Agroforest Syst (2011) 81:157–173
DOI 10.1007/s10457-010-9319-6

Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system?

A. C. Varella · D. J. Moot · K. M. Pollock · P. L. Peri · R. J. Lucas

Received: 31 January 2010 / Accepted: 1 June 2010 / Published online: 22 June 2010

Abstract Shade cloth is commonly used in agroforestry research. It produces a continuous, uniform reduced light environment. Shade cloth and a slatted structure were compared in relation to the inability to represent the light regime and plant responses of an agroforestry system. The split-split-plot randomised block experiment had main plots as covering status (with or without radiata pine trees), subplots as artificial shade (none, shade cloth or wooden slats) and sub-subplots as growth rotation, over sown alfalfa, in three replicates. The quantity of light transmittance was 49% under trees, 41% under cloth and 44% under slats. Temporal changes and spectral composition under trees were more accurately reproduced under the slats than shade cloth. The red to far red ratio was 0.64 under tree shade and 0.74 during the shaded period under slats. This compared with 1.31 in open pasture, 1.28 under shade cloth in open and 1.26 under slats during sunny periods. To compensate for low light quantity and quality, alfalfa had elongated stems and internodes. In open pasture and under cloth in the open, it produced short stems. The mean dry matter yield under trees was 68% of the 30.3 t ha^{-1} in open pasture, 56% under cloth and 57% under slats. The slats induced similar morphological responses in alfalfa to those in the agroforestry system. The magnitude of changes had little effect on growth and yield responses. The artificial slatted structure approximated the intermittent light environment and consequent plant responses observed in an agroforestry system.

Keywords Lucerne · Radiata pinus · Photosynthesis · Radiation use efficiency · Silvopastoral · Transmittance

A. C. Varella (✉)
Embrapa (The Brazilian Agricultural Research Corporation), BR 153, Km 603, P.O. Box 242, Bage, RS, Brazil
e-mail: avarella@cppsul.embrapa.br; varellanz@hotmail.com

D. J. Moot · K. M. Pollock · R. J. Lucas
Faculty of Agriculture and Life Sciences Division, Lincoln University, Canterbury, New Zealand
e-mail: moot@lincoln.ac.nz

K. M. Pollock
e-mail: pollockk@lincoln.ac.nz

R. J. Lucas
e-mail: lucasr@lincoln.ac.nz

P. L. Peri
INTA and Universidad Nacional de la Patagonia Austral, Austral, Argentina
e-mail: pperi@correo.inta.gov.ar

Introduction

In agroforestry research, artificial shade materials are used to replicate the effects of tree shade on understorey vegetation. Shade materials are used to screen plants for yield, quality, morphological and physiological responses. Often the aim is to select appropriate species or cultivars for widespread use as understorey plants in agroforestry systems. The success of the selection process is therefore dependent on the accuracy with which the artificial shade mimics the light environment and the plant responses to them. The most common artificial shade material used is plastic cloth (Devkota et al. 1997; Lin et al. 2001; Varella et al. 2001b; Baldwin 2009). This is easy to handle, light weight and manufactured in different colours and levels of light transmittance (Yates 1989). Under cloth shade, plants experience a continuous and uniform shade regime usually at predetermined light transmittance level for comparative purposes. However, shade cloth might not reproduce the periodic fluctuations in radiation transmittance and spectral composition more characteristic of a widely spaced conifer tree crop (Varella et al. 2001a, b; Wilson and Ludlow 1991; Gaskin 1965; Turnbull and Yates 1993). This is because understorey plants may experience periods of near full sun to near full shade (dense shade) as the sun passes overhead, particularly in low stocked plantation forests. In these circumstances a continuous uniform light regime only occurs during periods of moderate to heavy overcast sky conditions. Despite this, research has traditionally focussed on the mean daily light transmittance with almost total neglect for the sun/shade fluctuations induced in agroforestry environments. In this study cloth and wooden slatted artificial shade structures are compared to: (1) examine how closely they mimic the radiation environment of a radiata pine—alfalfa agroforestry system and (2) the consequent responses of the understorey alfalfa plants.

Materials and methods

This experiment was located at the Lincoln University agroforestry area, Canterbury, New Zealand (43°39′S and 172°28′E). The soil is classified as a Templeton silt loam in the New Zealand soil classification system (Udic Haplusteps in the U.S. Soil Taxonomy system) and consists of 1–2 m of fine alluvial sediments over gravels. Textures in the layered portion range from heavy silt loams to sands. Gravels are found below 1.6 m depth (Karageorgis et al. 1984). It is medium to free-draining with a moderate capacity to hold moisture at 320 mm in the top one metre (Watt and Burgham 1992). The soil is considered a productive cropping soil and is used for annual crops, ryegrass and white clover seed production and intensive pastoral grazing.

Prior to establishment of the trees, the experimental area was cropped with peas (*Pisum sativa* L.) in the 1989/1990 season. The area was then established in two parts. The first covered 5.2 ha and was a split-plot randomised block design with three replications. The six main plot treatments were various understorey pasture combinations aimed at providing a range of competitive swards under trees. They were: (i) bare ground; (ii) phalaris + clovers (white, red and subterranean clover); (iii) cocksfoot + clovers; (iv) perennial ryegrass + clovers; (v) alfalfa and (vi) some weeds dominated by *Polygonum aviculare*. Sub-plot treatments within these main plots compared five different tree genotypes of radiata pine. Four of these were clones produced by tissue culture by Tasman Forestry Ltd at Te Teko. The fifth was a seedlot of low genetic improvement. The second part of the experimental area was established in an open field adjacent to the agroforestry site. It covered 1 ha and had three replicates of the same pasture mixtures, but without trees (Mead et al. 1993). In the forested experimental area, trees were initially planted at 1000 stems ha^{-1} (7 × 1.4 m) in 1990, thinned to 800 stems ha^{-1} in 1992, to 600 in 1993, 400 in 1994 and finally to 200 in 1996, maintaining a 7 m space between rows and an average spacing within rows of 7 m.

In 1997, the *Phalaris aquatica* L. understorey and open pastures were sprayed with hexazinone at 2.5 kg a.i. ha^{-1} and resown with semi-dormant 'Kaituna' alfalfa (*Medicago sativa* L.). This was direct drilled into the plots at 10 kg ha^{-1} of coated seed. These six alfalfa plots (three in the full sun and three under trees) were used for this experiment from September 1999 to March 2001 which included nine alfalfa regrowth cycles. The average tree height ranged from 10.0 to 12.5 m and diameter at breast height (DBH) ranged from 210 to 256 mm during the experimental period (Peri et al. 2002). Trees had been pruned to a height of 6 m 1 year before this experiment. The experimental design was a split-split-plot randomised block with the main plots as covering status (with or without radiata pine tree cover), subplots as artificial shade structures (none, shade cloth or wooden slats) and growing rotation as a sub-sub plot in three replicates. Therefore, this imposed six light regimes on the unirrigated alfalfa crop. In this manuscript, treatments are identified as: (i) open pasture or full sunlight (FS); (ii) cloth in the open (FS + CL); (iii) slats in the open (FS + SL); (iv) trees (T); (v) trees plus cloth (T + CL) and (vi) trees + slats (T + SL). The main plots were 46.2 × 42.0 m (0.194 ha) under trees and 27.5 × 18 m (0.05 ha) in the open field. For this experiment, the subplots of artificial shade structures were set in the middle of the 7.0 m wide inter-row under trees and in the centre of open field plots, both orientated in an east–west direction (112°–292°). The subplot study areas were 2.5 m long × 2.5 m wide for the shade cloth and 5 m long × 2.5 m wide for the slatted structure. The control subplot had no artificial shading and was located adjacent to the two shade structures and covered a 5 m long × 2.5 m width area (Fig. 1). Analyses were performed for dry matter yield, radiation use efficiency (RUE), plant morphology and photosynthetic photon flux density (PPFD), instant net photosynthetic rate (Pn) and spectral composition.

The mean daily temperature was 11.4 ± 3.4°C under trees and 11.2 ± 3.3°C in the adjacent full sun area from September 1999 to March 2001. On a typical winter day at the experimental site, mean daily temperature was 0.4°C warmer under trees than in the open with maximum differences of 1.9°C at 15.00 h. Similar results were observed for a typical summer day when mean daily temperature was 0.6°C warmer under trees than in the open and maximum differences were 1.6°C between 10.00 and 15.00 h. Annual rainfall was similar to the long-term mean (659 mm) in 1999 (625 mm) and 2000 (668 mm), but below (419 mm) average in 2001. Monthly rainfall at the experimental site was below the long-term means from April to May 1999 and from December 2000 to March 2001. Mean annual potential evapotranspiration is near 1000 mm so there are usually periods of severe soil moisture stress during the summer (Pollock et al. 2009).

The shade structures using solid slats and shade cloth were the same as those described by Varella et al. (2001b) and Varella (2002) to examine alfalfa response to continuous shade and intermittent shade but in the absence of trees. The design of the shade slats and support structure had to meet a number of criteria:

1. Provide near full sunlight light and shade to the alfalfa canopy at a similar periodicity as the spaced trees in the pine agroforestry area during sunny conditions for several hours either side of noon.

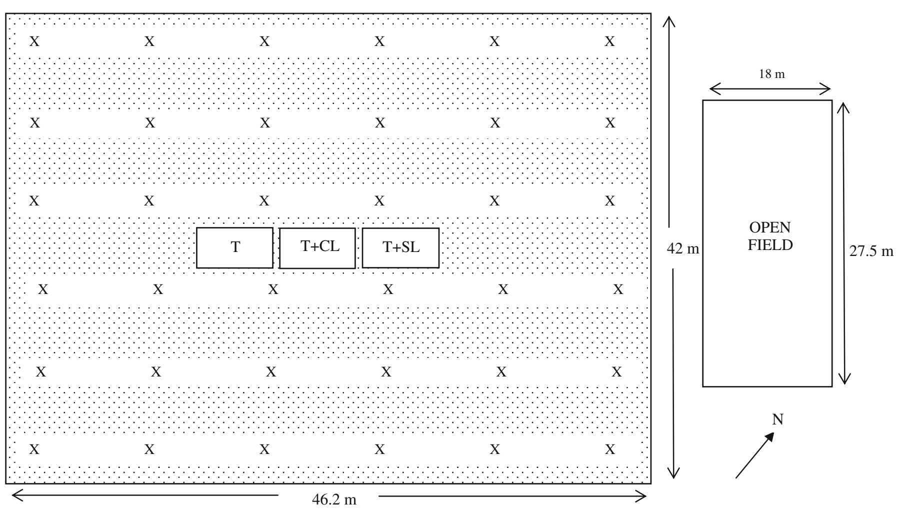

Fig. 1 Diagram of main plots established in *open field* and under the agroforestry and subplots (T; T + CL; T + SL; FS; FS + CL and FS + SL) at the experimental site in Canterbury, New Zealand. *X* individual trees with 7 × 7 m distance, *T* subplot pasture under tree (5 m long × 2.5 m width), *T + CL* subplot pasture under shade cloth under trees (2.5 m long × 5 m width), *T + SL* subplot pasture under wooden slats under trees (5 m long × 2.5 m width), *dotted area* underneath pasture area

2. Provide about 50% shade, i.e., similar to the shading factor of the agroforestry midway between tree rows.
3. Slats had to be relatively thin (20 mm) to avoid excessive shading during early morning and late afternoon.
4. Be of sturdy construction to avoid being blown away in strong winds, but light weight to remove for intermittent grazing by sheep.
5. Have removable sections to enable periodic measurement of alfalfa plants.
6. Be sufficiently large to allow a representative sampling area underneath yet small enough to meet condition 4.

The major compromise was that the shade slats were horizontal rather than vertical like trees. To ensure that the periodicity of direct sunlight and shade under slats was similar to the radiate-pine agroforestry, the ratio of slat spacing (width of slat plus width of gap between slats) to slat height above the alfalfa canopy was kept similar to the ratio of tree crown spacing to the crown distance (*D*) from its shadow (ca. 1:1.15). The distance, *D* (which is also the path length of a beam of sunlight from a gap opening between trees to the alfalfa canopy), was $h/\cos(\phi)$ where *h* was the height (7 m) of the widest part of the crown and ϕ was the solar zenith angle. *D* was calculated for a solar zenith angle of 30°, the average midday zenith angle in summer at this location (Fig. 2; Plate 1c). A ratio of 1:1 for the slat

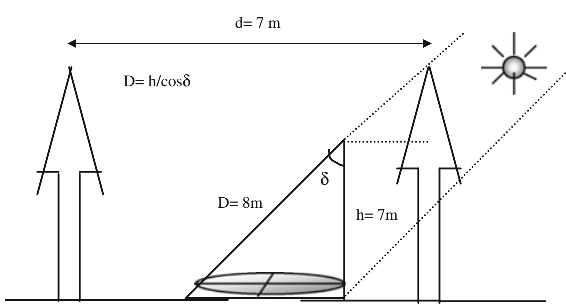

Fig. 2 Schematic representation of the Lincoln University agroforestry area on which the slatted structure construction and shade cloth rating were based. *H* is the actual distance of shadow from tree crown; *h* is the distance from tree crown to top of canopy; *d* is the mean distance between trees within the row and δ is the average solar zenith angle (30°) for summer in Canterbury, New Zealand. The ratio *D*:*d* (8 m:7 m) from the agroforestry site was kept similar to the ratio of slat spacing (300 mm) to slat height above the alfalfa canopy (300 mm)

plus gap width to height above canopy was chosen as a reasonable design objective to mimic the tree situation.

Physically the slatted structure had 0.15 × 2.4 m pine wood slats (painted white on top) and 0.15 m gaps between each slats covering the total area of 2.4 × 5.2 m. The same width for the slats and gaps was designed to produce a theoretical light transmittance of about 50%. This structure was supported horizontally on a vertically adjustable metal pipe frame, which allowed the slats to be kept at 0.30 m above the alfalfa canopy. The selection of slats positioned at 0.3 m above the alfalfa canopy was a compromise between the construction issues and having equivalent light periodicity to the agroforestry area. The 1:1 ratio of slat spacing to distance from alfalfa canopy achieved the desired periodicity of light similar to that in the agroforestry area.

Shade cloth produces a continuous and diffuse light regime, but the aim was to produce a similar level of light transmittance to the agroforestry environment. Thus, black plastic shade cloth with a nominal 50% light transmittance was purchased from a commercial supplier and used to cover an adjacent 2.3 × 1.8 m area. The shade cloth structure had an overhang of 0.40 m of material at both the East and West ends to prevent direct radiation on plants at low solar elevation angles. The cloth and slatted structures were supported on the same metal pipe frame, adjusted weekly to maintain the 0.30 m height above the elongating alfalfa crop canopy. Shade cloth and wooden slat structures were set in the field on 9th September 1999. Shorn Coopworth ewe lambs were rotationally grazed as required in the alfalfa plots in the open and under trees for 6 ± 2 days after 36 ± 12 days regrowth. Sampling areas were isolated from grazing until alfalfa reached the bud stage and the stock only had access to the measurement area for 362 days.

Light measurement

The PPFD of treatments was monitored with four quantum sensors (LI-190SB, Lincoln, USA), one pair under trees and one pair in the open pasture. One sensor of each pair was above the shade structure and the other alternately placed below either cloth or slats every 15 days. Each pair of sensors was moved at 30 day intervals to another replicate (Plate 1a, b). For the slatted structure, one sensor was installed directly on top of a wooden slat and the canopy level sensor was installed directly under the edge of a slat near the middle of the shade structures. As the sun elevation angle changed over the day, sensors were exposed to alternating periods of full sunlight and slat shade. For the shade cloth, one sensor was installed immediately above the shade cloth and another one below that, keeping it at canopy height. PPFD data was continuously recorded every 30 s and averaged for 15 min intervals using two dataloggers (Datataker DT100, Roseville, Australia). Mean radiation PPFD transmittances were calculated on a daily basis.

Spectral radiation data were measured with a portable Spectroradiometer LI-1800 (LI-COR Inc., Lincoln, USA). Readings were the average of five scans and were taken between the wavelengths of 300 and 1100 nm at 5 nm intervals. Measurements were performed on three occasions: on 7th March 2000 for a partial overcast day at 12.00 PM (51.6° solar elevation angle), on 10th October 2000 for a sunny and clear day at 12.30 PM (52.6° solar elevation angle) and on 11th October 2000 for a cloudy day at 12.30 PM. In addition, spectral composition measurements were taken in two light situations when fluctuating light was observed (Plate 1c, d): (i) during full sun period (FS + SLsun, Tsun, T + CLsun and T + SLsun) and (ii) during the shaded period (FS + SLsh, Tsh, T + CLsh and T + SLsh). The differences in spectral radiation between treatments focuses on the proportions of red (R = 600–700 nm) and far red (FR = 700–800 nm) wavelengths to the total short wave radiation (PPFD + FR = 400–800 nm). The red (660 nm) to far red (730 nm) ratio (R:FR) was calculated for all treatments.

Calculations for canopy radiation interception used data collected from the canopy analyser (LAI 2000, LI-COR Inc., Lincoln, USA). Readings were taken in predominantly diffuse light conditions at 7–10 day intervals. The equipment was set to take two series of one reading above and five readings below the canopy (50 mm above the ground level) in each plot. The same equipment automatically calculated the proportion of diffuse light transmittance (DIFN) at ground level. The final DIFN values result from the integration of five different zenith angle readings (7, 23, 38, 53 and 68°) measured by the canopy analyser. The above and below canopy readings for the cloth treatment were taken immediately under the shade material when light conditions were uniform and predominantly diffuse. However, for the slatted structure, wooden slats were removed completely for the measurement period (2–5 min) to take the above and below canopy readings and to avoid inaccuracies due to the fluctuating light regime. Light transmittance within the canopy was assumed to be equal to the DIFN value. The canopy radiation interception (%) in diffuse light conditions was calculated as (1-DIFN) × 100.

Agronomic measurements

Measurements of alfalfa yield, physiology and morphology were also collected. The dry matter (DM) yield was measured prior to grazing at the end of each of the nine regrowth periods. Samples were cut from a 0.2 m^2 quadrat at ~0.05 m above ground level to avoid damaging alfalfa crowns. From these main samples, a randomised sub-sample of at least 100 g fresh matter was selected to measure leaf to stem ratio (L:S). At the beginning of each rotation five dominant stems from different plants were marked in the centre of each treatment to measure stem height (STH) and internode length (INTNOD). These morphological responses were measured at the end of each rotation over the experimental period. New plants were marked at the beginning of each rotation.

Estimates of RUE were based on final DM yield in each rotation and accumulated PPFD intercepted (PPFDi) by the canopy over the rotation period. Effectively, RUE was calculated as the coefficient of slope for the regression line obtained between mean shoot dry matter (g m^{-2}) and accumulated intercepted photosynthetically active radiation (PAR in MJ m^{-2}) for each rotation period. Estimates of intercepted PAR (PAR_i) were calculated according to Gosse et al. (1982) for an alfalfa canopy:

$$PAR_i/PAR_o = 0.97 * [1 - \exp(-LAI * k)]$$

where PAR_o is the incident PAR above the canopy (in full sun and under the cloth and slat structures) and LAI was assumed to be the green area index measured by the canopy analyser. Light flux (μmol photons m^{-2} s^{-1}), measured by the quantum sensors in each treatment, was converted to PAR units (W m^{-2} = J m^{-2} s^{-1}) and used as daily accumulated PAR_o values (1 W m^{-2} = 4.61 μmol photons m^{-2} s^{-1}). Specific extinction coefficient (k) values for each treatment were calculated based on data collected from the canopy analyser and calculated from Beer's Law.

Potential leaf net photosynthesis rate (Pn) was measured on three of the youngest fully expanded leaves per treatment at the late vegetative stage for six rotation periods from October 1999 to December 2000. Measurements were performed at an artificial light flux (PPFD) of 1000 μmol photons m^{-2} s^{-1}, using a portable infra-red gas analyser (LI-6400, LI-COR Inc., Nebraska). Readings were taken in each of the six different light regimes. In addition, under the intermittent light regimes (T, T + CL and T + SL), leaf net photosynthesis rates were taken in two extra light regimes: (i) during the sunny and (ii) during the shaded periods as it was measured for spectral composition. In addition, the weighted average for photosynthesis rates over the experimental period was calculated. These were weighted under the intermittent regimes by the average length of time in which leaves were exposed to shade and full sun during sunlight hours or between 5.45 and 19.45 h in summer. According to PPFD readings, alfalfa under trees experienced near full sun for 68% of the time and was under tree crown shade for 32% of the time. Under slats in the open, these proportions were 48% in sun and 52% in shade. Under cloth plus tree (T + CL), leaves were 54% of time under cloth shade only and 46% under cloth plus tree crown shade. Under the slats plus trees (T + SL), this proportion was 40% of time in full sun and 60% in slats plus tree crown shade (Fig. 3).

Results for most variables were analysed using a split-split-plot analysis of variance (ANOVA), where covering (C) status (with or without trees cover) was the main plot, shade (S) was the sub-plot (control = no artificial shade structure, shade cloth or wooden slats) and growth rotation (R) was the sub-sub plot. This analysis was performed with data collected over two growing seasons (from October 1999 to January 2001) or nine rotational grazings for plant morphology, physiology and accumulated DM yield. In addition, data were analysed for accumulated DM yield, mean STH, mean INTNOD and mean L:S ratio over the experimental period as a split-plot ANOVA where covering was the main plot and shade the sub-plot. For leaf net photosynthesis rates, because of sun/shade fluctuations under slats and trees, there were 10 light regimes as main treatments and treatments were unbalanced. Thus a complete block analysis was performed for leaf photosynthesis rates under FS, FS + CL, FS + SL (during sun and shade stages), T (during sun and shade stages), T + CL (during sun and shade stages) and T + SL (during sun and shade stages). Differences between means were tested using Fisher's protected least significant difference (LSD) test at the 5% level.

Results

PPFD

The mean daily PPFD transmittance of trees alone was higher than slats and cloth in the open in all seasons (Table 1). Overall PPFD transmittance was 49% under trees, 44% under slats in the open and 41% under cloth in the open. The radiation quantity under trees reached a maximum of 93% transmittance (1871 μmol photons m^{-2} s^{-1}) of that in the open pasture during the sun period (1100 h) and a minimum of 9% (184 μmol photons m^{-2} s^{-1}) during the shade period (1200 h) on a clear summer day. Under slats in the open, the mean PPFD transmittance was 94% of that in the open pasture during the sun periods and 6% during the shade period. In overcast sky conditions (diffuse light), the proportion of radiation transmittance under all shade treatments increased compared with a clear sunny day. Total radiation transmitted under trees and the two shade structures declined from summer to winter. Some variation in PPFD transmittances between seasons and overcast sky observed in Table 1 were possibly because of error at the sensors level whereby changes may have occurred as wind passed through the agroforestry site. The absolute period of shade under the cloth and slats treatments located within the agroforestry area was the longest because the artificial shade was in addition to tree shade. This led to these treatments having the lowest mean annual PPFD of 16% under cloth plus trees and 17% under slats plus trees.

Temporal radiation periodicity

PPFD measurements under the trees and the two artificial shade materials showed distinct light periodicity (Fig. 3; Plate 1). Specifically, an intermittent

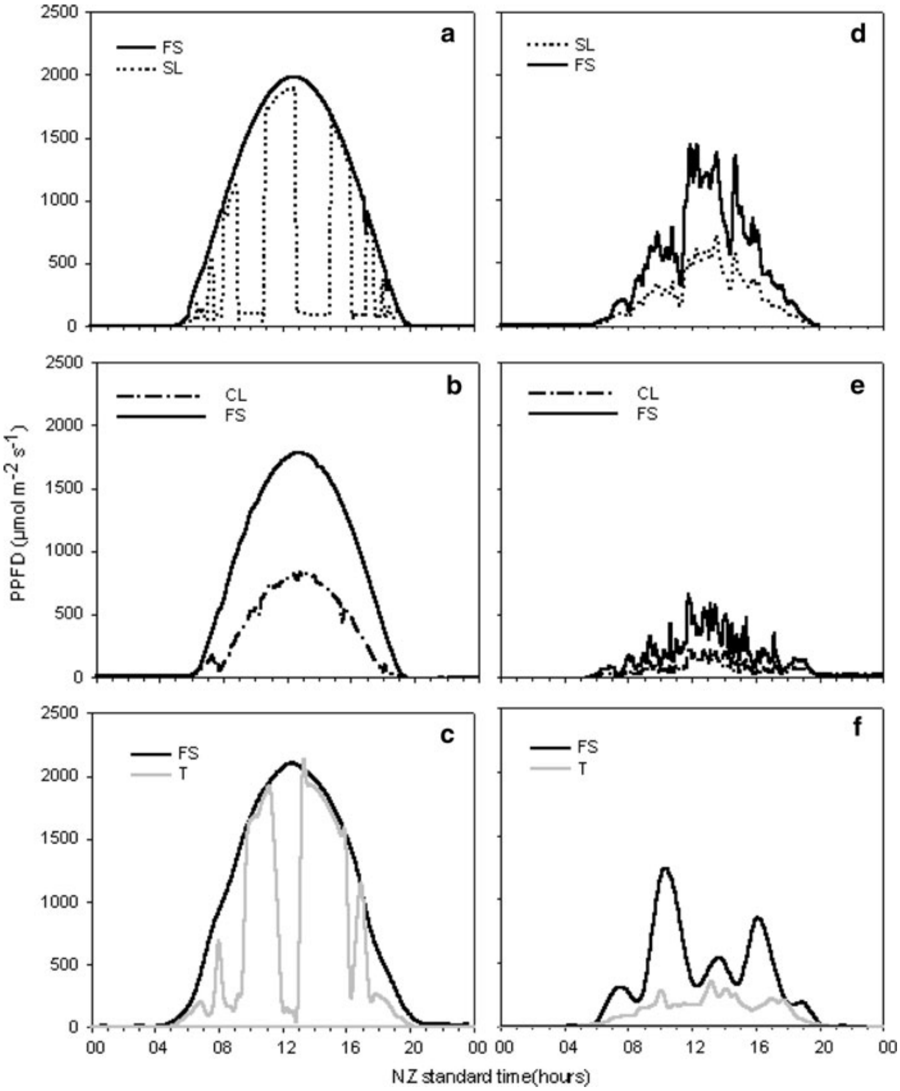

Fig. 3 Photosynthetic photon flux density (PPFD) measured in full sunlight (FS), under wooden slat (SL), shade cloth (CL) and trees (T) under typical clear sunny (**a**–**c**) or overcast (**d**–**f**) sky conditions in mid-summer (6–10th January 2000) in Canterbury, New Zealand

light regime was observed under the trees (Fig. 3c), with a maximum of 165 min of full sun and 90 min of heavy shade in summer at noon. The intermittency of light was also observed under the slatted structure with approximately equal and alternate periods of near full sunlight and heavy shade (Fig. 3a). Under slats in the open, a maximum period of 120 min of either dense shade or full sunlight was measured in mid-summer around noon. The sun and shade time course was inversed at low solar angle elevations, when 30 min of full sun and 165 min of shade were observed under trees, whereas under slats there was 50 min of light and 40 min of shade. A total of 510 min of full sunlight and 375 min of heavy shade were measured under trees on a daily basis in summer, whereas under slats in the open alfalfa plants were exposed to a total of 445 min of full sunlight and 440 min of dense shade on a daily basis in summer. Therefore, the total light periodicity measured under the trees was approximated by that under slats in the open. Light periodicity changed to 330 min of near full sunlight and 495 min of dense

Table 1 Mean daily photosynthetic photon flux density (PPFD) transmittances (relative to the incident light in the open pasture or FS) measured under shade cloth in the open field (FS + CL), wooden slats in the open field (FS + SL), under radiata pine trees (T), shade cloth under trees (T + CL) and slats under trees (T + SL) for sunny days in different seasons and for a diffuse overcast day in summer

Treatment	Summer (21/12/00) (%)	Autumn (21/03/00) (%)	Winter (21/06/00) (%)	Spring (21/09/00) (%)	Diffuse[a] (18/12/00) (%)	Mean (%)
FS	100	100	100	100	100	100
FS + CL	42 (65°)	40 (54°)	40 (24°)	40 (52°)	43 (56°)	41
FS + SL	46 (66°)	45 (43°)	41 (23°)	45 (52°)	51 (61°)	44
T	55 (70°)	48 (50°)	45 (23°)	47 (55°)	58 (70°)	49
T + CL	22 (70°)	15 (50°)	10 (24°)	16 (55°)	23 (50°)	16
T + SL	23 (70°)	16 (50°)	13 (23°)	18 (55°)	25 (70°)	17

Values in parenthesis indicate the maximum sun angle for the day when PPFD was measured

[a] PPFD measured on an overcast day

shade under the slats plus trees and 465 min of partial full sunlight (average of 40% transmittance) and 390 min of dense shade under the cloth plus trees. In contrast, shade cloth in the open produced a continuous uniform light regime of 40% transmittance compared with the open pasture (Fig. 3b). In midsummer on an overcast day, the difference in light periodicity between cloth and slats in the open was minimised and both artificial shade structures produced equivalent light regimes to those in the open field (Fig. 3d–f).

Values of PPFD within an individual tree crown shade (about 6.0 m maximum length and 5.0 m maximum width at noon) and within the slatted shade were also measured to describe variations within the crown shadow. The flux of radiation was 7% of full sunlight in the majority (70%) of the individual crown tree shade area. There was an edge area of 0.5 m inside the total shade zone where PPFD was gradually reduced from full sunlight to nearly full shade as a result of a change in the trees crown density from the edge to the mid crown area. However, wind movements across the tree branches and alfalfa stems could also have contributed to the diffuse edge effect in any of the treatments. As a consequence of the dense material, the projected shade area under the slatted structure was more severe than under trees and produced a uniform and abrupt shade (5% of full sunlight) with no gradual transmittance changes (Plate 1). Therefore, the alternating periods of sun and shade under slats in the open approximated to those observed under trees. However, trees (T) and the slatted structures (FS + SL and T + SL) were different in terms of the duration of sunlight and shade. This was mainly because of the size and shape of the shading components (tree crown and wooden slat). Under the trees, the location of the sensor could also have influenced the duration of sunlight and shade.

Spectral composition

The results showed (Table 2) the spectral composition from the tree shade was more closely reproduced by the slatted structure (FS + SLsh) than the shade cloth in the open (FS + CL). For example, under trees during a sunny period, the red to far red ratio was 1.23. This was similar to the ratio of 1.31 measured in the open pasture, 1.28 under the cloth and 1.26 under slats in the open during a sunny period. The red to far red ratio decreased to 0.64 under the shade produced by tree crown and to 0.74 under the shade of the slats in open. The amount of red and far red light (Fig. 4) was severely reduced under the shade of trees and under the shade of wooden slats. The red light decreased to 4% (0.6×10^6 w m^{-2} nm^{-1}) of that in the open pasture under the tree shade and under the slats. Similarly, the far red light decreased to 8% of that in the open pasture under the tree crown shade (0.9×10^6 w m^{-2} nm^{-1}) and 7% under the shade of slats (0.8×10^6 w m^{-2} nm^{-1}). During the sunny period under both of these intermittent light regimes (T and FS + SL), the amount of red and far red light were equivalent to that measured in the open pasture (15.4×10^6 w m^{-2} nm^{-1} for red and $11.8 \times$

Table 2 Spectral ratios between red (R) and far red (FR) wavelengths to photosynthetic photon flux plus far red (PPFDFR) and red to far red (R:FR) measured in different light regimes at noon under sunny (10 October 2000) or cloudy (11 October 2000) sky conditions in Canterbury, New Zealand (sun angle of 52.6°)

Treatment	R[a]/PPFDFR	FR[a]/PPFDFR	R:FR
Sunny day			
FS	0.342	0.262	1.307
FS + CL	0.341	0.266	1.285
FS + SLsun	0.344	0.272	1.262
FS + SLsh	0.236	0.319	0.739
Tsun	0.340	0.277	1.228
Tsh	0.218	0.339	0.644
T + CLsun	0.342	0.275	1.243
T + CLsh	0.207	0.370	0.560
T + SLsun	0.340	0.288	1.178
T + SLsh	0.182	0.395	0.461
Cloudy day			
FS	0.326	0.284	1.146
FS + CL	0.324	0.290	1.117
FS + SL	0.321	0.301	1.066
T	0.315	0.312	1.008
T + CL	0.322	0.295	1.092
T + SL	0.318	0.308	1.033

FS full sunlight, *FS + CL* shade cloth, *FS + SLsun* slats in sun period, *FS + SLsh* slats in shade period, *Tsun* tree in sun, *Tsh* tree in shade, *T + CLsun* tree + cloth in sun, *T + CLsh* tree + cloth in shade, *T + SLsun* tree + slats in sun, *T + SLsh* tree + slats in shade

[a] PPFDFR = 400–800 nm; R = 600–700 nm; FR = 700–800 nm

10^6 w m^{-2} nm^{-1} for far red light). Under the shade cloth in the open, the amount of red (7.5×10^6 w m^{-2} nm^{-1}) and far red (5.8×10^6 w m^{-2} nm^{-1}) light were reduced in proportion to the decrease in PPFD transmittance. Although the amount of red and far red light decreased under shade cloth in the open, the red to far red ratio was maintained similar to that in the open pasture and under slats in the open during a sunny period.

Under diffuse sky conditions, the differences in spectral composition between treatments were less pronounced (Table 2). It was impossible to identify distinct shade patches under the intermittent tree or slatted regimes on an overcast day and differences between treatments for red wavelengths were less evident than on clear sunny days. All spectral ratios decreased on cloudy days compared with those under clear sky conditions. The R:FR ratio was 1.01 under trees, 1.07 under the slatted structure, 1.12 under cloth and 1.15 in the open.

Leaf photosynthetic rates

The shade treatments also affected ($P < 0.001$) alfalfa photosynthesis rate on the youngest fully expanded leaves (Fig. 5). Leaf Pn rates decreased ($P < 0.001$) rapidly when exposed to shade after a period of full sun light under the intermittent light regimes. The Pn rates were lowest ($P < 0.001$) during the period of shade under trees (Tsh, T + CLsh and T + SLsh) or under the slats in open (FS + SLsh). Leaf Pn rates under shade cloth in the open (27.6 μmol CO_2

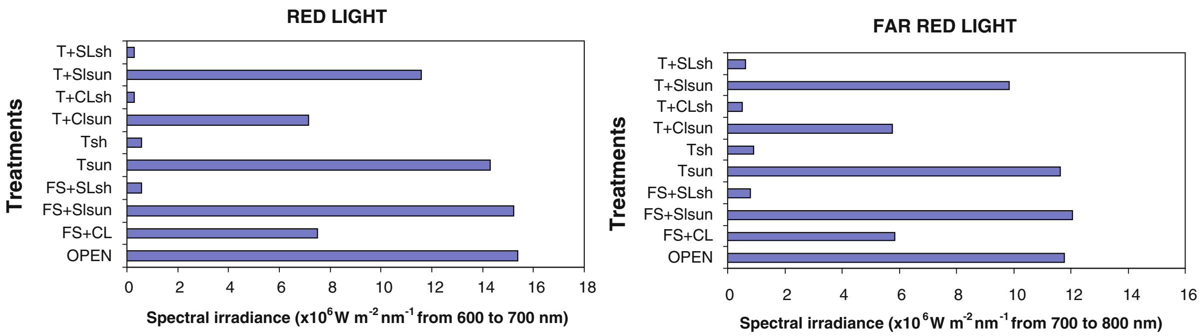

Fig. 4 Spectral irradiance for red (600–700 nm) and far red (700–800 nm) wavelengths measured under 10 different light regimes on October 10th at noon time on a clear and sunny day in Canterbury, New Zealand. Measurements were collected under: (i) full sunlight (FS); (ii) cloth in the open (FS + CL); (iii) slats in the open during sun period (FS + SLsun) and shade period (FS + SLsh); (iv) trees during sun period (Tsun) and shade period (Tsh); (v) trees plus cloth during sun period (T + CLsun) and during shade period (T + CLsh) and (vi) trees + slats during sun period (T + SLsun) and shade period (T + SLsh)

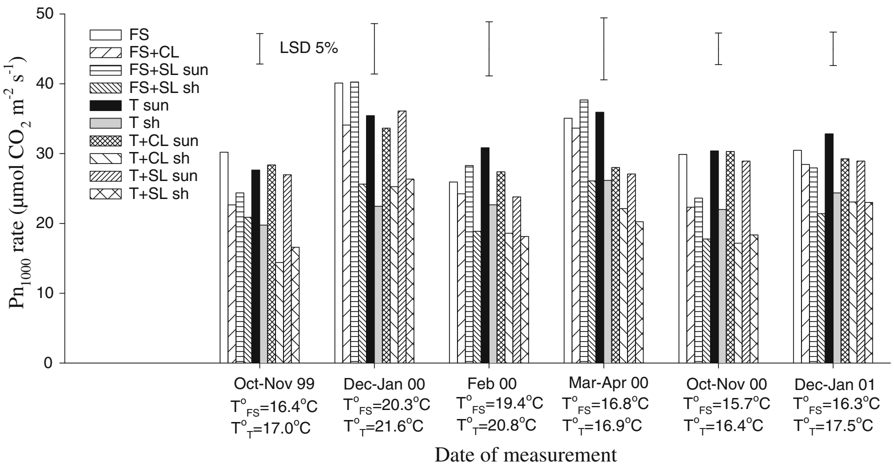

Fig. 5 Mean net photosynthesis rate at 1000 µmol photons m^{-2} s^{-1} (Pn_{1000}) of the youngest fully expanded leaf in alfalfa plots. Measurements were performed for 10 light regimes, during the late vegetative stage and at noon time, for six consecutive rotations under: FS (full sunlight), FS + CL (shade cloth), FS + SLsun (slats in sun period), FS + SLsh (slats shade period), Tsun (tree in sun), Tsh (tree in shade), T + CLsun (tree + cloth in sun), T + CLsh (tree + cloth in shade), T + SLsun (tree + slats in sun) and T + SLsh (tree + slats in shade). Instant air temperatures in full sun (T^o_{FS}) and under trees (T^o_T) at the moment Pn rate was measured are shown at the *bottom* of the graph. Data are averages of three replicates and *error bars* on the *top* indicate the least significant difference ($LSD_{5\%}$)

m^{-2} s^{-1}) were also lower ($P < 0.001$) than in open pasture (31.9 µmol CO_2 m^{-2} s^{-1}). Photosynthesis was similar during a sunny period under trees and under the slats in the open to that in the open pasture. When weighted averages were analysed, results showed an effect of shade on leaf Pn rates. The weighted averages for leaf photosynthesis in full sun and under trees during sun period (30.2 µmol CO_2 m^{-2} s^{-1}) was greater ($P < 0.001$) than under slats (25.3 µmol CO_2 m^{-2} s^{-1}) and cloth (26.6 µmol CO_2 m^{-2} s^{-1}). The most shaded treatments resulted in a weighted average Pn rate of 80% under T + CL and 77% under T + SL of that in the open pasture.

Mean dry matter yield and RUE

There was an effect of cover ($P < 0.001$), shade ($P < 0.001$) and the interactions between cover and rotation ($P < 0.001$) and between shade and rotation ($P < 0.001$) for alfalfa DM yield over the experimental period (Fig. 6). Alfalfa under trees yielded less ($P < 0.001$) than in the open pastures and this was consistent over the nine rotations. For most of the rotations, alfalfa pasture production under the trees was equivalent to those under the shade cloth and under the slats in the open. The mean DM yield per rotation under trees was 2051 kg ha^{-1} compared with 1805 under shade cloth in open and 1797 under slats in the open. Alfalfa DM production declined substantially under the two most shaded treatments (T + CL and T + SL). Over 19 months of experiment, the accumulated DM yield was 29.4 t ha^{-1} in the open pasture, 21.1 under trees shade, 17.7 under slats in the open, 17.6 under shade cloth in the open, 11.0 under trees plus slats and 9.9 t ha^{-1} under trees plus cloth.

There was a three way interaction ($P < 0.001$) between cover, shade and rotation for RUE (Fig. 7). Alfalfa shoot RUE under trees (T) was always equivalent to those under slats in the open (FS + SL) and mostly to those under the cloth in the open (FS + CL), except in rotation 3 (January 2000) and rotation 7 (December 2000). Shoot RUE under the shade cloth was always similar to that under the slats in the open. Plants in the open pasture usually showed the lowest ($P < 0.001$) RUE over the nine rotations. A rapid decline ($P < 0.001$) in alfalfa shoot RUE was observed under the most shaded treatments (T + CL and T + SL) from the beginning of the experiment to the third rotation period (January 2000) and then they were stabilized and maintained higher than in all other treatments for most of the experimental period.

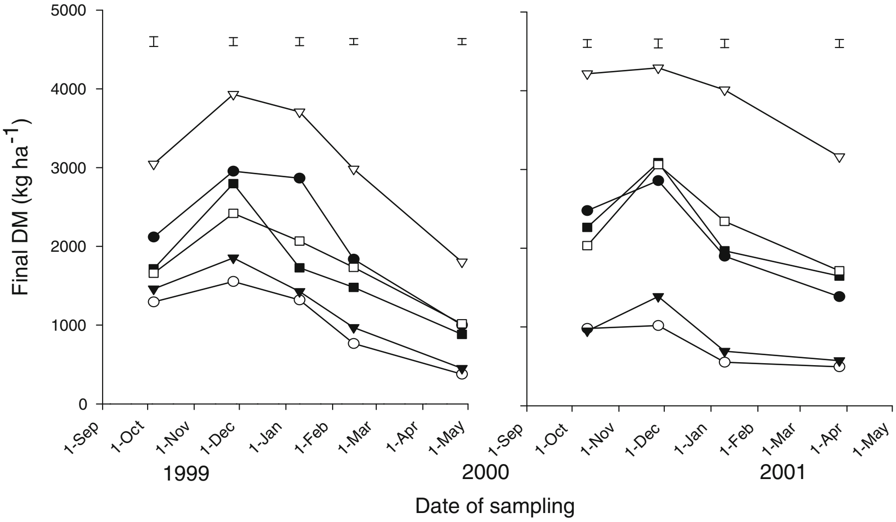

Fig. 6 Mean final herbage dry matter yield (DM) after each rotation for alfalfa grown under six different light regimes: full sunlight (*open inverted triangle*), shade cloth (*filled square*), wooden slats (*open square*), radiata pine trees (*filled circle*), trees + cloth (*open circle*) and trees + slats (*filled inverted triangle*). Data were analysed with cover as main plots (with and without trees) and shade as subplots (control, cloth and slats) and graphs show the average of three replicates collected from October 1999 to March 2001. *Bars* indicate the standard error of means (SEM) for an individual rotation. No data were collected from May to September 1999, when alfalfa was in winter-dormancy ($LSD_{5\%}$ for shade = 164.3; $LSD_{5\%}$ for cover × rotation = 412.9; $LSD_{5\%}$ for shade × rotation = 440.0)

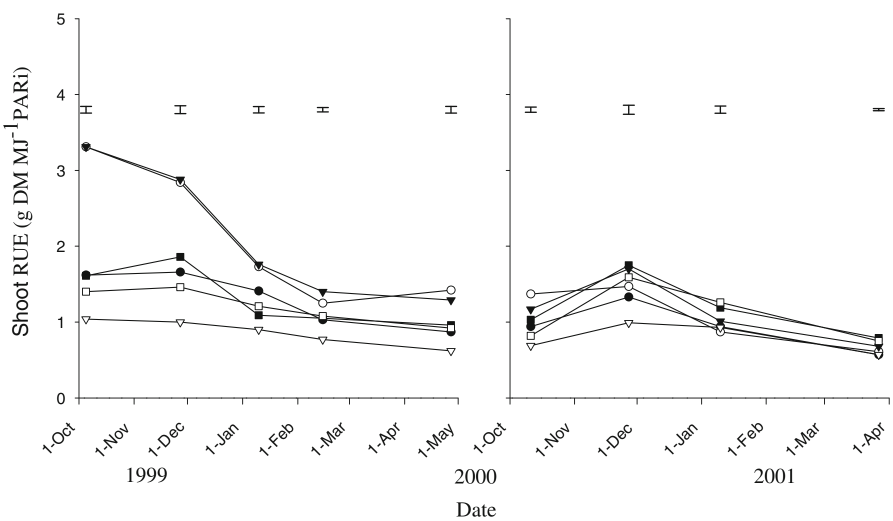

Fig. 7 Mean radiation use efficiency (RUE) calculated for each regrowth period for alfalfa crops grown under six different light regimes: full sunlight (*open inverted triangle*), shade cloth (*filled square*), wooden slats (*open square*), radiata pine trees (*filled circle*), trees + cloth (*open circle*) and trees + slats (*closed inverted triangle*). Data were analysed with cover as main plots (with and without trees) and shade as subplots (control, cloth and slats) and graph shows the average of three replicates collected from October 1999 to March 2001. *Bars* indicate the standard error of means (SEM) for an individual rotation. No data were collected from May to September 1999, when alfalfa was in winter-dormancy ($LSD_{5\%}$ for cover × shade × rotation = 0.3028)

Over the 19 months, mean alfalfa shoot RUE was 1.15 g DM MJ^{-1} PAR under the trees (T), 1.26 under shade cloth in open (FS + CL), 1.17 under slats in the open (FS + SL), 1.65 under cloth plus trees shade (T + CL), 1.69 under slats plus trees shade (T + SL) and 0.84 in the open pasture (FS).

Plant morphology

The source of shading influenced alfalfa morphology over the experimental period (Table 3). There was an interaction ($P < 0.001$) between cover and shade for STH and INTNOD. Within the agroforestry site, plants under trees (T) were the tallest and had the greatest INTNOD. Alfalfa STH under the slats in the open (516 mm) was similar to trees (523 mm) and taller ($P < 0.001$) than those under cloth in the open (462 mm) or in the open pasture (469 mm). Mean INTNOD showed a similar result as mean STH with an interaction between cover and shade ($P < 0.001$). It was 46 mm under the trees, 45 mm under the slats in the open and 41 mm under the shade cloth in open. There was also an interaction between cover and rotation for alfalfa leaf to stem ratio ($P < 0.05$) over the experimental. Alfalfa leaf to stem ratio were always greater ($P < 0.05$) in the open than under the trees. Mean values for the nine growing rotations also showed that plants under trees and under the slats in the open had the lowest ($P < 0.05$) leaf to stem ratio of all treatments and this was also lower ($P = 0.032$) than the leaf to stem proportions under the cloth and under the slats in open.

Table 3 Mean stem height (STH), internode length (INTNOD) and leaf to stem (L:S) ratio from October 1999 to March 2001 measured at the end of each rotation for the alfalfa crop under six different light regimes

Treatment	STH (mm)	INTNOD (mm)	L:S ratio
FS	467	41.03	0.78
FS + CL	462	40.53	0.76
FS + SL	516	45.23	0.70
T	523	46.23	0.69
T + CL	458	41.60	0.75
T + SL	482	43.23	0.71
F probably cover × shade (P)	<0.001	<0.001	0.032
$LSD_{5\%}$ cover × shade	90.8	1.341	0.041
$LSD_{5\%}$ cover × shade when comparing with the same levels of cover	16.4	0.781	0.037

Data are averages of three replicates for nine experimental rotations at Canterbury, New Zealand

FS full sunlight, *FS + CL* shade cloth in the open field, *FS + SL* wooden slats in the open field, *T* under radiata pine trees, *T + CL* trees plus shade cloth, *T + SL* trees plus slats

Discussion

Light environment

The quantity of PPFD transmittance under the trees over the measurement period (Table 1) was successfully reproduced under both slat and cloth structures in the open. However, the temporal changes and spectral composition under trees were most closely mimicked by the slatted treatment in the open. These wooden slats provided a cheap, easy to handle method to simulate tree shade. They could be adapted to reproduce different light periodicity and transmittance by simply alternating the ratio of the slat height above canopy to slat width, the gap space between the wooden slats and the individual slat width (Plate 1). Only a few studies have attempted to apply this type of artificial shade to simulate the light agroforestry environment. For example, Peri et al. (2002) and Garcez Neto et al. (2010) used this artificial shade method and different ratios of the gap and the slat width to study the physiological and morphological responses of orchardgrass (*Dactylis glomerata* L.) and other temperate pastures to different fluctuating light regimes. Specifically in this study, the ratio 1:1.15 of slat spacing to slat height above the alfalfa canopy was adequate to resemble the light quantity of the agroforestry experimental area and this resulted in a light transmittance of about 50%. Plants were exposed longer to a dense shade under the slats in the open than under trees, but mean PPFD was 182 μmol photons m^{-2} s^{-1} under the shade of trees and only 89 μmol photons m^{-2} s^{-1} under the slats shade. This resulted in a greater PPFD transmittance under trees compared with wooden slats. The small difference found in light transmittance might be also a consequence of the distinct shape of the shade sources (conical tree crown versus long slatted wood), tree canopy discontinuity and the additional presence of tree trunks in the agroforestry site (Plate 1b, c). Future studies of different light transmittances using slatted structures are possible simply by changing these ratios and the gap to slat widths.

The shade cloth was unable to mimic the intermittent periodicity of light and dark observed in the agroforestry area because it produces a continuous and uniform light regime. However, the shade cloth used was rated to and did reproduce the light quantity approximated under the agroforestry area. In contrast,

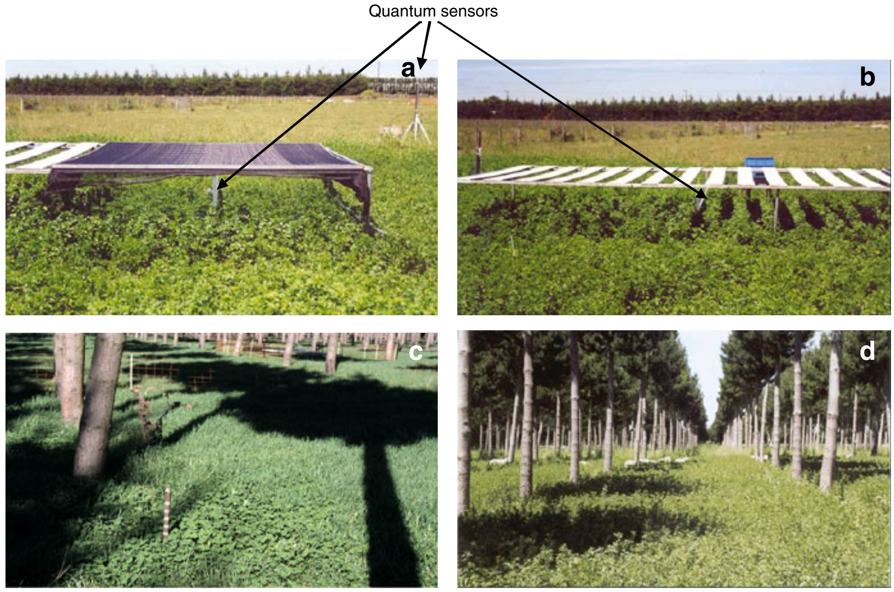

Plate 1 Quantum sensors installed under the centre of plastic shade cloth (**a**) and under the wooden slats structures the sensor positioned directly under the edge of a slat (**b**), tree crown shape of shade in the afternoon in spring where shade structures were set (**c**) and an overview of the alfalfa grazing by sheep at the experimental agroforestry area (**d**) in the late afternoon in summer. Lincoln University, Canterbury, New Zealand

the slatted structure was designed to mimic the light periodicity of the agroforestry area (Figs. 2, 3) and achieved this with a reasonable degree of accuracy. The shade cloth could create an alternating light regime, such as that used by ginseng growers (Brun 1999) with a mix of full sunlight and partial shade. However, understorey plants in agroforestry areas are usually exposed to fluctuating full sunlight and dense tree crown shade regime rather than a partial shade. Similarly, Feldhake and Belesky (2009) pointed out that forages growing in deciduous silvopastoral systems experience fluctuating PPFD caused by the net effects of solar angle, cloudiness, and location relative to trees. Changes in the temporal pattern of radiation (sun and shade time course) are important issues in agroforestry research because they influence the physiological responses of understorey vegetation (Pearcy 1988). For example, Peri et al. (2002), studying the responses of orchardgrass to alternate sun/shade light regimes, showed that leaf photosynthesis decreased and increased as a function of intensity and duration of the PPFD that the understorey plants had previously experienced. These results highlight the importance of using slatted structure to realistically reproduce the periodicity of light of an agroforestry system (Fig. 3).

For the purpose of this work, the main focus of the discussion on spectral composition changes is between the artificial shade structures in the open and under trees. The spectral composition changes under the two most shaded treatments (T + CL and T + SL) were influenced by the incidence of tree shadow on the cloth and slatted structure. Results in Table 2 showed that the R:FR ratio under trees (Tsun and Tsh) was similar to that observed under the slats in the open (FS + SLsun and FS + SLsh), although the explanations for these results may be different. During the full sunlight period under the trees (Tsun) and under the slats in the open (FS + SLsun), there was a greater amount of red light than far red light (Fig. 4). This was consistent with many reports in the literature for open pasture conditions (Wilson and Ludlow 1991; Devkota et al. 1997; Bell et al. 2000). For example, Bell et al. (2000) found R:FR ratios of 1.0 in full sunlight and 0.8 under coniferous tree shade (18% light transmittance). In the present study, spectral composition changed under the shade of tree crowns (Tsh) and slats in the open (FS + SLsh), showing that the amount of far red light became greater than the amount of red light photons measured and both decreased substantially. Under the shade of slats in the open, the assumption was that the red and far red wave bands, originated primarily from direct sunlight, was blocked by the wooden slats and reflected back to the sky. In the agroforestry area, red light was preferentially absorbed by tree crown leaves to be used for photosynthesis. The far red light penetrated the tree canopies but did not penetrate the slats. So that, part of far red light measured under the shade of tree crowns and slats in the open originated from the diffuse portion of sunlight. The hypothesis is that another part of direct far red light coming through the gaps between slats was reflected upwards by the alfalfa canopy and then re-reflected downwards by the wooden slats in the direction of the shade area sensor. This would explain the larger amount of far red photons observed under the shade of slats compared with the shade of trees.

Therefore, all understorey plants growing beneath the intermittent light regimes (FS + SL, T and T + SL) experienced similar changes in spectral composition in this study. Under shade cloth in the open, the amount of red and far red light decreased to about 49% of that observed in the open pasture (FS), but the R:FR ratio remained the same (Fig. 4; Table 2). This is an indication that under shade cloth the amount of red and far red light decreased in proportion to the reduction in PPFD quantity (Fig. 3b). The spectral composition was then dependent on the shade density of the material. In addition, spectral composition may vary with the colour of cloth material as shown by Baldwin (2009). The indication was that the black shade cloth neither absorbed nor blocked any of the light wave bands and, as proposed by Bell et al. (2000), this material only approximated a neutral filter of photons. Thus, shade cloth was less effective at reproducing the temporal changes in spectral composition of light under trees than the slats when both were used in the open field.

Alfalfa responses

Shading from trees, slats and cloth in the open resulted in similar alfalfa mean DM yields (Fig. 6), despite the differences observed in radiation periodicity and spectral composition. The decline in DM yield in the shade was consistent with the photosynthetic activity. Alfalfa leaves exposed to intermittent regimes during periods of full sunlight (FS + SLsun, Tsun, T + SLsun) had similar leaf photosynthesis to those measured in the open pasture (FS). However, when they were exposed to the shade of tree crowns or slats, the photosynthesis reduced to between 63 and 72% of that observed in the open pasture (Fig. 5). These declines in leaf net photosynthesis were consistent with the mean DM yield, which showed a reduction of 72% under trees and 60% under slats and cloth in the open. Thus, alfalfa was able to maintain reasonable photosynthetic activity during the dense shade periods under the trees and under slats in the open, while leaves were exposed to low PPFD levels (7% transmittance under trees and 5% under slats). Similar responses were observed for alfalfa plants under trees plus cloth (T + CL) and trees plus slats (T + SL) when light transmittance was the lowest of all treatments. In addition, alfalfa photosynthesis rate under shade cloth in the open (FS + CL) operated close to that in the open pasture (86% of the open pasture), but yield under the cloth was still equivalent to the trees and slats in the open. This suggests that alfalfa leaves operated near the saturation point under the cloth in the open. Furthermore, leaves were able to maintain a positive carbon gain when exposed to the amount and time of shade observed under the intermittent light regimes in this experiment.

The performance of alfalfa plants under intermittent light regimes seemed to be influenced by the light periodicity and this agrees with previous results reported by Peri et al. (2002) for orchardgrass. In our experiment, the length of time plants were submitted to sun and shade events under trees approximated to that under slats in the open. This explains the equivalent yields and photosynthetic performances of alfalfa under these treatments. When plants were exposed to longer periods and amounts of shade under the trees plus cloth and trees plus slats, the mean leaf photosynthesis rates and DM yields were the lowest. Therefore, results for instantaneous net photosynthesis (Fig. 5) confirmed the intermittency light-response effect under trees and under the slatted shade structure in the open (FS + SL) compared with the steady-state conditions in full sunlight and under shade cloth in open. This was an indication that the top leaves under the intermittent light regimes (T, FS + SL, T + CL and T + SL) developed the photosynthetic phenomena of induction (gradual rise of photosynthesis after a prolonged shade period from a low initial rate to a steady final level) and deactivation (gradual decrease of photosynthesis from high to low irradiance), as defined by Rabinowitch (1956), under the present alternating sun/shade regimes.

As a consequence of the ability to operate photosynthesis and growth at reasonable levels and to remobilize reserves under the low irradiance conditions in this experiment, alfalfa plants typically showed a greater shoot RUE (Fig. 6) under shaded treatments than those in the open pasture. From rotation 1–3, there was a rapid decline in alfalfa shoot RUE under the two most shaded treatments (T + CL and T + SL). This indicates that these plants needed almost 90 days to adjust their carbon gain to compatible levels under the 16–17% PPFD transmittance. In addition, it implies that the high shoot RUE of these treatments over the experimental period might be a result of reserves remobilization to shoot growth, favourable canopy architecture (Varella 2002) and an ability to increase the efficiency of light capture and use by increasing leaf area, chlorophyll content and photosynthetic efficiency. Overall RUE values for shoot production decreased from summer to autumn rotations. This is consistent with reports of greater partitioning to roots and slower leaf appearance rates in autumn reported by Brown et al. (2005) and Teixeira et al. (2007).

The mean shoot RUE values showed an exponential increase with shading levels. This agrees with results reported by Feldhake and Belesky (2009) for C_3 grasses (*Dactylis glomerata* and *Schedonorus phoenix*) exposed to a similar gradient of shade to this experiment, but their shading was from a natural deciduous forest (mixed *Quercus* spp.). Finally, the shoot RUE of alfalfa plants was similar between trees, cloth and slats in the open for most of the study and this was consistent with the other yield components and the mean daily PPFD measured at the experimental site. Plants under trees had lower RUE compared with the two artificial shade regimes only in the last rotation, when possibly water and light stress from tree competition might have interacted and reduced DM yield more severely in the agroforestry site than in the open pasture (Varella et al. 2001a). Overall, yield and physiological measurements showed that alfalfa responses under the two artificial shade structures in the open and under the trees were consistent over time.

Alfalfa morphological changes (Table 3) were the main indication of differences between trees and the two artificial shade structures in this experiment. Under trees, the alfalfa strategy appeared to be to compensate for low PPFD and reduced quality of light through elongation of stems and INTNOD, possibly in search of the light source. This response was also observed under slats in the open. In contrast, in the open pasture and under cloth in the open, plants showed the highest proportion of short plants. As a consequence, alfalfa grown under intermittent shade (FS + SL, T and T + SL) had a mean L:S ratio 0.70 compared with 0.78 in full sunlight and 0.76 under shade cloth in the open over the experimental period (Table 3). In this study, alfalfa plants responded typically as a shade avoider by increasing the proportion of stems rather than expanding leaf area for light capture in response to a decrease in the red to far red ratio under the intermittent light regimes. In other studies, there has been an indication of leaf elongation and increased leaf area in grasses under low irradiance environments (Smith 1982; Dias-Filho 2000; Lin et al. 2001; Peri et al. 2007), but that is usually followed by a decrease in nutritive value measured in available herbage energy (Lin et al. 2001; Belesky et al. 2006). For example, Kephart et al. (1992) noted that some grasses and legumes responded to reduced light by allocating a higher proportion of carbohydrates to maintain or increase leaf area and stem length, while decreasing dry matter for root growth. In contrast to the results in this experiment, Lin et al. (2001) reported a significant increase in alfalfa INTNOD and a decrease in leaf to stem ratio under 50 and 80% shade cloth compared with full sun. These authors commented that a high proportion of far red to red light under the shade resulted in stem elongation of both legumes and grasses by promoting the allocation of carbohydrate resources for rapid extension growth, but they never presented evidence of the light quality under the shade cloth treatments. Surprisingly, the greater mean RUE of alfalfa under the shade treatments compared with full sunlight was inconsistent with changes in plant morphology. Shaded alfalfa invested more in stem than leaf growth in this study while most shade adapted plants reportedly allocate carbohydrates preferentially to expand leaf area (Wilson and Ludlow 1991; Kephart et al. 1992; Peri et al. 2007; Feldhake and Belesky 2009). Therefore, the highest RUE of alfalfa under shade was more likely to be a result of anatomical (great light absorption efficiency) or physiological (lower maintenance respiration, increase photosynthetic efficiency and lower photosynthetic saturation point) adaptations rather than morphological changes.

Although there was evidence of morphological changes on shaded alfalfa under trees and slats in this study, they were insufficient to affect canopy growth and yield components. Shading duration (with low quantity and quality) under the trees and the slatted structure in this experiment was probably not long enough to allow the morphological changes to affect canopy growth. This highlights the efficiency of the alfalfa canopy to capture available light (Gosse et al. 1982; Lin et al. 2001). The length of time plants were submitted to sun/shade under these intermittent regimes seemed to be a critical point to determine the plant responses under an intermittent light regime. Genetic factors and the plants ability to adapt to reduced light are also important (Smith 1982). It has been speculated that, for a certain plant, productivity and physiological changes under an intermittent light regime can only be observed when PPFD levels are above a critical point. This was first postulated by Rabinowitch (1956), who stated that "*photosynthesis production could be expected to be larger in alternating light compared with continuous illumination if the periods of shade and sun are very long or very short*". This hypothesis was partially supported by Turnbull and Yates (1993) who observed that, while a small number of high PPFD events had a significant influence on the daily average of PPFD under a forest plantation, this short sunlight and long shade intermittent regimes had little influence on the daily R:FR ratio. For alfalfa in this study, alternating periods of 510 min in near full sunlight and 375 min of heavy shade under trees, 445 min of near sunlight and 440 min in a dense shade under slats in the open and 800 min of partial continuous light under shade cloth in the open resulted in equivalent plant yield responses (DM yield, mean weighted net photosynthesis and shoot RUE) over the experimental period. The interaction between light quantity, periodicity and quality is unclear. However, these results suggest careful analysis is required when understorey pastures and crops are exposed to environments with similar or longer shade periodicity than those observed in this study. Overall, the results indicated that the use of the slatted structure is an adequate artificial shade structure to simulate the agroforestry light environment and plant responses may vary to those observed under shade cloth, particularly those responses dependent on the quantity and duration of sun and shade events (width and spaces between slats) and on the plant genetic and physiological ability to tolerate low irradiance.

Conclusions

Overall, the slats and shade cloth were able to produce a similar quantity of light transmittance to that under trees. The temporal pattern of light under trees approximated to slats in the open, but was different than shade cloth. Spectral composition under trees was also closely resembled by slats rather than shade cloth in the open by decreasing the ratio of red to far red light. Shade decreased alfalfa DM yield and net photosynthesis and increased shoot RUE in alfalfa plants. Trees produced similar DM yield and had equivalent shoot RUE to slats and shade cloth in the open. Changes in alfalfa instantaneous net photosynthesis under trees were equivalent to those measured under slats in the open. Alfalfa morphology under trees was also closer to those observed under slats in the open than under shade cloth. Alfalfa plants responded typically as a shade avoider by increasing the STH, INTNOD and the proportion of stem to leaf. The slat structure was a practical and accurate artificial shade material to mimic the agroforestry light environment and consequent plant responses.

Acknowledgements This study was part of a Ph.D. thesis at Lincoln University, which was fully supported by CAPES (The Brazilian Foundation for Higher Education Studies) from the Ministry of Education of Brazil. EMBRAPA (The Brazilian Agricultural Research Corporation). The manuscript preparation was supported by a post doctoral period at Lincoln University. Finally, we thank an anonymous reviewer for comments that improve the clarity of this manuscript.

References

Baldwin CM (2009) Impacts of altered light spectral quality on warm-season turfgrass growth under greenhouse conditions. Crop Sci 49:1444–1453

Belesky DP, Neel JP, Chatterton NJ (2006) *Dactylis glomerata* growing along a light gradient in the Central Appalachian Region of the Eastern USA: III. Nonstructural carbohydrates and nutritive value. Agrofor Syst 67:51–61

Bell GE, Danneberger TK, McMahon MJ (2000) Spectral irradiance available for turfgrass growth in sun and shade. Crop Sci 40:189–195

Brown HE, Moot DJ, Teixeira EI (2005) The components of lucerne (*Medicago sativa*) leaf area index respond to temperature and photoperiod in a temperate climate. Eur J Agron 23(4):348–358

Brun CA (1999) Crop profile for ginseng in Washington. Washington State University Web. www.tricity.wsu.edu/~cdaniels/profiles/ginseng.pdf. Accessed 10 May 2010

Devkota NR, Kemp PD, Hodgson J (1997) Screening pasture species for shade tolerance. In: Proceedings of the Annual Conference, vol 27. Agronomy Society of New Zealand, pp 119–128

Dias-Filho MB (2000) Growth and biomass allocation of the c_4 grasses *Brachiaria brizantha* and *B. humidicola* under shade. Scielo Brasil Web. http://www.scielo.br/scielo.php?pid=S0100-204X2000001200003&script=sci_arttext&tlng=en. Pesquisa Agropecuaria Brasileira 12(35):2335–2341. Accessed 12 May 2010

Feldhake CM, Belesky DP (2009) Photosynthetically active radiation use efficiency of *Dactylis glomerata* and *Schendonorus phoenix* along a hardwood tree-induced light gradient. Agrofor Syst 75:189–196

Garcez Neto AM, Garcia R, Moot DJ, Gobi KF (2010) Morphological acclimation of temperate forages to patterns and levels of shade. Br J Anim Sci 39(1):42–50

Gaskin T (1965) Light quality under saran shade cloth. Agron J 57:313–314

Gosse G, Chartier M, Varlet Grancher C, Bonhomme R (1982) Interception of photosynthetically active radiation by alfalfa: variations and modeling. Agronomie 2(6):583–588

Karageorgis D, Tonkin PJ, Adams JA (1984) Medium and short range variability in textural layering in an ochrept developed on an alluvial floodplain. Aust J Soil Res 22:471–474

Kephart KD, Buxton DR, Taylor SE (1992) Growth of C3 and C4 perennial grasses in reduced irradiance. Crop Sci 32:1033–1038

Lin CH, McGraw RL, George MF, Garrett HE (2001) Nutritive quality and morphological development under partial shade of some forage species with agroforestry potential. Agrofor Syst 53:269–281

Mead DJ, Lucas RJ, Mason EG (1993) Studying interactions between pastures and Pinus radiata in Canterbury's subhumid temperate environment—the first two years. New Zealand Forestry 38:26–31

Pearcy RW (1988) Photosynthetic utilization of light flecks by understorey plants. Aust J Plant Physiol 15:223–238

Peri PL, McNeil DL, Moot DJ, Varella AC, Lucas RJ (2002) Net photosynthetic rate of cocksfoot leaves under continuous and fluctuating shade conditions in the field. Grass Forage Sci 57:157–170

Peri PL, Moot DJ, Jarvis P, McNeil DL, Lucas RJ (2007) Morphological, anatomical, and physiological changes of orchardgrass leaves grown under fluctuating light regimes. Agron J 99:1502–1513

Pollock KM, Mead DJ, McKenzie BA (2009) Soil moisture and water use by pastures and silvopastures in a subhumid temperate climate in New Zealand. Agrofor Syst 75(3):223–238

Rabinowitch EI (1956) Photosynthesis and related processes. Kinetics of photosynthesis. In: Rabinowitch EI (ed) Time effects. II. Photosynthesis in intermittent light, vol II, Part 2 (34). Interscience Publishers, New York, pp 1433–1483

Smith H (1982) Light quality, photoperception, and plant strategy. Annu Rev Plant Physiol 33:481–518

Teixeira EI, Moot DJ, Mickelbart MV (2007) Seasonal patterns of root C and N reserves of lucerne crops (*Medicago sativa* L.) grown in a temperate climate were affected by defoliation regime. Eur J Agron 26(1):10–20

Turnbull MH, Yates DJ (1993) Seasonal variation in the red/far-red ratio and photon flux density in an Australian subtropical rainforest. Agric For Meteor 64(1–2):111–127

Varella AC (2002) Modelling lucerne (*Medicago sativa*) crop response to light regimes in an agroforestry system. Doctoral Thesis, Lincoln University, Canterbury, New Zealand. Lincoln University Archive Web. http://hdl.handle.net/10182/1477. Accessed 03 May 2010

Varella AC, Peri PL, Lucas RJ, Moot DJ, McNeil DL (2001a) Dry matter production and nutritive value of alfalfa (*Medicago sativa* L.) and orchardgrass (*Dactylis glomerata* L.) under different light regimes. In: Gomide JA, Mattos WRS, Silva SC (eds) Proceedings of the XIX International Grassland Congress. Grassland Ecosystems: an Outlook into 21st Century, 11–21 February 2001. Brazilian Society of Animal Husbandry, Sao Paulo, Brazil, pp 660–661

Varella AC, Moot DJ, Lucas RJ, McNeil DL, Peri PL, Pollock KM (2001b) Different methods of artificial shade for agro-silvipastoral research. In: XIX International Grassland Congress, Sao Pedro, Sao Paulo, Brazil

Watt JPV, Burgham SJ (1992) Physical properties of eight soils of the Lincoln area, Canterbury Derived data and hydraulic character statements. DSIR Land Resources, New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand, pp 72–76

Wilson JR, Ludlow MM (1991) The environment and potential growth of herbage under plantations. In: Shelton HM, Stur WW (eds) Forages for plantation crops: proceedings of a workshop, Sanur Beach, Bali, Indonesia, 27–29 June 1990. ACIAR, pp 10–24

Yates DJ (1989) Shade factors of a range of shade cloth materials. Acta Hortic 257:201–218