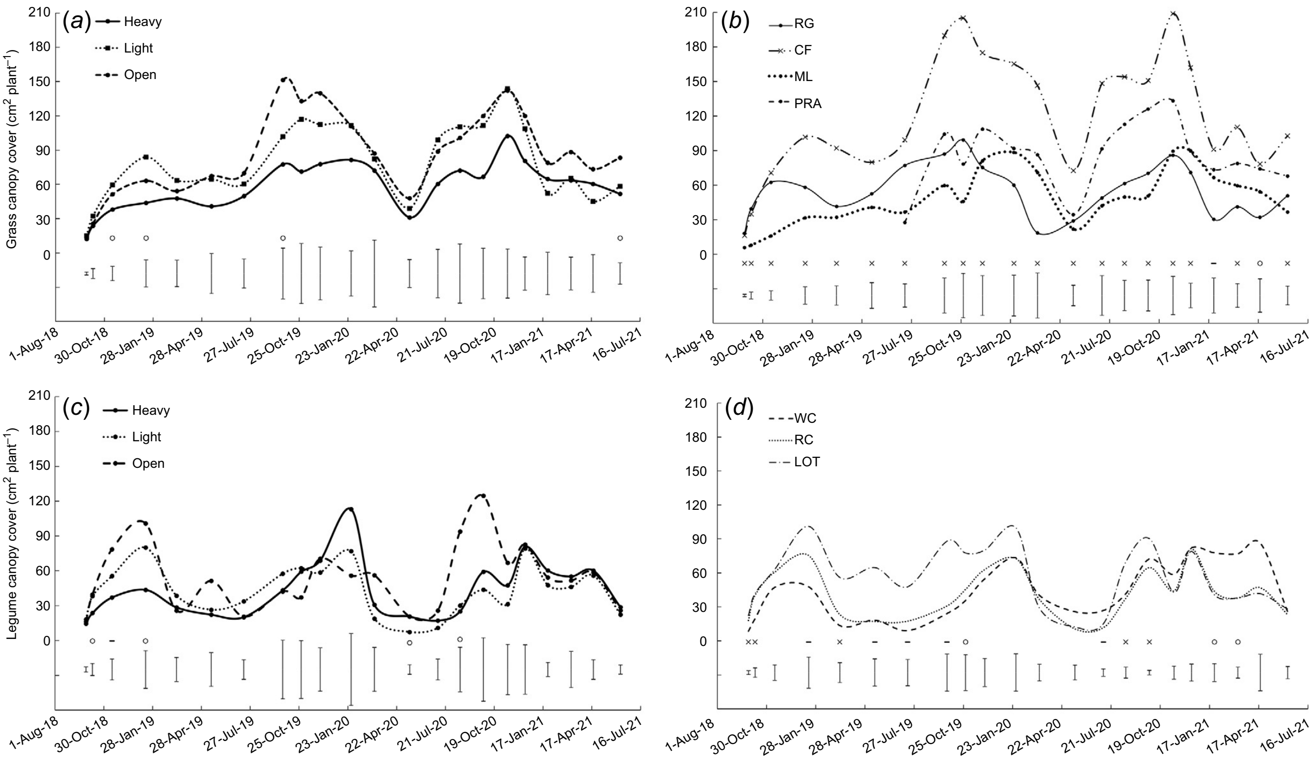

Fig. 7. Canopy cover per plant for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

($P < 0.05$, Fig. 8*b*). Damage levels remained <2 (up to 50% of tillers/stolons dying) for all grass species for the study duration.

In autumn 2021, perennial ryegrass sustained more damage in both light shade and heavy shade than in open pasture, but levels of damage were similar across shade treatments for cocksfoot, microlaena and prairie grass (shade × grass species interaction $P < 0.05$, Table 4).

Legumes

There was an effect of shade on plant damage in legumes on four occasions ($P < 0.05$, Fig. 8*c*), with damage being greater in open pasture than in one or both shade treatments on three of the four occasions. There were significant differences in plant damage among legume species on 16 occasions ($P < 0.05$, Fig. 8*d*). White clover sustained the most damage and lotus the least, with red clover intermediate but not always significantly different from either of the other species ($P < 0.05$, Fig. 8*d*). The damage score was >2 for white clover and red clover for most of the second and third years, whereas the score fluctuated for lotus.

In 2018–19, compared with open pasture, light shade reduced damage to white clover and heavy shade increased damage to red clover, but lotus was unaffected by shade treatment (shade × legume species interaction $P < 0.01$, Table 5).

Subterranean clover growth and survival

Survival

There was no difference between cultivars on any of the measurement occasions ($P > 0.05$, Fig. 9*a*).

Emergence from the soil seedbank

There was no effect of shade treatment on subterranean clover seedling populations that emerged from the seedbank beneath the Denmark or Antas planting positions in autumn 2019, which averaged 32 seedlings m^{-2} in March 2019 and 52 seedlings m^{-2} in May 2019. In addition, there was no difference in seedling emergence between Antas and Denmark subterranean clover in autumn 2019 ($P > 0.05$, data not shown).

Dry weight, canopy cover and damage score

Total dry weight and average annual canopy cover of subterranean clover were greater in open pasture than in heavy or light shade in 2019–20 ($P < 0.001$, Table 6). Canopy cover was also greater for Denmark than for Antas in September and October 2018 ($P < 0.001$, Fig. 9*b*). There was no difference between the cultivars for damage score on any of the measurement dates (Fig. 9*c*). There was a trend towards greater damage in heavy and light shade than in open pasture in 2019–20, although differences were not significant ($P = 0.053$, Table 6).

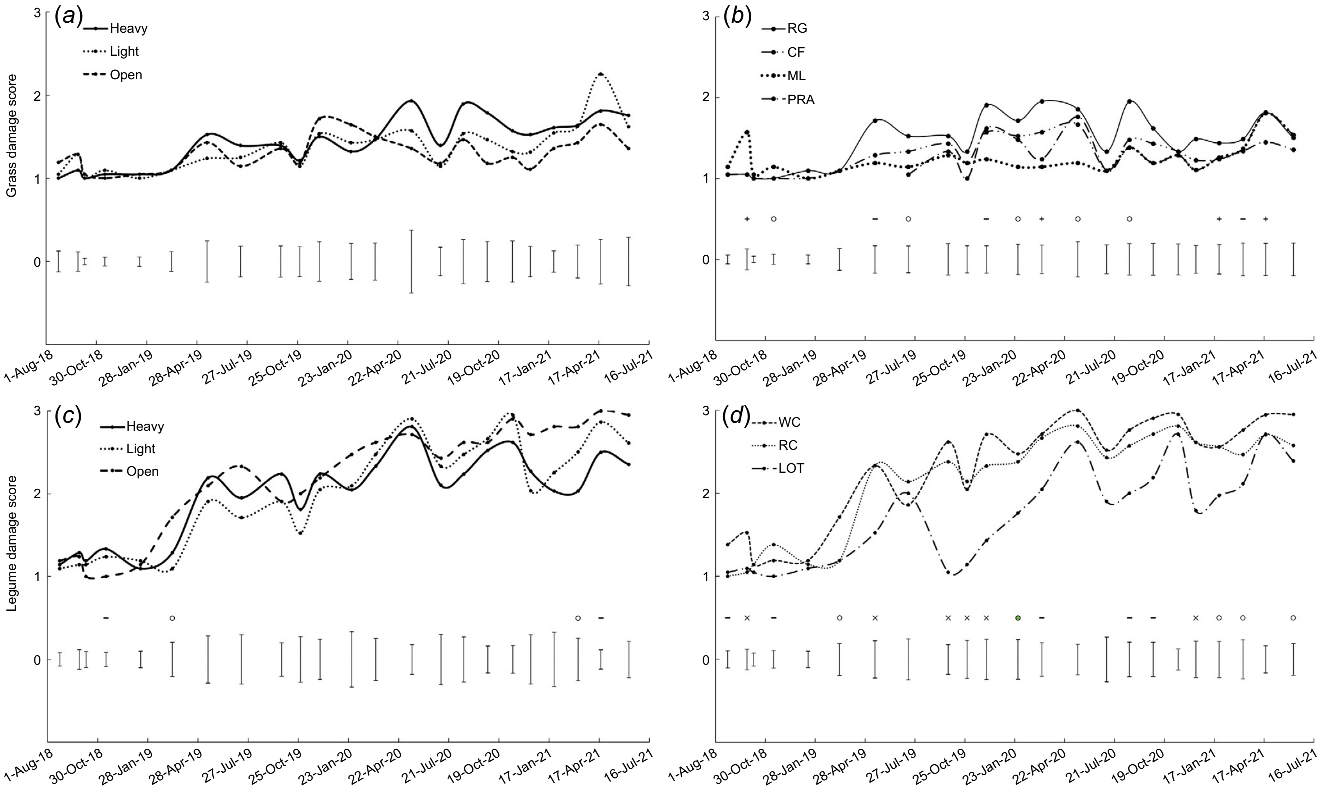

Fig. 8. Plant damage caused by invertebrates or disease for: (*a*) the three shade treatments averaged over grass species; (*b*) perennial ryegrass (RG), cocksfoot (CF), microlaena (ML) and prairie grass (PRA) averaged over shade treatments; (*c*) the three shade treatments averaged over legume species; and (*d*) white clover (WC), red clover (RC) and lotus (LOT) averaged over shade treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$; x, $P < 0.001$.

There was no difference between cultivars, and no shade × cultivar interaction, for total dry weight, average canopy cover or average damage score in either 2018–19 or 2019–20 ($P > 0.05$, Table 6). In the first and second years, there was no effect of shade or cultivar on the average content of ME, crude protein, NDF or ash (data not presented, $P > 0.05$). Soluble sugar content was lower in heavy and light shade than in open pasture (average of 9.8% vs 31.2%, $P < 0.01$) in the first year and greater for Denmark than Antas in the second year (10.7% vs 8.8%, $P < 0.01$).

There were no shade × cultivar interactions for any of the nutritive value measurements in either year ($P > 0.05$).

Denmark had higher contents than Antas of ME in September 2019 ($P < 0.05$, Fig. 10*a*), soluble sugars in December 2019 ($P < 0.01$, Fig. 10*c*), and NDF in October 2018 and 2019 ($P < 0.01$, Fig. 10*d*), and a lower content of crude protein in October 2019 ($P < 0.05$, Fig. 10*b*). There was no difference between Antas and Denmark in ash content ($P > 0.05$, Fig. 10*e*).

Soil moisture

There was no difference in average soil moisture content among the grasses or among annual or perennial legumes other than in January 2019 when soil moisture content was greater for microlaena plots than cocksfoot plots (9% vs 7%, $P < 0.05$). There were no shade × species interactions ($P > 0.05$).

Discussion

Performance of grass species

There were large differences among shade treatments in levels of solar and photosynthetic radiation throughout the study, but fewer differences among the shade treatments in soil moisture or soil nutrient content (Tozer *et al.* 2023). This suggests that the effects of increasing proximity to tagasaste on plant growth and survival were strongly associated with increased shading, although competition for other resources cannot be ruled out. On this basis, we have focused on species performance in relation to shade, although other factors such as moisture stress are discussed to a lesser extent.

There was minimal impact of proximity to tagasaste on perennial grass survival, except when survival decreased in the light shade treatment towards the end of the study. However, increasing proximity to tagasaste severely reduced

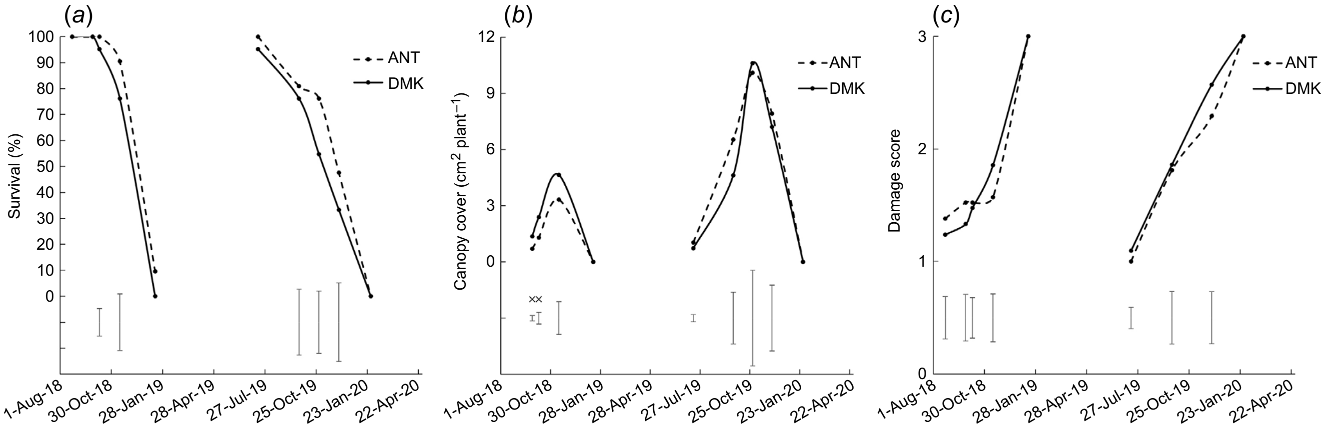

Fig. 9. (*a*) Survival, (*b*) canopy cover per plant , and (*c*) damage score of subterranean clover cvv. Antas (ANT) and Denmark (DMK) averaged over the heavy shade, light shade and open pasture treatments. Error bars represent the standard error of the difference for each measurement date. x, $P < 0.001$.

Table 6. Total annual herbage production, average canopy cover and average damage score for Antas (ANT) and Denmark (DMK) subterranean clover in 2018 and 2019.

	Measurement	Shade treatments					Cultivar treatments				Interaction *P*-value
		Heavy	Light	Open	s.e.d.	*P*-value	ANT	DMK	s.e.d.	*P*-value	
2018–19	Total dry weight (g DM plant^{-1})	2.0	5.4	5.8	1.88	n.s.	3.5	5.3	1.58	n.s.	n.s.
	Average canopy cover (cm^2 plant^{-1})	1.1	1.4	1.5	0.24	n.s.	1.2	1.5	0.25	n.s.	n.s.
	Average damage score (1–3)	2.2	2.1	2.2	0.08	n.s.	2.1	2.2	0.06	n.s.	n.s.
2019–20	Total DM (g DM plant^{-1})	3.6a	6.6a	25.7b	3.55	<0.001	12.0	12.0	3.65	n.s.	n.s.
	Average canopy cover (cm^2 plant^{-1})	2.9a	2.8a	8.1b	0.71	<0.001	4.9	4.3	0.72	n.s.	n.s.
	Average damage score (1–3)	2.2b	2.2b	2.0a	0.08	0.053	2.1	2.1	0.06	n.s.	n.s.

Means of shade treatments are averaged over cultivars and means of cultivars are averaged over shade treatments.
s.e.d., standard error of the difference; n.s., not significant.
Within rows and shade or cultivar treatments, means followed by the same letter (or no letter) are not significantly different ($P > 0.05$). Interaction *P*-value is for the shade treatment × cultivar interaction.

herbage production, canopy cover and the content of soluble sugars, increased the contents of crude protein and ash, and had negligible effect on plant damage, ME and NDF. As hypothesised, there were differences in how the species responded to the shade treatments as demonstrated by the interactions.

Cocksfoot was the most productive of the grass species and has been recommended for dry hill country where perennial ryegrass fails to persist (Lolicato and Rumball 1994). Survival was high, with >75% of transplants surviving for the duration of the study. Although its production was suppressed under shade more than some of the other species such as prairie grass, it was still the most productive species in terms of both quantity and quality, with a high content of ME and crude protein when shaded.

Peeters (2004) noted that cocksfoot 'tolerates shade very well, for instance in old orchards' (p. 129). It was abundant in the resident pasture at the field site. Others have also found cocksfoot to be tolerant of shade under controlled conditions, although effects are cultivar-dependent (Lin *et al.* 1998). By contrast, Grime *et al.* (2007) found in their survey of British flora that cocksfoot was much more common in unshaded environments, disturbed habitats, wastelands and grasslands than in woods and plantations and shady environments. Douglas *et al.* (2006) recommended cocksfoot for use in lightly shaded and lightly grazed poplar (*Populus* spp.) silvopastures, where it established and grew well. The ability of cocksfoot to tolerate shade may be moderated by the defoliation regime; cocksfoot swards can deteriorate under heavy grazing and are sensitive to trampling (Peeters 2004). Possibly, the defoliation regime for the spaced plants in our study was not optimal for cocksfoot and reduced its productivity, particularly when heavily shaded by tagasaste.

Perennial ryegrass can grow in a wide range of microsites in New Zealand hill country owing to its large genotypic and phenotypic variation (Wedderburn and Pengelly 1991). Perennial ryegrass was not well adapted to the field site, as demonstrated by the strong decrease in survival by the end

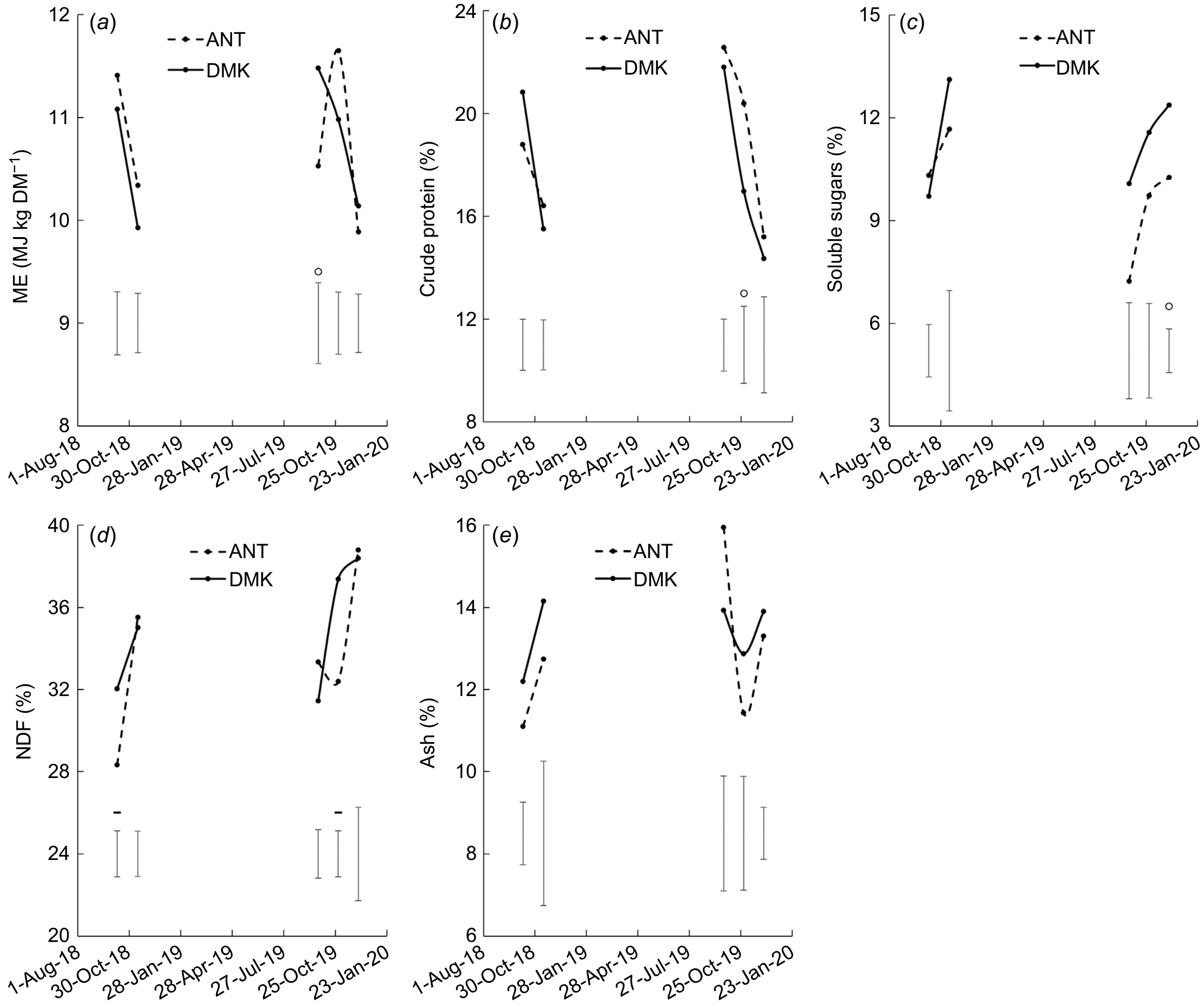

Fig. 10. (*a*) Metabolisable energy (ME), (*b*) crude protein (% of DM), (*c*) soluble sugars (% of DM), (*d*) neutral detergent fibre (NDF, % of DM), and (e) ash (% of DM) of subterranean clover cvv. Antas (ANT) and Denmark (DMK) averaged over the heavy shade, light shade and open pasture treatments. Error bars represent the standard error of the difference for each measurement date. o, $P < 0.05$; -, $P < 0.01$.

of the measurement period, when only 40% of transplants survived, and its absence in the resident pasture.

Perennial ryegrass growth was suppressed when near the tagasaste trees in the heavy and light shade treatments. This was demonstrated by a reduction in perennial ryegrass herbage production, canopy cover, ME content and soluble sugar content, and an increase in plant damage and NDF content with shading. In their floristic survey of Britain, Grime *et al.* (2007) found that perennial ryegrass was absent in shaded environments such as woodlands, plantations and hedgerows and negligible where the soil pH was <5. Peeters (2004) also noted that perennial ryegrass is not tolerant of shade, is sensitive to drought and is best adapted to mild and wet climates. At this field site, there was shade, low soil pH (averaging 5.3), drought for three consecutive summers (comparing the average monthly rainfall with the long-term monthly rainfall in fig. 1 of Tozer *et al.* 2023), and consequently low soil moisture content, which decreased to ~15% during summer. If rainfall had approached the long-term average, the outcomes for ryegrass may have been considerably different.

Although prairie grass was assessed for only 2 years, its survival had decreased to 70% by the end of the study and was similar to that of the 3-year-old cocksfoot. Webby *et al.* (1990) also found that prairie grass failed to persist for more than three growing seasons in summer-wet hill country of the Upper North Island of New Zealand. Prairie grass was more tolerant of shading than perennial ryegrass and cocksfoot. Its herbage production, canopy cover, plant damage and NDF content were unaffected by proximity to tagasaste, although the content of soluble sugars declined. Prairie grass is heat- and drought-tolerant (Peeters 2004) and can be productive over summer in hill country of the North Island of New Zealand, given appropriate grazing management (Sithamparanathan 1979). It is also more tolerant of shade than perennial ryegrass owing to its more upright growth habit (Langer 1970).

Microlaena was the grass most tolerant of shading, as demonstrated by the lack of significant shade-treatment effects on herbage production, canopy cover, plant damage, and contents of ME, soluble sugar, NDF and ash. In pastures in the Northern Tablelands of New South Wales, Australia, microlaena is prevalent in swards under shade trees frequented by resting livestock, near the edges of sheep camps and around tree stumps (Whalley *et al.* 1978; Magcalemacandog and Whalley 1991), indicating that it is shade-tolerant and can withstand intensive trampling. It also forms pure swards under trees in New Zealand (Smith 2005). Microlaena has a rhizome a few centimetres below ground, which can enable it to recover after close grazing and drought (Mitchell 2013; Mitchell *et al.* 2016). The ability of microlaena to produce low levels of forage in heavy shade and withstand trampling confers some advantages over cocksfoot for dry, shady areas, although its lack of herbage production and low nutritive value compared with perennial ryegrass and cocksfoot limit its usefulness as a pasture species. Microlaena is present in North Island hill-country pastures such as those where this study was conducted (e.g. Smale *et al.* 1997) and was the most abundant species in both the shade and open resident pasture treatments. If the environment is not suitable for perennial ryegrass, cocksfoot or prairie grass, such as in dry areas subject to heavy shade, microlaena could enable the maintenance of groundcover, despite summer droughts and stock trampling. Microlaena lines have been selected for grazing in Australia, but it is expensive to purchase, it cannot be established using standard drilling methods, and its establishment is sporadic over an extended period, which leaves it vulnerable to weed ingress (Whalley and Jones 1997). The most realistic option is to manage existing swards of microlaena in New Zealand hill country to maintain groundcover where more desirable pasture species are unable to survive.

The prevalence of microlaena in the resident pasture as described in Tozer *et al.* (2023), and its ability to produce a similar yield in the open and in light shade, would also explain why the yield of resident pasture was similar in open pasture and light shade. If tagasaste had been more widely spaced so that there was less shading, and the resident pasture had been dominated by other species such as perennial ryegrass, there may have been a much greater decline in pasture production with increasing proximity to tagasaste.

Performance of perennial legume species

Legume survival was low regardless of the shade treatment; legumes were much less resilient than the grasses and were highly susceptible to disease and insect damage. Poor survival of test legume species in this study is consistent with the absence of legumes in the resident pasture.

The lack of persistence of legumes in pastures has been attributed to selective grazing by livestock and competition with grasses (Haynes 1980; Hoveland 1989). In this study, stock were excluded from the plots and the plants were spaced to reduce competition with neighbouring pasture species. Other factors such as moisture-deficit stress, heat stress, shading, pest invertebrates and disease pressures were the more likely causes leading to their demise (Hoveland 1989; Benavides *et al.* 2009). Although it is not known which invertebrate pests were present, clover root weevil (*Sitona lepidus* Gyllenh) is abundant in New Zealand and causes severe damage to pasture legumes (Zydenbos *et al.* 2011).

Shading reduced legume herbage production severely in the first year, after which production was low for all legumes regardless of the shade treatment. However, there were differences in how the legumes responded to shade.

During the first 18 months, lotus was the most productive of the legumes with the highest survival, but its productivity was severely suppressed by shading compared with red clover and white clover. This was demonstrated by a reduction in herbage production, canopy cover, and contents of ME and soluble sugars with increased proximity to tagasaste, and an increase in the content of NDF. Lotus is best suited to damp, acidic, low-fertility soils with infrequent defoliation (Sheath 1980; White 1995; Grime *et al.* 2007). Although lotus was found to be more tolerant of shading than white clover or subterranean clover in a pot study when moisture was not limiting (Devkota *et al.* 1997), its absence from woodlands and plantations in a survey of British flora (Grime *et al.* 2007) suggests that its shade tolerance is low. The combination of frequent defoliation and low soil moisture content, particularly under the tagasaste canopy, is a likely reason for its lack of persistence in this study.

White clover was largely unaffected by proximity to tagasaste. This may reflect that it was the most unproductive of the perennial legumes with high levels of plant damage, such that shading had little additional impact. Given the multiple summer droughts that occurred and low soil moisture content, low productivity of white clover is to be expected. White clover is typically associated with higher rainfall, summer-wet pastures in New Zealand, and its persistence is compromised by drought (Knowles *et al.* 2003). Grime *et al.* (2007) also found that white clover was not tolerant of drought, and was not present in woodland or plantation habitats in Britain. Severe shading (by ~80% of full sunlight) reduced white clover productivity by up to 93% in mixtures of perennial ryegrass and white clover under controlled conditions simulating different shading patterns of trees (Ehret *et al.* 2015). White clover was also found to be less tolerant than lotus of shading (Devkota *et al.* 1997). Possibly, shade in our study ameliorated drought stresses experienced by white clover, because plant damage was lower under light shade than in open pasture in the first year, and the contents of

ME and ash were higher under heavy shade than open pasture in autumn 2019.

Red clover produced more herbage than white clover. Suckling (1960) also found red clover to be more productive than white clover in summer-moist hill country in the Central North Island. However, its productivity was reduced by increased proximity to tagasaste and there was an increase in plant damage and a reduction in the ash content as shading increased. The ability of red clover to tolerate shading depends on temperature and moisture-deficit stress (Gist and Mott 1957), both of which occurred during the study. Grime *et al.* (2007) found that it was abundant in moist environments, absent from woodlands and not tolerant of shade.

Subterranean clover test cultivar performance

Subterranean clover cultivars vary in the extent to which they can tolerate shade (Mauromicale *et al.* 2010). In our study, the two cultivars tested were similarly affected by shade, which reduced their productivity (i.e. herbage production and canopy cover) and increased visual signs of damage in the second year. Mauromicale *et al.* (2010) found that cultivars which established and grew rapidly were more able to tolerate shade than those with a slower growth pattern. The two cultivars in our study had similar growth patterns, so it is unlikely that differences in shade tolerance would be detected based on their growth habit.

Species mixtures for a tagasaste silvopasture

A tagasaste silvopasture may require periods of infrequent and lax grazing to limit overgrazing of the more slowly regenerating tagasaste. This may enhance the persistence of legumes in a tagasaste silvopasture. White clover, red clover and lotus can benefit from infrequent and lax defoliation during their reproductive period and during drought to enable seed production and protect the carbohydrate reserves. Subterranean clover must also be grazed lightly to enable the seed production necessary for its continued regeneration (Sheath 1980; Brock *et al.* 2003; Stevens *et al.* 2020; Moss *et al.* 2022). Given the lack of persistence of legumes in our study, we suggest that a less frequent and/or less severe defoliation regime may be required to improve legume persistence.

Perennial ryegrass, cocksfoot and prairie grass can also benefit from grazing exclusion during their reproductive period in late spring–summer. This enables reseeding and stimulates regrowth tillering when conditions are suitable for growth in autumn (Hume *et al.* 1990; Dowling *et al.* 1996; Tozer *et al.* 2021). In our study, all species were defoliated at the same time. However, each species has different functional traits that necessitate different defoliation management strategies to maximise their production and persistence (Duru *et al.* 2005). Grazing frequency and intensity would therefore need to be tailored for the sown pasture species. Further research is required to develop grazing guidelines for a tagasaste silvopasture to ensure persistence and productivity of both the pasture and woody components.

Based on our results, there are several possibilities for understorey mixtures that require further investigation. Cocksfoot–subterranean clover mixtures have been regularly sown in dryland environments in New Zealand where summer droughts are recurrent and the inclusion of subterranean clover can lead to significant increases in pasture yield (Ates *et al.* 2010). Subterranean clover can be oversown (e.g. White *et al.* 1972). Hard grazing or herbicide application prior to oversowing is critical to reduce competition with resident pasture species and allow establishment (Tozer and Douglas 2016). Alternatively, hill country pastures can also be managed to increase the content of subterranean clover when drilling is not possible (Olykan *et al.* 2019). Microlaena can also grow well with cocksfoot (Magcalemacandog and Whalley 1991) and could occupy the shadier areas in a tagasaste silvopasture to which cocksfoot is less suited. The intended use of the mixtures is also to be considered. In this study, we have focused on characteristics such as herbage production and nutritive values for improving livestock production. If other ecosystem services are required (e.g. pollination or erosion control), other characteristics such as flowering duration and root length should be considered (Hanisch *et al.* 2020).

An alternative strategy could be to introduce lotus when establishing a tagasaste silvopasture, which is fenced to exclude livestock for several years during the tagasaste establishment period. This may enable lotus to establish and ensure its persistence, even in drought-prone areas. In the central northern area of the North Island of New Zealand, lotus comprised >50% of total DM in Years 3–5 on oversown, drought-prone, low-fertility landslips that had been fenced for the first 2 years to exclude livestock (Lambert *et al.* 1993). To avoid the high levels of lotus mortality that occurred in our study, grazing post-establishment would need to be infrequent (e.g. three or four times each year) and competition with grasses would also need to be managed (Charlton and Brock 1980).

Conclusions

Cocksfoot shows potential for sowing on summer-dry hillsides between and under trees in a tagasaste silvopasture. In close proximity to tagasaste, where growth of all species is strongly suppressed, microlaena may provide limited, low-quality forage, but may assist in maintaining pasture cover, which has environmental benefits.

Lotus could be oversown when establishing a tagasaste plantation in which grazing is excluded during the first few years. However, it may be difficult for perennial legumes to persist beyond several years in a tagasaste silvopasture subject to dry summers with high temperatures, especially when growing near tagasaste. In these environments, subterranean clover may be a more useful companion legume for cocksfoot.

Spaced-plant studies are useful for screening of species, but larger scale studies are required before establishment and management guidelines for a tagasaste silvopasture can be developed. We recommend that: (1) research is undertaken on establishing cocksfoot–subterranean clover mixes in tagasaste silvopastures; (2) strategies be developed to increase microlaena abundance in the shadier areas; (3) lotus establishment strategies are developed for summer-dry hill country in new plantings of tagasaste from which stock are excluded; (4) the research is expanded to different environments; and (5) the value proposition for such a system in hill country is developed.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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