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The effect of shade and shade material on white clover/perennial ryegrass mixtures for temperate agroforestry systems

M. Ehret · R. Graß · M. Wachendorf

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Abstract White clover/perennial ryegrass mixtures (*Trifolium repens* L., *Lolium perenne* L.) are potential understory candidates for temperate agroforestry systems. A 2-year artificial shade experiment was conducted to determine the effects of shade on herbage production and quality and on changes in sward composition under field conditions. Wooden frames covered by shade cloth or a slatted structure were used on the sward to mimic different shade patterns of trees. The sward was exposed to 30, 50, and 80 % reduction in sun irradiance as well as a non-shaded control (0 % reduction). Total annual herbage production was highest in non-shaded swards in second and third year after establishment (8 and 16 t DM ha^{-1}, respectively) and declined with increased shade (up to 70 % with 80 % shade). Compared to the control (24 t ha^{-1}), 50 % shade cloth and 50 % slatted structure reduced biennial herbage production by 4 and 7 t ha^{-1}, respectively. A decline in clover content of up to 93 % under severe shade compared to the control in the second year of the field experiment highlighted the sensitivity of clover to reduced radiation. No differences in forage nutritive qualities were detected in response to shade intensity during either growing season. On a dry matter basis, average biennial quality values were 2.7 % N, 41.8 % NDF, 34.4 % ADF, and 4.7 % ADL. The findings of the biennial field experiment confirm a white clover/perennial ryegrass sward is a suitable understory under light to moderate shade conditions; however, within a temperate agroforestry practice under dense shade, sward productivity and clover content will rapidly decline. Long-term effects of shade on white clover/perennial ryegrass mixtures as an understory in temperate agroforestry systems need to be evaluated in future research activities.

Keywords Agroforestry · *Lolium perenne* L. · Sward composition · *Trifolium repens* L. · Understory · Yield

Introduction

Agroforestry, the integration of perennial woody plants and agricultural crops or pastures as understory on the same agricultural land, is considered to be a promising land use system for diversification of local biomass production. It offers an (alternative) agro-ecological approach to a sustainable intensification of concomitant food and wood production (Smith et al. 2012). The diversified production increases resilience, and offers various ecosystem services in view of changing environmental conditions and human utilization preferences (Folke et al. 2009).

M. Ehret (✉) · R. Graß · M. Wachendorf
Faculty of Organic Agricultural Science, Section Grassland Science and Renewable Plant Resources, University of Kassel, Steinstrasse 19, 37213 Witzenhausen, Germany
e-mail: m.ehret@uni-kassel.de; gnr@uni-kassel.de

Unlike sole cropping systems, for example wheat or maize, agroforestry systems require special agronomic practices. Results of previous agroforestry research confirmed that woody and herbaceous plants compete for the same resources like water, nutrients and light (Jose et al. 2009; Udawatta et al. 2014). The productivity of an agroforestry system depends on the extent of the competition between trees and understory (Devkota et al. 2009), and on how the system can cope with the induced changes to the microclimate (Lin et al. 1999).

The quantity and quality of light absorbed by crops has an important impact, since all plants react physiologically and morphologically to reduced light interception (Björkmann and Holmgren 1963). Bellow and Nair (2003) suggested investigating which levels of photosynthetically active radiation (PAR) optimize or diminish yields of the understory crops in agroforestry systems under various site conditions.

In temperate agroforestry systems light availability and quality are expected to be the most limiting factors throughout the growing season. In a silvopastoral aspen stand in Alberta, Canada, understory net primary production increased by up to 275 % when the tree canopy was removed, compared to the non-shaded control with full tree canopy (Powell and Bork 2006). Abraham et al. (2014) tested the responses of *Dactylis glomerata* L. in an artificial shaded pot experiment (shade intensities of 0, 60, and 90 %) in three geographically different habitats in Greece. They found that shade reduced tillering and productivity of the grass, and modified the leaf characteristics.

Until now, little empirical research has been done on light assessment in Central European agroforestry systems. There is still a need to investigate the extent to which shade influences yield, sward composition and quality of food and/or fodder crops in temperate agroforestry systems. Furthermore, it is not yet fully understood how the mechanisms of shade tolerance work (Lin et al. 2001).

In agroforestry research, it is a common practice to evaluate shade tolerance of understory plants. For example, by placing artificial shade structures over sole cropped plants, the influence of reduced PAR on the understory candidate can be evaluated without belowground competition from the trees. The shade levels chosen for the artificial shade structures are often related to shade levels measured under trees in agroforestry systems. For example, Devkota et al. (2009) derived from alder tree heights of 2.5 m (unpruned), 5.0 and 7.0 m (from the ground after pruning), canopy closures of 89, 75, and 41 %, respectively. In an alley cropping stand in Ontario, Canada, PAR levels decreased in the alleys by 29 % from silver maple tree rows (Reynolds et al. 2007).

Shade materials used for artificial shade are often plastic cloth. Under shade cloth the plants experience uniform light regimes according to the predetermined level of light transmission (Varella et al. 2011). However, an artificial shade experiment from the southern island of New Zealand, with a temperate climate, showed that a slatted structure reproduced the spectral composition of trees better than plastic cloth (Varella et al. 2011). In particular, the periodic light fluctuations of trees during a day could be mimicked by the slatted structure. Also, morphology of the alfalfa plants under the slats was closer to those under the trees of the adjacent agroforestry system than those under the shade cloth. Dufour et al. (2012) conducted a study on light assessment within an agroforestry system in the southern part of France with a sub-humid Mediterranean climate. Beside the set-up of crop growth models, they evaluated the influence of different shade material (slatted structure, shade cloth) on winter wheat. Their results showed no differences in wheat development between the two shade materials, and they suggested long-term experiments to include seasonal effects.

The present study was embedded in a research project which investigated a willow-clover/grass alley cropping stand (clone Tordis (*Salix schwerinii* × *S. viminalis*) × *S. vim.*) in multi-rows, *Lolium perenne* L. and *Trifolium repens* L. in the alleys) for biofuel production in Germany. The overall objective was to identify possible competition effects between willows and clover/grass. Since light seemed to be the factor most affecting the yield performance of the understory in temperate agroforestry systems, an artificial shade experiment was established over a clover/grass stand. The shade levels, which were chosen for the experiment, represented the expected canopy closures of the willows in the adjacent alley cropping system. Willows were grown in short rotation which might result in shade levels of 30, 50, and 80 % during the whole growing cycle of the short rotation willow coppice.

The primary aim of the present study was to quantify the effects of shade level and material (shade cloth and slatted structure) on productivity, sward composition and nutritive value of a clover/grass sward by an in situ 2-year artificial shade experiment. It was hypothesized that: (i) dry matter yield of clover/grass swards decreases with increased shade intensity; (ii) sward composition in a clover/grass sward changes with increased shade intensity; and (iii) the nutritive value of the plants declines with increased shade intensity. The results could confirm whether a clover/grass sward is sufficiently shade tolerant to be used as an understory in temperate agroforestry systems in central Western Europe.

Materials and methods

Site description

The study site was part of an agroforestry research experiment in Lower Saxony, Germany (51°39′83″N and 9°98′75″E, 325 m a.s.l.). The climate was characterized as temperate with an average temperature of 9.2 °C and a mean annual precipitation of 642 mm over a 20 year period. The predominant soil type is classified as a stagnosol according to the FAO World Reference of Soil Resources (2006) and consists of sedimentary deposits from sandstone, siltstone and claystone (Hartmann et al. 2014). The preceding crop on the experimental area was winter barley.

Experimental design

A binary mixture of white clover and perennial ryegrass was sown by tillage drilling in March 2011. The mixture consisted of *Trifolium repens* L. 'Riesling' and *Lolium perenne* L. (with a mixture of 10 cultivars with a wide range of flowering dates in the first cut). The seeding rate of the commercially available seed mixture was 30 kg ha^{-1}. No herbicides, fertilizers or irrigation were applied during establishment or the entire experiment.

After the sward had established, a fully randomized artificial shade experiment with two replicates was set up, in April 2012. Experimental plots of 2.4 by 2.4 m, with different shade levels, were established on a larger grassland area, aiming to mimic the incident radiation transmitted through tree crowns and received by the surface of the grassland. The experiment consisted of a control (0 %) without any shade cloths or slats, and three shade levels using shade cloths with different shade intensities (light (30 %), medium (50 %) and severe (80 %)). The cloth structures produced continuous diffuse light. An overhang of 0.4 m at east and west ends prevented direct radiation on the sward.

A slatted wooden structure with a light transmission of 50 % was included to simulate the fluctuating light regime of trees over a day. The slatted structure consisted of 0.15 by 2.4 m larch wood slats (painted black beneath and white on the top) and had 0.15 m gaps in between each slat to achieve 50 % of full sunlight. An east–west direction was chosen for the slats to reproduce the orientation of the trees on the adjacent agroforestry system. According to Varella et al. (2011), the slatted structure had to fulfill a number of criteria. The major compromise, also relevant to our experiment, was the horizontal arrangement of the shade structures, as opposed to the vertical orientation of trees.

The shade structures were supported on a metal pipe frame. Therefore, the structures were removable for the harvest and could be vertically adjusted to 30 cm above the top of the actual canopy height. The shade structures were mounted above the white clover/ryegrass sward when the leaves of the willow trees in the neighboring agroforestry system started to emerge (end of April). At the end of the growing season the shade structures were removed, when the trees were leafless, and remounted over the sward in the upcoming spring. The study was conducted during the growing seasons from April to September in 2012 and 2013.

Microclimatic measurements

Microclimatic conditions under each of the artificial shade constructions and in the non-shaded control were investigated using light quantum, soil moisture and soil temperature sensors (Decagon Devices, Inc. Pullman, WA, USA). All data were recorded between leaf emergence (30th April) and leaf fall (30th September) of the willows in the adjacent agroforestry system. For this study, light quantum was defined as the photosynthetically active photon flux density (PPFD) measured in µmol m^{-2} s^{-1} with PPFD sensors (model QSO-S) directly at the top of the grassland canopy in the centre of each plot. Sensors used a hemispherical field of view of 180°, a spectral range of 400–700 nm and a resolution of flux density of 2 µmol m^{-2} s^{-1}. The quantum sensor was fixed on an adjustable metal arm below the shade construction which was lifted concomitantly with the increasing sward height. For simplification, the applied shade levels are referred to as light (30 %), medium (50 and 50 % slats), severe (80 %) and control (0 %). To assess the soil moisture content and soil temperature under the shade structure, sensors were permanently buried into the centre of each plot. Volumetric soil moisture content was monitored at 15 and 35 cm soil depths in the core of each plot. EC-5 soil moisture sensors determined the volumetric water content (VWC) by measuring the dielectric constant of the media using capacitance/frequency domain technology. Soil temperature records were taken at 5 cm soil depth below soil surface in the core of each plot. Pre-tests were conducted, to confirm an equally distributed rainfall pattern under the different shade materials. Precipitation was measured on open field conditions on the study area. High resolution rain gauges with one tip per 0.2 mm of rain were permanently installed 20 cm above a clover/grass sward (Decagon Devices, Inc. Pullman, WA, USA). All data were measured every minute and hourly means (soil moisture and soil temperature) or totals (PPFD and precipitation) stored on data loggers.

Plant measurements

Plots were harvested on three dates per year (mid May, mid July, end of September) during the two growing seasons in 2012 and 2013. At each harvest date, a 0.25 m^2 quadrat within the centre area of each plot was sampled at 50 mm stubble height and herbage fresh mass was recorded. Samples of 100–200 g from the harvested herbage fresh mass of each plot were dried at 105 °C, and weighed to determine herbage dry mass.

Total annual biomass yield was calculated as the sum of biomass from the first, the second and the third cut. Sward composition was determined by a botanical separation of the biomass samples into the following functional groups; grass (i.e. *Lolium perenne* L.), non-leguminous forbs (segetal species, dominated by *Taraxacum officinale* L. and *Chenopodium album* L.), and legume (i.e. *Trifolium repens* L. and hereafter referred to as clover). Furthermore, the proportion of dead material was measured. Representative samples of the harvested herbage of 200–300 g from each subplot were oven-dried at 65 °C for 48 h and ground to pass through a 1 mm screen with a FOSS sample mill (CyclotecTM 1093, Haan, Germany).

Near infrared spectroscopy (NIRS) measurements were carried out to obtain reflectance spectra with an XDS-spectrometer (Foss NIR System, Hillerød, Denmark). Spectra of visible and infrared range (400–2500 nm) were collected with a data collection of every 2 nm. The spectrum of a sample was an average of 25 subscans and was recorded as the logarithm of the inverse of the reflectance (log (1/R)). Spectral data were reduced by using the first of every eight consecutive spectral points. Standard normal variate and detrend scatter correction (SNV-D) was used to correct for differences in particle size and spectral curvature of the samples. Samples for reference data analysis were selected according to spectral similarity within a Mahalanobis-distance of 0.5–1.0 (Biewer et al. 2009).

The ANKOM filter paper bag method (ANKOM-200 fiber analyzer, ANKOM Technology Corp., Fairport, NY) was used to determine acid detergent fiber (ADF), acid detergent lignin (ADL) and neutral detergent fiber (NDF) of the selected samples for calibration development (Vogel et al. 1999). Neutral detergent fiber was determined with a heat stable amylase and ADF and NDF were expressed exclusive of residual ash. Ash was determined by a 5-h-long dry oxidation at 550 °C in a muffle furnace. Nitrogen (N) was measured by an elemental analyzer (Vario MAX CHN Elementar Analysensysteme GmbH, Hanau, Germany).

Based on the selected reference samples, NIRS calibrations were developed with WinISI software (version 1.63, Foss NIRSystems/Tecator Infrasoft International, Silver Spring, MD), using the range between 1100 and 2498 nm. With the resulting calibration models for N (R2CV = 0.97; SECV = 0.10 g kg^{-1} DM), ADF (R2CV = 0.88; SECV: 1.98 g kg^{-1} DM) and ADL (R2CV = 0.75; SECV: 1.32 g kg^{-1} DM), all remaining samples which were not included in the calibration process were predicted for the quality parameters N, ADF, and ADL.

The relationship between annual herbage production and shade was described by an allometric power equation for the year 2012

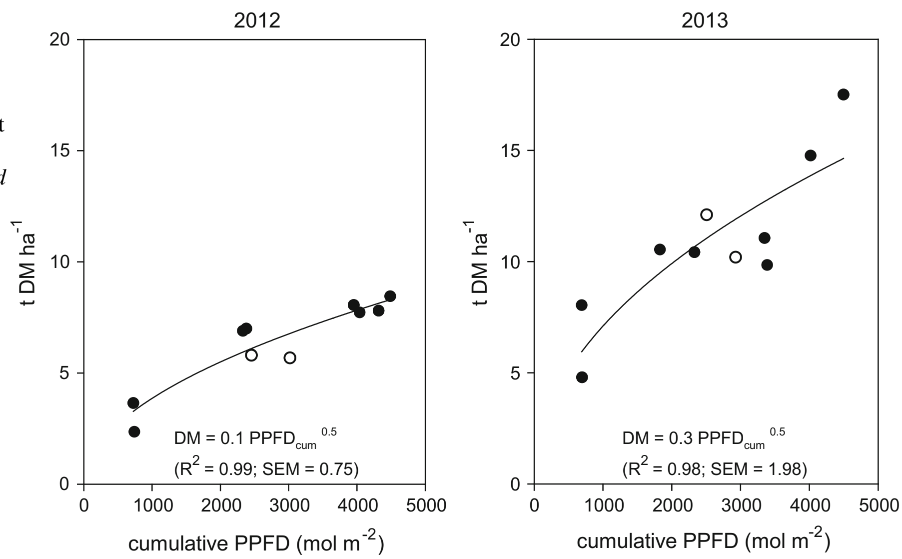
$$y = 0.1\,(\pm 0.07)X^{0.5\,(\pm 0.08)}$$

for the year 2013

$$y = 0.3\,(\pm 0.26)X^{0.5\,(\pm 0.13)}$$

where y was the herbage production, x was cumulative PPFD, and a, b were the determined regression factors ($R^2 = 0.99$ in 2012, SEM = 0.75; $R^2 = 0.98$, SEM = 1.98 in 2013, Fig. 1).

Fig. 1 Relationship between cumulative PPFD ($PPFD_{cum}$) and annual herbage production in the growing seasons 2012 and 2013. The points of the slatted treatment are indicated as *open circles* and the shade cloth treatments as *filled circles*



Statistical analyses

Data were analyzed with the MIXED procedure of the Statistical Analysis System (SAS Institute Inc., Cary, North Carolina, USA) with shade intensity as fixed effect. Production year was included as a repeated measure because the experimental treatments were applied to the same plots every year and therefore reflected the cumulative effects of shade intensity applications. Appropriate covariance structures for the repeated measures effects were identified using Akaike's information criterion (AIC). Linear contrasts were calculated to compare least square means between different shade material (i.e. cloth and slats) at the same level of shade intensity (i.e. 50 %). Data normality was assessed using the UNIVARIATE procedure (SAS Institute Inc., Cary, North Carolina, USA). Homogeneity of variance was verified through the analysis of residuals, and none of the data required transformation. Differences between treatment means were considered statistically significant at $P < 0.05$ using the LSMEANS statement (SAS Institute Inc., Cary, North Carolina, USA).

Results

Microclimate

Microclimatic parameters were aggregated on a weekly basis to allow a visual discrimination among shade levels over the growing season (Fig. 2). Shade intensities of the shade cloth, as indicated by the cloth manufacturer, were almost confirmed by PPFD measurements (Table 1). PPFD under the slatted structure was lower than the control value with no shade treatment, and higher (11 % on average) than the values under the cloth with medium (50 %) shade treatment. PPFD under the severe (80 %) shade treatment was seven times lower than the control. PPFD of the light shade treatment (30 %) was only 1.5 times lower than the control.

Shade significantly affected mean soil temperature in 2012 but not in 2013 (Table 1). In both years soil temperature beneath the severe shade was approximately 1 °C lower than in the non-shaded control, whereas light and medium shade reduced soil temperature by 0.5–0.9 °C (Fig. 2b). From the temperature profiles it becomes apparent that differences among the shade levels only occurred in the second half of the growing season (Fig. 2b).

Soil moisture fluctuations in the upper soil layer were more pronounced after rainfall events under both the slatted structure and the control than in the other shade treatments (Fig. 2c, e). Seasonal variability of soil moisture content at 35 cm depth was low in the severe shade treatment (80 %) and remained nearly at steady state during the 2-year experiment (Fig. 2d, e). The mean values of soil moisture for both growing seasons showed that the severe shade treatment remained near field capacity (Table 1). The soil moisture content under the control was 25 % reduced

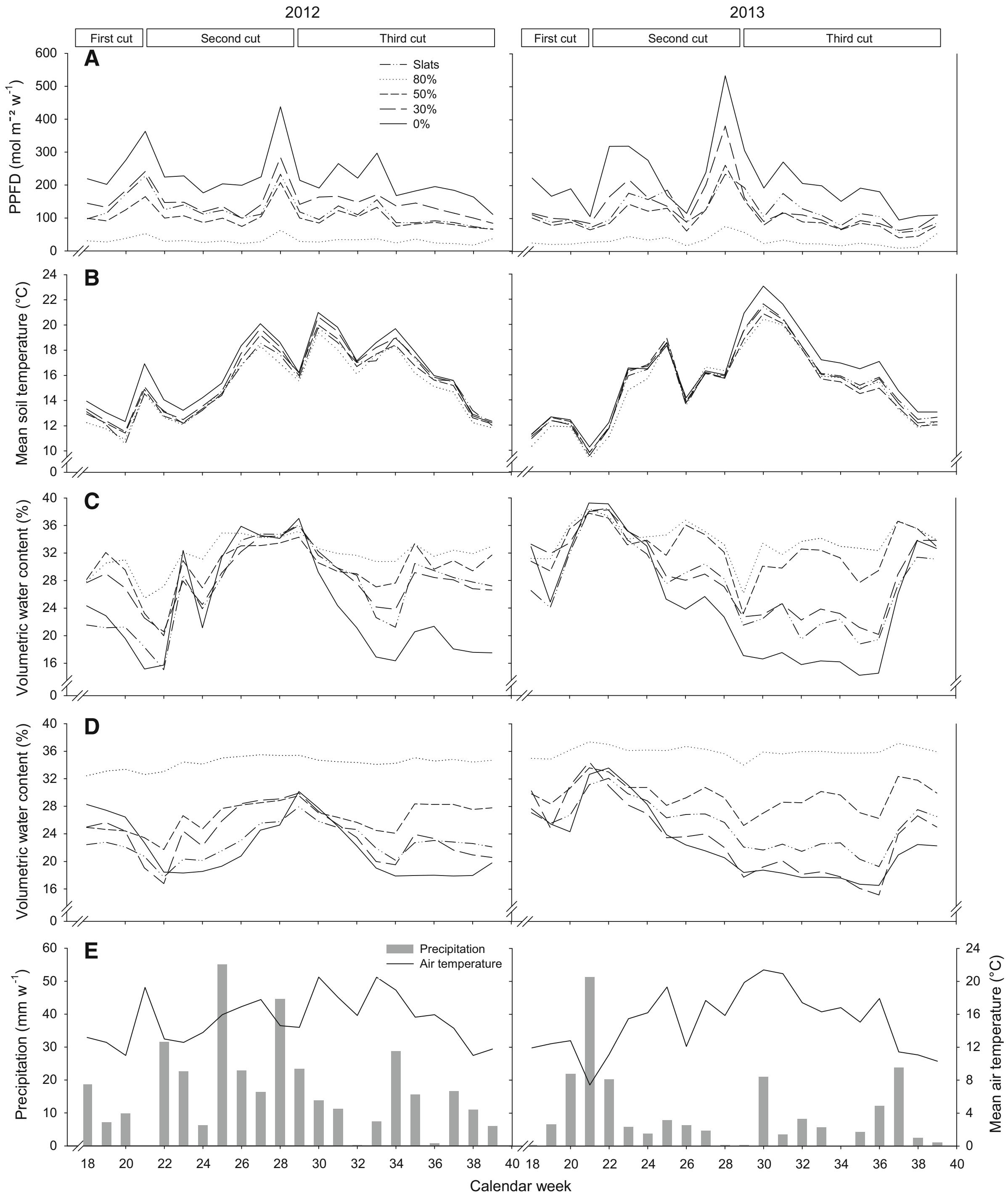


Fig. 2 Environmental parameters measured under different levels of shading (0, 30, 50, 80 % and a slatted structure with 50 % shade). Displayed are weekly values of **a** mean photosynthetic photon flux density (PPFD), **b** mean soil temperature at 5 cm depth, mean volumetric soil moisture content at 15 cm **c** and 35 cm **d** depth, **e** total weekly precipitation between April and September in 2012 and 2013 at the study site in southern lower Saxony, Germany, central Western Europe

Table 1 Mean cumulative transmitted photosynthetically active photon flux density (PPFD), mean soil temperature (°C) and mean volumetric soil moisture content (%) at 15 and 35 cm depths during 30 April–30 September in 2012 and 2013

Shade level	PPFD (mol m^{-2} w^{-1})				Soil temperature (°C)				Volumetric soil moisture content (%)			
	2012		2013		2012		2013		2012		2013	
	M ± SEM[§]	Δ (%)	M ± SEM	Δ (%)	M ± SEM	Δ (°)	M ± SEM	Δ (°)	15 cm M ± SEM	35 cm M ± SEM	15 cm M ± SEM	35 cm M ± SEM
0 %	4946 ± 4.3	0	4678 ± 10.8	0	16.3 ± 0.16		15.9 ± 0.13		24.0 ± n.d.[‡]	22.0 ± 1.17	25.2 ± n.d.[‡]	22.7 ± 0.01
30 %	3270 ± 2.7	34	2823 ± 0.3	40	15.7 ± 0.09	−0.52 °C	15.2 ± 0.28	−0.71 °C	28.3 ± 0.13	23.9 ± 4.27	28.8 ± 0.26	23.6 ± 0.03
50 %	2259 ± 1.2	54	2196 ± 3.6	53	15.4 ± 0.15	−0.85 °C	15.1 ± 0.40	−0.86 °C	29.8 ± 1.07	26.4 ± 1.23	32.4 ± 0.01	29.6 ± 0.02
80 %	697 ± 3.2	86	681 ± 0.1	85	15.0 ± 0.01	−1.28 °C	14.8 ± 0.08	−1.07 °C	31.8 ± 2.83	34.3 ± 0.13	33.9 ± 0.00	36.0 ± 0.00
50 % slats	2660 ± 11.2	46	2656 ± 12.1	43	15.4 ± 0.03	−0.90 °C	15.2 ± 12.13	−0.68 °C	27.1 ± 1.31	22.8 ± 1.66	27.3 ± 0.03	25.4 ± 0.03
Probability[†]												
First cut	***		*		***		ns		ns	ns	ns	ns
Second cut	***		***		**		ns		ns	ns	ns	ns
Third cut	***		***		*		ns		ns	*	*	**

Treatment effects were tested separately for each cutting period (first cut form calendar week 18–21, second cut from 22 to 29, and third cut from 30 to 39)

ns not significant

§ Mean ± standard error of the mean 'SEM'

‡ Not defined 'n.d.'

Δ Difference compared to control

† *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$

in the upper soil layer and 19 % reduced in the deeper soil layer, compared to the severe shade. Soil moisture content under the light shade treatment differed from the severe treatment by 13 % in the upper layer. Soil moisture content under the slatted treatment with medium shade differed from the severe shade in the upper layer by 17 %, and in the deeper layer by 16 %. In comparison, soil moisture under the cloth with medium shade was reduced by only 5 % in the upper layer and by 11 % in the deeper layer, compared to the severe shade treatment. Generally, soil moisture variation was larger under the lower shade treatments and after rainfall. Comparing the cumulative precipitation of both years from 30th April to 30th September, the amount of rainfall was lower in 2012 (370 mm) than in 2013 (424 mm). Variations in moisture patterns, rainfall distribution and air temperature indicated that moisture depletions were more prominent in 2012 than in 2013.

Herbage production

Total annual herbage production was highest in non-shaded swards in both 2012 and 2013 (8 and 16 t DM ha^{-1}, respectively; Fig. 3) and declined with increased shade. Severe shade resulted in maximum yield reduction by nearly 70 % in both years, while light and medium shade led to intermediate productivity. Linear contrasts did not reveal any difference in yield between shade by 50 % shade cloth and slats. While shade did not impose a yield reduction in the first cut of 2012, yield decline due to shade increased

Fig. 4 Dry matter contribution of functional groups (grasses, ▶ white clover, forbs) and dead material under different levels of shade cloth (0, 30, 50, and 80 %) and a slatted structure (50 %) in 2012 and 2013. Inter-correlation among the functional groups was low (mean correlation coefficient <0.1) in both years

in the following cuts of the same and the following year.

Sward composition

Shade reduced clover and increased grass contribution in both experimental years (Fig. 4; Table 2). While clover contribution decreased in 2012 from 70 % of DM in the control to 40 % of DM under severe shade, it was lower in 2013 even in the control (50 % of DM) and declined to 7 % of DM under severe shade. In the first year, the decline of clover became apparent only in the third cut. Forbs and dead material were of marginal importance in all cuts (Fig. 4). In contrast, contribution of forbs remarkably increased under severe shade (40 % on average across all cuts) in 2013, and dead material increased from first to third cut, but without a clear effect of shade. Sward composition did not differ between 50 % shade cloth and 50 % slats in both years.

Herbage quality

There was no significant influence of shade on herbage quality, irrespective of year and cutting date (Table 2). The weighted mean (±standard deviation) of two replicates from any year, shade treatment, and cutting combination on a dry matter basis was 2.7 ± 0.28 %

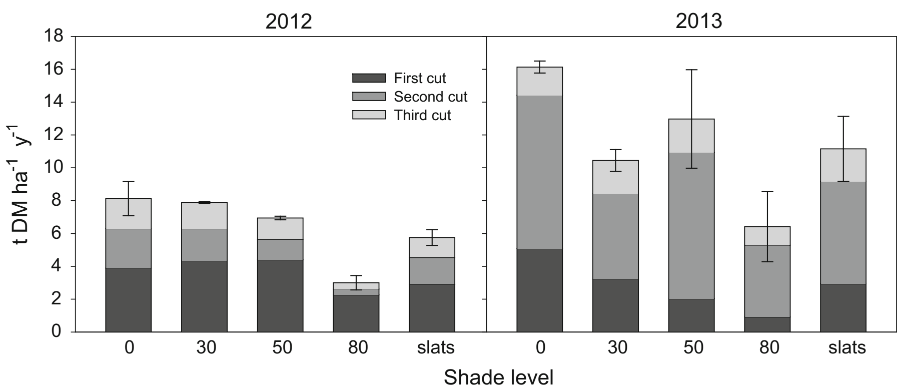


Fig. 3 Total annual herbage production of a white clover/perennial ryegrass sward under different levels of shade cloth (0, 30, 50, and 80 %) and a slatted structure (50 %) in 2012 and 2013

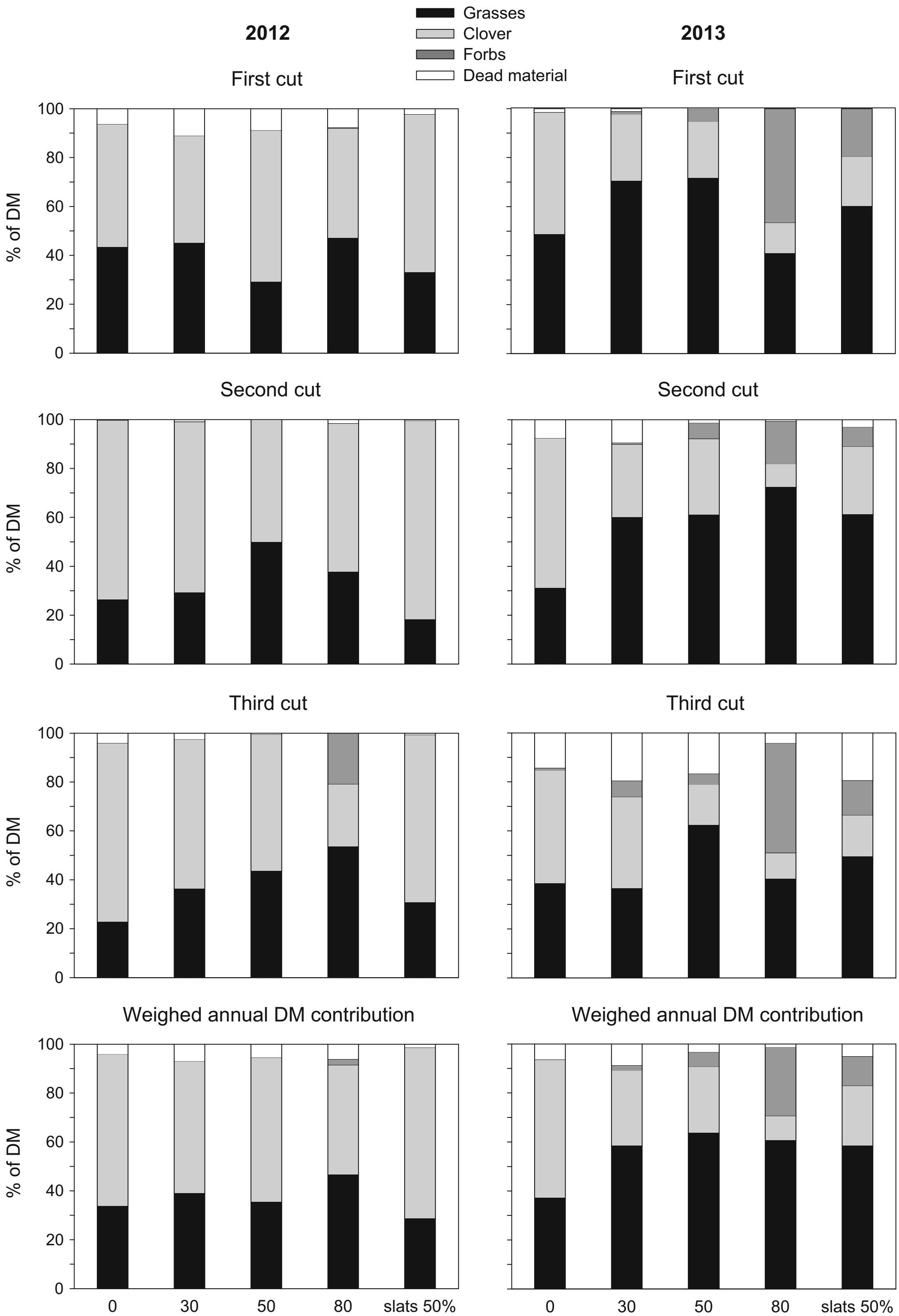

Grasses
Clover
Forbs
Dead material
2012
2013
First cut
Second cut
Third cut
Weighed annual DM contribution
% of DM
0
20
40
60
80
100
0
30
50
80
slats 50%

Table 2 Effects of shade and year on total annual herbage production and weighted mean dry matter (DM) contribution of the functional groups grasses, clover and forbs and nitrogen, ADF and ADL concentration in 2012 and 2013

	Shade	Year	Shade × Year
Total herbage production (t DM ha^{-1} a^{-1})	***	***	ns
Grasses (% of DM)	ns	**	ns
White clover (% of DM)	*	***	ns
Forbs (% of DM)	**	***	*
Nitrogen concentration (% of DM)	ns	ns	ns
ADF concentration (% of DM)	ns	ns	ns
ADL concentration (% of DM)	ns	ns	ns

ns not significant

*** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$ not significant 'ns'

for N, 41.8 ± 4.47 % for NDF, 34.4 ± 3.13 % for ADF, and 4.7 ± 0.74 % for ADL. Minimum and maximum values ranged on a dry matter basis from 1.9 to 3.1 % for N 27.2 to 48.6 % for NDF, 23.6 to 38.0 % for ADF, and 2.8 to 5.8 % for ADL.

Discussion

There is ample knowledge that shade by trees reduces plant yield (Devkota and Kemp 1999; Li et al. 2008; Peri et al. 2007; Perry et al. 2009). However, yield reduction varies and strongly depends on the level of shade (Belesky 2005a; Peri et al. 2007; Devkota et al. 2009). Previous studies showed that some forage grasses and legumes grown at 50 % full sun achieved similar dry matter yields to the non-shaded control (Lin et al. 1999). To gain information on the effect of shade on the dynamics of some agriculturally relevant sward characteristics, we exposed an unfertilized white clover/ryegrass mixture to different levels of artificial shade over two succeeding growing seasons. Compared to the non-shaded control (24 t ha^{-1}), 50 % shade cloth and 50 % slatted structure reduced biennial herbage production by 4 and 7 t ha^{-1}, respectively. Contrary to pure grass swards, yield formation in species mixtures is a final outcome of species-specific responses to various environmental factors and of a complex set of intra- and inter-specific interactions (Kirwan et al. 2007; Sanderson et al. 2006; Wachendorf et al. 2001).

Shade reduced the sward productivity, and influenced the change of several microclimatic parameters, of which plant available radiation was the most prominent. A decline in clover content of up to 93 % compared to the non-shaded control in the second year of the field experiment highlights the sensitivity of clover to reduced radiation. Wachendorf et al. (2001) concluded from a European multi-site experiment on clover/grass systems, that radiation is the main driving force in the annual cycle of clover growth and that poor sward clover content in spring persists throughout the summer. There is also evidence that ryegrass is more susceptible to environmental stress (i.e. reduced radiation) than other cool season grasses like *Dactylis glomerata* L. or *Bromus inermis* Leyss. (Devkota et al. 2009; Lin et al. 1999; Van Sambeek et al. 2007). Therefore, the low shade tolerance of ryegrass and white clover may have limited the productivity of swards investigated in this study compared to other temperate pasture species.

The presented artificial shade experiment was accompanied by research on an adjacent alley cropping system composed of clover/grass and willows. By comparing the actual shade pattern of the willows on the adjacent clover/grass alleys in the agroforestry system, the light quantity of the 30 % shade cloth treatment was most similar (data not shown). Since the willows were planted in 2011, the influence of shade on the productivity of the clover/grass alleys might have been rather low. However, it is suggested that the combination of shade from trees with intra-seasonal and annual fluctuations of photoactive radiation reinforces the impact of shade on the success of clover/grass alleys in agroforestry systems in a long term perspective.

In this experiment only light quantity was measured as PPFD, but not light quality i.e. the spectral composition. Light quality can be measured in red to far red ratio due to its strong correlation to the state of the phytochrome equilibrium (Leuschner et al. 2006). The phytochrome system of plants alters their growth and metabolism (Baraldi et al. 1995). Regarding forage plants, it is known that the ratio of red to far red light changes stolon growth in clover (Robin et al. 1994) and also tillering in grasses (Davis and Simmons 1994). In agroforestry systems, tree canopies absorb both the longest and the shortest wavelengths of the visible light spectrum (red and blue light being effective for photosynthesis) (Jose et al. 2009). The understory mainly receives diffuse radiation primarily composed of medium wavelengths (green and far-red being not effective for photosynthesis). Therefore, the red to far-red ratio is lower in the understory because canopy leaves absorb more red light than far-red (Holmes and Smith 1977).

In forests and agroforestry systems the red to far red ratio can vary greatly because of sunflecks. For the reproduction of sunflecks in an artificial shade experiment slatted structures are suitable shade materials. In the presented experiment, we mimicked the orientation of the willows within the adjacent agroforestry system and chose accordingly an east–west orientation of the slats. Therefore, some plants of the sward were exposed to longer periods of full sun and some to longer periods of dense shade through the day. A north–south orientation would have produced a series of sunflecks and dense shade of a shorter duration which might have produced more favorable light conditions for clover/grass.

Several studies have compared the development of understory under slatted structures and shade cloth with similar light transmittance, and have shown that slatted structures were very effective at reproducing the periodic light fluctuations in radiation transmittance and spectral composition of trees (Varella et al. 2011; Peri et al. 2007). Obviously, periods of full sun and dense shade are more distinct under slats compared with shade cloths, altering the ratio of red to far red between the two shade materials (Peri et al. 2007), which may have eventually affected sward development. In this study slats and cloths in the 50 % shade treatment produced a similar light transmittance. However, microclimatic characteristics, productivity and sward composition of the sward under the slatted structure responded slightly different to that under the shade cloth. For example, soil moisture content was higher under the shade cloth, which may be related to no periods of full sun under the uniform shade regime of the cloth.

On the other hand, the slats probably produced stronger evapotranspiration in periods of full sun, which might be a cause of the lower yield. Herbage production under the slats was lower than under the shade cloth, even though the slats allowed greater quantity of light. Sward composition was also different to that under cloth. It is proposed that the differences in yield and sward composition are due to the light quality. Possibly, the filtering of light by the slats caused a different ratio of red to far red which had an impact on sward growth. Results of Varella et al. (2011) showed that, under slats and trees, the amount of red and far red light was severely reduced. The differences in spectral composition between the treatments were less pronounced under diffuse light conditions. Varella et al. (2011) investigated an alfalfa stand under 40 % shade cloth, which reproduced similar light quantity to the trees in the neighboring agroforestry system. The amount of red and far red light decreased in proportion to the reduction in PPFD quantity, but the red to far red ratio remained the same.

In the second year of the experiment the dry matter contribution of forbs was higher under the slats than under light and medium shade cloths, which may be due to the shade sensitivity of ryegrass and white clover to the periodic light fluctuations, whereas forbs, mainly segetal species in this study, have broader amplitudes of shade tolerance (Ellenberg et al. 1992). Furthermore, the sward development in 2013 was already influenced by the shade treatments of the previous year.

Soil temperature was significantly lower in the shaded treatments in all cuts of 2012 and in the last cut of 2013. On the one hand, continuously low soil temperatures, especially in spring, may cause a retarded growth of the clover/grass sward and a shift in sward composition towards lower clover content (Wachendorf et al. 2001). On the other hand, light shade can ameliorate growth conditions by reducing evapotranspiration during peak temperatures (Belesky 2005b). This may have been the case in the third cut in 2013, where high temperatures and low soil moisture content limited the productivity of the non-shaded control, whereas sward growth was enhanced in most shaded treatments.

Previous studies on sward composition in a silvopastoral system in New Zealand found an increase in grass content and a decrease in clover content of the understory pasture (Douglas et al. 2006). The consequences of reduced clover content in the shaded swards might diminish their functionality in the ecosystem, e.g. by a reduced N fixation rate and by reduced floral fodder supply for pollinators. If a white clover/perennial ryegrass mixture is integrated as an understory in a temperate agroforestry system, i.e. alley cropping with forage crops or a silvopastoral system, the long-term effects of shade on sward productivity and composition have to be considered.

No influence of shade on fiber content (NDF, ADF and ADL) of the harvested biomass was detected, which is consistent with studies from Lin et al. (2001) and Peri et al. (2007). Furthermore, no changes in N content were established along the shade gradient, which was also reported from an alfalfa-black walnut alley-cropping practice in Missouri, USA (McGraw et al. 2008). In contrast, numerous experiments in temperate and Mediterranean regions reported an increase in N content (as a component of protein) for shade-grown pure stands of cool-season grasses (Burner and Belesky 2004; Burner and Brauer 2003; Abraham et al. 2014; Sanchez-Jardon et al. 2010). This suggests that a binary structured clover/grass sward responds differently to shade than non-leguminous and/or sole-cropped swards. The mixture in the present study was composed of ten different cultivars of ryegrass with widely differing spring flowering dates and one clover cultivar. The interactions between them may have generated facilitative as well as competitive effects, which may have been reinforced under the impact of shade.

Hence, the increase in N content observed for shaded pure grass swards in the previously mentioned studies cannot be simply transferred to clover/grass mixtures, as the simultaneous decline of clover contribution may prevent an increase in N content in the overall harvested biomass. This assumption is supported by the fact that clover N fixation may be reduced, both by the reduction in clover content of the sward (Høgh-Jensen et al. 2004), and by reduced energy supply from the host plant to the N fixing rhizobium bacteria through shade (Thomas and Bowman 1998; van der Heijden et al. 2006). In a study on the effects of shade on growth and nodulation of three native legumes with potential for use in agroforestry, it was reported that both the number of nodules and total plant biomass decreased proportionately for two of the three legume species when grown in hydroponic solutions in a greenhouse with full sunlight reduced to 20 % (Houx et al. 2009).

Conclusions

The aim of this study was to quantify the effects of shade on a white clover/perennial ryegrass mixture under field conditions by exposing the sward to different shade levels between 0 and 80 %, which may also occur at different developmental stages of trees in agroforestry systems. Shade by 80 % reduced herbage productivity on average by 50 % compared to a non-shaded control. White clover as a heliophilous plant responded negatively to increasing shade, whereas forbs (mainly segetal species) benefited. Effects on nutritive value by shade could not be confirmed by the biennial field experiment. Although the experimental design did not enable interpretation of the various microclimatic effects on plant growth, the findings show it is feasible to manage white clover/ryegrass swards under low to moderate shade as an understory in temperate agroforestry systems in central Western Europe. For a comprehensive evaluation, long-term effects of shade on white clover/perennial ryegrass swards as understory in temperate agroforestry systems need to be considered in future research activities.

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