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Productivity at the tree-crop interface of a young willow-grassland alley cropping system

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Abstract Alley cropping multi-rows of shrub willow hybrids and grassland is a promising temperate agroforestry practice for an environmentally sound provision of bioenergy feedstock. The effect of willows, aged 2–3 years, on two grassland mixtures (clover-grass, diversity oriented mixture) was determined at three positions along the tree-crop interface at a study site in Central Germany. Willows modified the incident light on understory along the interface. Biennial mean daily light integral at position south-west (SW) was 22 mol m^{-2} w^{-1}, in the center of the alley 30 mol m^{-2} w^{-1} and at position north-east (NE) 26 mol m^{-2} w^{-1}. Accordingly, soil temperature was lower at the positions SW and NE being adjacent to the willows. There was no clear pattern of the distribution of volumetric soil moisture content along the tree-crop interface in 15 cm depth, except that moisture content was highest in 35 cm depth at SW position in both years. In the early establishment phase, the diameter at breast height (DBH) of pooled inner willow rows (17 mm) was significantly different from pooled outer rows (21 mm). Direction had a significant influence on DBH in 2012, but not in 2013. The impact of willows on productivity of the two grassland mixtures was not confirmed until the third year after establishment. Dry matter yield was on par with those reported for single-cropped grassland adjacent to the agroforestry system. Sward composition of clover-grass changed along the tree-crop interface. Dry matter contribution of legumes was lower at the position SW. No remarkable impact of trees on quality parameters of grassland mixtures were found along the interface. Horizontal and vertical growth of the trees may modify the microclimate during the life-span of the alley cropping system consisting of willows and grassland. More research is needed on long-term monitoring of competitive, complementary and facilitative effects along the tree-crop interface.

Keywords Alley cropping · Grassland · Interactions · Sward composition · Willow · Yield

Introduction

Intercropping lignocellulosic or cellulosic crops in temperate agroforestry systems shows particular promise for an environmentally sound provision of bioenergy feedstock (Gruenewald et al. 2007; Holzmueller and Jose 2012; Gamble et al. 2014). Suggested lignocellulosic crops are, for example, fast-growing

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tree species like willow or poplar grown under a short rotation coppice (SRC) regime. SRC has received particular attention over the last 30 years for its high potential dry matter yield and suitability for use in conventional combined heat and power plants (Ericsson et al. 2012). Also perennial grasses produce large biomass yields with relatively few inputs compared to annual crops and can be appropriate biofuel candidates (Heaton et al. 2008; Albaugh et al. 2014).

Historically, the coexistence of trees and grassland/pasture has been a common land use practice as a means of income diversification or erosion control in the temperate zones (Pollock et al. 1994; Douglas et al. 2006a; Gargaglione et al. 2014). The agroforestry practices applied were mainly silvopastoral systems or pasture combined with widely spaced or scattered trees. In general, positive (facilitation) or negative interactions (competition) or complementary effects can appear while intercropping woody and non-woody (understory, herbaceous) components (Gargaglione et al. 2014).

Comprehensive studies in New Zealand on interactions between rows of young *Pinus radiata* D.Don (3 years) intercropped in pasture (clover-ryegrass, ryegrass, lucerne, and bare ground as control) showed a reciprocal yield relationship with lowest tree weight during a one-year-period in the agroforestry plots, when lucerne or clover-ryegrass were grown as understory (Yunusa et al. 1995). Douglas et al. (2006a, b) conducted a 3-year research on widely spaced intermediate aged poplar (8–11 years) and pasture in New Zealand and found that understory pasture received 33 % less radiation relative to the open pasture. Furthermore, the poplars under temperate climate had significant effects on surrounding aerial and soil hill pasture micro-environment (Douglas et al. 2006a). In a second study on widely spaced poplar (8–11 years) and introduced pastures species, including legumes, understory production and composition was significantly affected by intermediate aged poplar, e.g. decrease in legumes under trees, reduction of 23 % of pasture growth under trees (Douglas et al. 2006b).

Guevara-Escobar et al. (2007) stated pasture accumulation of 40 % less under mature poplar (>29 years, 34–40 stems/ha) than under young poplar (5 years, 50–100 stems/ha) and changes in sward composition. Therefore, they suggested a frequent control of tree canopy. Silvicultural practices should be imposed to improve penetration of solar irradiance to the understory crop (Burner and Belesky 2008). For example, site selection (i.e. direction, slope) and practices like thinning, pruning or logging created favorable light conditions for the understory crops (Garrett et al. 2004).

Alley cropping or growing a crop between rows of trees might be a convenient temperate agroforestry practice in certain agricultural production zones to improve total light energy capture and productivity per unit land (Reynolds et al. 2007; Burner and Belesky 2008; Holzmueller and Jose 2012). Studies on black walnut and alley cropped smooth brome showed that grass yield was lower in the center of the alleys than in open area with no tree influence (Geyer and Fick 2015). Gamble et al. (2014) reported that alley crops (switch grass, prairie cord grass, mixture of three grassland species and polyculture) showed no evidence of competition from multi-rows of poplar or willow in the third year after establishment.

The examples showed the success of understory and overstory in temperate agroforestry systems is highly site, species and age specific. Therefore, it is important to minimize resource competition between trees and crops, while maximizing the use of available resources, to improve yield and overall productivity in alley cropping (Zamora et al. 2009). As Thevathasan and Gordon (2004) stated, understanding the ecological interactions between trees and crops in intercropped systems is crucial for designing efficient systems with potential for wider applicability. Information on yield performance in spatio-temporal dimensions is necessary to evaluate the success/potential of temperate alley cropping systems.

Until now little information is available on the overall performance of temperate alley cropping systems based on willow SRC and perennial herbaceous grassland species. Therefore, the present study aimed to understand possible interactions at the tree-crop interface of a young alley cropping system consisting of willows in multi-rows and grassland as crop in the alleys for biofuel production. Since productivity, sward composition, and quality are important values for the economic success of a grassland-tree-system, an approach was developed to monitor the interactions along the tree-crop interface which is later referred to tree-grassland interface. Following research questions were addressed: (i) is there an effect of willows on aerial and soil micro-environment within the grassland alleys, (ii) does growth within the multi-rows of willows alter in space and time, (iii) is there a shift in understory productivity along the tree-grassland interface during early establishment, and (iv) does sward composition and quality alter along the tree-grassland interface.

Materials and methods

Site and design

This study was conducted as a part of an alley cropping experiment established in Lower Saxony (51°39′83″N and 9°98′75″E, 325 m a.s.l.), Central Germany, in 2011. Climate at the experimental site was characterized as temperate with an average temperature of 9.2 °C. Mean annual precipitation was 642 mm over a 20 year period (Hartmann et al. 2014). The predominant soil type is classified as a stagnosol according to the FAO World reference of soil resources (IUSS Working Group 2006), and consisted of sedimentary deposits from sandstone, siltstone and claystone (Hartmann et al. 2014). The preceding crop on the experimental area was winter barley.

The alley cropping experiment covered a total of 0.7 ha and was a factorial combination of two understory types (two grassland mixtures) in a split-plot randomized block design and multi-rows of shrub willow hybrids, each replicated three times (Fig. 1a). Willow rows were 7.5 m wide and 80 m long. The alleys were 9 m wide and 80 m long and each divided into 12 plots (9 m wide and 6.5 m long). Alley orientation was north-west to south-east.

Microclimate

Soil moisture content, soil temperature and precipitation

Soil moisture and soil temperature recordings were started in an unfertilized clover-grass plot (CG, 0 N, 3-cut) of one alley of the agroforestry system from March 2012 to September 2013. Measurements were made at three positions along an interface of an alley between two shrub willow multi-rows within the alley cropping system (Fig. 1b):

1. at the position south-west (SW) 1 m from the outer willow row
2. at the position in the center of the alley (C)
3. at the position north-east (NE) 1 m from the outer willow row

EC-5 soil moisture sensors were used to record volumetric soil moisture content in 15 and 35 cm soil depth below soil surface at each position by measuring the dielectric constant of the media using capacitance/frequency domain technology (Decagon Devices, Inc. Pullman, WA, USA). To avoid disturbances in measurements the sensors were buried slightly shifted from each other. Soil temperature records were taken at 5 cm soil depth below soil surface at each position (Decagon Devices, Inc. Pullman, WA, USA). Precipitation was measured along the tree-grassland interface of an adjacent plot with a permanent stubble height of 5 cm. The rain gauges (Decagon Devices, Inc. Pullman, WA, USA) were mounted on metal arms at a level of 15 cm above soil at the positions SW, C, and NE. The resolution of the rain gauges was 0.2 mm and the sensor type used was a double-spoon tipping bucket.

Photosynthetically active photon flux density (PPFD) and daily light integral (DLI)

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, Decagon Devices, Inc. Pullman, WA, USA). 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 sensors were mounted on a metal arm at a level of 15 cm above soil to record the light quantity absorbed by the grassland species. The sward was permanently kept at a stubble height of 5 cm. PPFD was taken at three positions along an interface between two shrub willow rows. The positions were chosen in accordance to the biomass and soil moisture/temperature measurements. All data on microclimate were measured every minute and hourly means (soil moisture and soil temperature) or totals (PPFD) stored on data loggers. The data for calculations were processed from budburst (30th April) to leaf fall (30th September) in 2012 and 2013, respectively.

The daily light integral (DLI) was defined as a measurement of a total amount of photosynthetically active photon flux density delivered over a 24-hour period (Korczynski et al. 2002). DLI was calculated

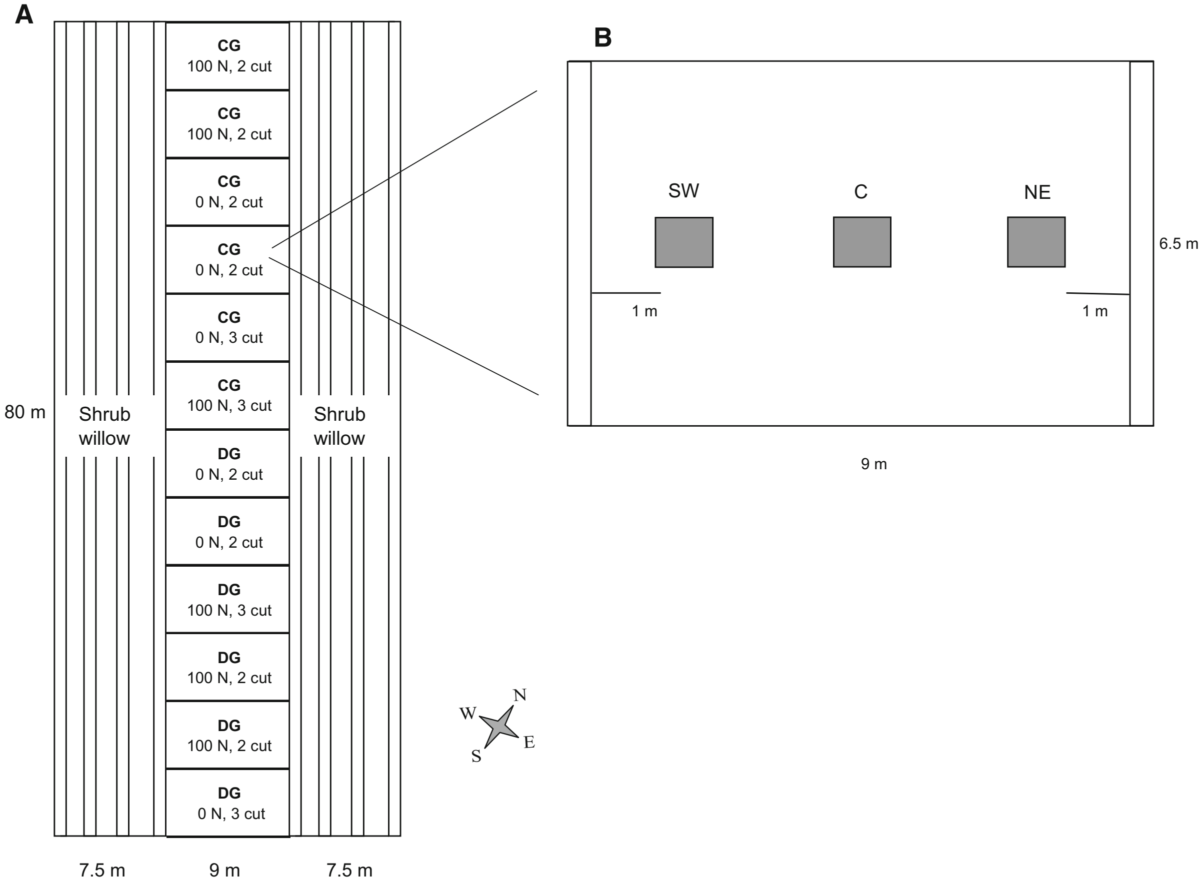

Fig. 1 Schematic representation of the experimental design showing an alley of clover-grass (CG) and a diversity-oriented grassland mixture (DG) integrated in multi-rows of shrub willow hybrids. As experimental factors different cutting regimes and fertilization levels for CG and DG were included in the split-plot alleys of the agroforestry system with three replicates: (i) Two cuts per year which is later referred to (2-cut). (ii) Three cuts per year which is later referred to (3-cut). The fertilization levels applied were 0 kg N ha^{-1} yr^{-1} (0 N) or 100 kg N ha^{-1} yr^{-1} (100 N). Samples were taken along the tree-grassland interface for each replicate of the alleys, in the centre of each plot (*C*) and adjacent to the willow rows *SW* and *NE* as shown in the sketch (*B*). Also, soil moisture content, soil temperature, precipitation and PAR were measured at these positions, but only along the interface of one plot in one alley

for each day and position along the interface. Then weekly average of DLI was taken for each position and within the time period from March to September 2012 and 2013, respectively.

Trees

Dormant stem cuttings with 3–4 buds of the willow clone (clone ‘Tordis’, *Salix schwerinii* × *S. viminalis* × *S. vim.*) were planted by hand using a double-row system with 1.5/0.75 m spacing at a density of 12,000 trees per ha in March 2011. No herbicides and no fertilizer were applied within the rows of willows in the agroforestry system. Weed management was done manually by hoes and by lawn mowers.

Willow growth data were collected annually from 2011 to 2013. Tree height of the main shoot was measured by height pole. Diameter at breast height (DBH) (1.30 m above ground) was measured with a caliper. DBH of every shoot per single willow (coppiced willows produce multiple shoots) was added as a sum of total diameter. Average total diameters were calculated using arithmetic means. Ten trees per single row of willows were examined—in total 320 trees. All measured trees were sorted into five classes of different DBH. With respect to the DBH classes, 15 trees from the edge area and 15 trees from the centre area were selected randomly for harvesting and cut at a stump height of 0.10 m. Based on the biomass yields of the harvested trees and their DBH regression models were developed and applied to all trees investigated. Yield was estimated by using the allometric power equations, as high accuracies were shown for willows (Verwijst and Telenius 1999; Hartmann et al. 2014). Further details of the methodology are described in Ehret et al. (2015a).

Grassland

In the alleys of the agroforestry system two grassland mixtures were established in March 2011: a mixture of *Trifolium repens* L. and *Lolium perenne* L. (clover-grass, CG) and a diversity-oriented mixture with 32 species (DG). The species composition of DG is provided as supplemental material. As experimental factors different cutting regimes and fertilization levels for CG and DG were included in the split-plot alleys of the agroforestry system with three replicates: (i) two cuts per year which is later referred to 2-cut, (ii) three cuts per year which is later referred to 3-cut. The fertilization levels applied were 0 kg N ha^{-1} yr^{-1} (0 N) or 100 kg N ha^{-1} yr^{-1} (100 N). Samples of grassland biomass were taken in the alleys along the tree-grassland interface for each replicate: in the centre of each plot (C) and adjacent to the willow rows SW and NE (Fig. 1a, b).

For the determination of herbage fresh mass, samples were taken from subplots sizing 50–50 cm along the interface at the position SW, C, and NE for each treatment in the grassland alleys and for each harvest date in 2012 and 2013. Samples of 100–200 g from each subplot were dried at 105 °C for 48 h, and weighed to determine herbage dry matter content. Biennial dry matter yield was calculated as the sum of all cuts from 2012 and 2013. Sward composition was determined by separating the biomass samples into the following functional groups: grasses, forbs and legumes. 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, ground to pass through a 1 mm screen with a FOSS sample mill (CyclotecTM 1093, Haan, Germany) and analyzed for the quality parameters nitrogen (N), acid detergent fiber (ADF), acid detergent lignin (ADL) and neutral detergent fiber (NDF) according to standard methods (Biewer et al. 2009).

Statistical analysis

As the control plots of pure grassland and shrub willow stands were not integrated in the randomized factorial layout of the agroforestry field experiment, only the agroforestry treatments were analyzed statistically. Due to a lack of randomization the effect of position along the tree-grassland interface was not tested in the statistical model. Cutting frequency and fertilizer treatments of alley-cropped grassland (sub-plot factors) were assigned randomly in a split-plot arrangement within each grassland mixture treatment (M; main-plot factor) and block (B). The cutting frequency treatments (C) were (i) two cuts per year and (ii) three cuts per year and the fertilizer treatments (F) comprised (i) control (no treatment) and (ii) N fertilization (100 kg N ha^{-1}). The mixture treatments were (i) standard white clover/perennial ryegrass seed mixture and (ii) diversity oriented seed mixture. Treatments, as well as all two- and three-way interactions were tested, using analysis of variance based on the mixed procedure in SAS (SAS Institute Inc., Cary, North Carolina, USA). The split-plot structure of the experiment was described by the random error terms $B \times M$, $B \times M \times C$, $B \times M \times F$ in the model. 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

PPFD and DLI

From April to September in 2012 and 2013, respectively, PPFD was aggregated on a weekly basis for the positions SW, C, and NE along the interface and compared to a non-shaded control neighboring the agroforestry system (Table 1). In 2012, PPFD values at position C were highest (4865 mol m^{-2} w^{-1}), intermediate at position NE (4618 mol m^{-2} w^{-1}), and lowest at the position SW (4450 mol m^{-2} w^{-1}). In general, less PPFD was available for the understory in 2013. At position C 4603 mol m^{-2} w^{-1} and at position SW only 3371 mol m^{-2} w^{-1} was measured. The PPFD value at position NE was 3991 mol m^{-2} w^{-1}. In comparison to the adjacent control, 10 % less PPFD was available for the understory in 2012 and 28 % less PPFD in 2013. At position NE, PPFD values differed 7 % from the control in 2012 and 15 % from the control in 2013. No changes in PPFD were observed at position C compared to the control.

During the second year after the establishment of the alley cropping system (2012), weekly means of the DLI discriminated barely between the positions SW and NE being next to the outer willow rows and between position C being in the centre of the grassland alleys (Fig. 2). In the third year after establishment (2013), the pattern of DLI changed concomitantly to the growth pattern and habit of the willows. The values of DLI were more distinct during periods with high solar radiation compared to the previous growing season. Mean values at position SW were 22 mol m^{-2} w^{-1}, at position C 30 mol m^{-2} w^{-1} and at position NE 26 mol m^{-2} w^{-1}.

Precipitation, soil moisture and temperature

There was no evidence that willows decreased the available rainfall to the grassland understory along the interface. Soil temperature in 5 cm depth at position SW and NE, both being adjacent to the outer willow rows, was lower than values in the centre of the grassland alley (position C) in 2012 and 2013 (Table 1).

Volumetric soil moisture content in 35 cm depth was highest at position SW along the interface in 2012 and 2013, respectively (Table 1). At position NE the soil moisture content in 35 cm depth was lowest, and at position C intermediate in both years. Unlike the volumetric soil moisture content in 15 cm depth showed lowest values at position SW in 2012, but highest in 2013. At position C and NE no remarkable differences revealed in both years.

Trees

Total height of willow increased among the years (82 cm in 2011; 245 cm in 2012; 397 cm in 2013). No significant differences in height were observed between pooled outer and pooled inner rows within the agroforestry system among the years. In the years of establishment mean DBH increment was low in the outer rows (edge) compared to the inner rows (center). In 2012, DBH of the willows in the outer rows adjacent to the grassland alleys was not significantly lower compared to the inner rows (Fig. 3). In the following season 2013, DBH more than doubled on average (9 mm in 2012; 20 mm in 2013). Significant differences occurred, when the DBH of pooled inner rows (17 mm) was compared to pooled outer rows (21 mm) in 2013. There were no significant differences in height between southwestern and northeastern outer

Table 1 Biennial mean cumulative transmitted PPFD, biennial mean soil temperature (°C) and biennial mean volumetric soil moisture content (%) at 15 and 35 cm depths measured in a clover-grass plot of the alley cropping system at three different positions along the tree-grassland interface in SW direction, in the center of the alley (C), in NE direction from 30th April to 30th September 2012 and 2013

Interface position	PPFD (mol m^{-2} wk^{-1})				Soil temperature (°C)				Volumetric soil moisture content (%)			
	2012		2013		2012		2013		2012		2013	
	Mean	Δ (%)	Mean	Δ (%)	Mean	Δ (%)	Mean	Δ (%)	15 cm mean	35 cm mean	15 cm mean	35 cm mean
SW	4450	−10.0	3371	−27.9	15.85	−2.4	15.67	−0.2	20.01	25.89	25.48	29.21
C	4865	−1.7	4603	−1.6	16.28	+0.17	16.21	+1.9	22.39	23.94	22.77	27.75
NE	4618	−6.6	3991	−14.7	15.62	−3.9	15.82	−0.6	20.78	23.29	23.56	26.49
Control	4946		4678		16.25		15.91		23.98	22.00	25.24	22.69

Δ difference compared to the control adjacent to the alley cropping system

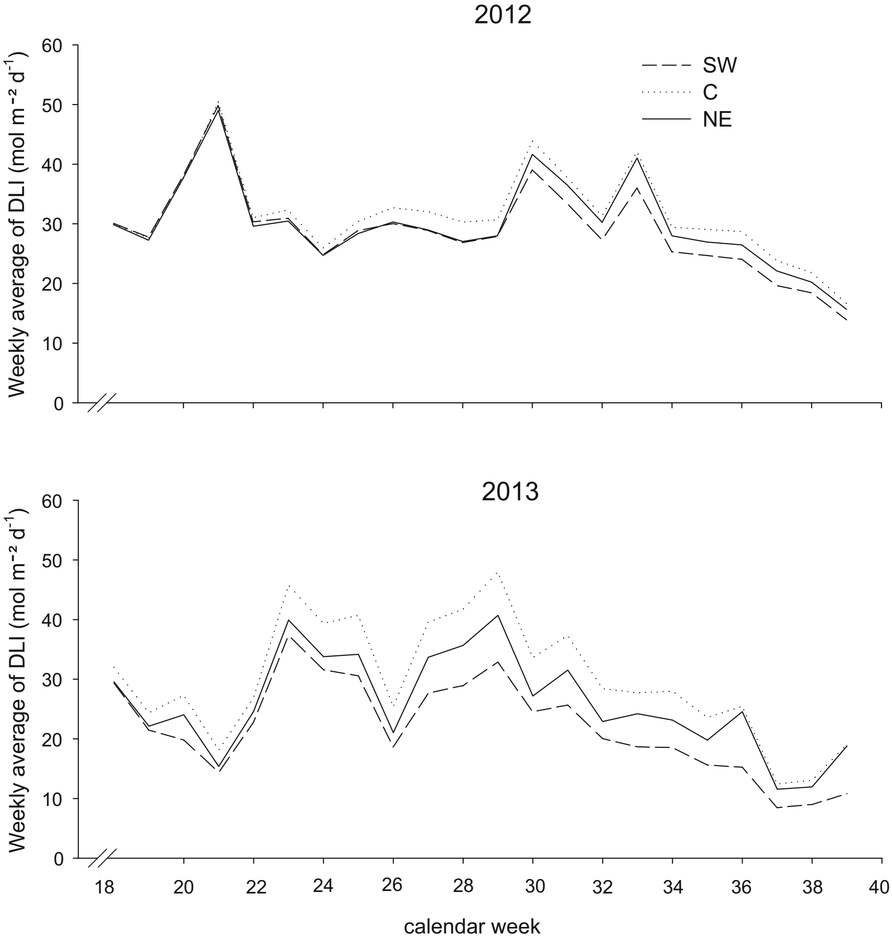

Fig. 2 Weekly average of DLI measured in a grassland plot of the alley cropping system at three different positions along the tree-grassland interface: (i) adjacent to the willows in *SW* direction, (ii) in the center of the alley (*C*), (iii) adjacent to the willows in *NE* direction from calendar week 18 (mid of April) to 39 (end of September) in 2012 and 2013. The sward in this plot was always kept on a stubble height of 5 cm

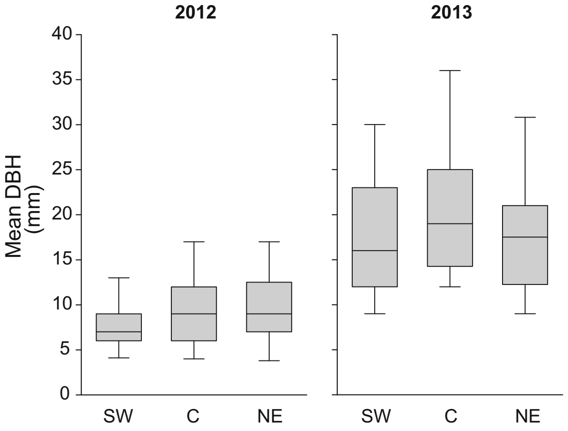

Fig. 3 Mean of diameter at breast height (DBH, mm) of intercropped shrub willow hybrids in the year 2012 and 2013 in the south-western edge row (*SW*) adjacent to the grassland alleys, in the center row (*C*), in the north-eastern edge row (*NE*) adjacent to the grassland alleys. Willows were established in the year 2011. Whiskers show the standard error of the mean

rows. Direction had a significant influence on DBH in 2012, but not in 2013. Estimated biennial dry matter yield at position SW was 3.9 t ha^{-1}, at position C it was 4.1 t ha^{-1} and at position NE 4.0 t ha^{-1}.

Grassland

Productivity

The impact of outer willow rows on productivity of CG and DG plots was not confirmed until the third year after establishment (Fig. 4). CG tended to be more productive in the center of the alleys and less productive at the SW position along the interface. DG showed lower biennial yields at position C compared to SW and NE in three of four treatments. In general, biennial dry matter yield of CG was in all treatments higher than that of DG. Fertilization affected the

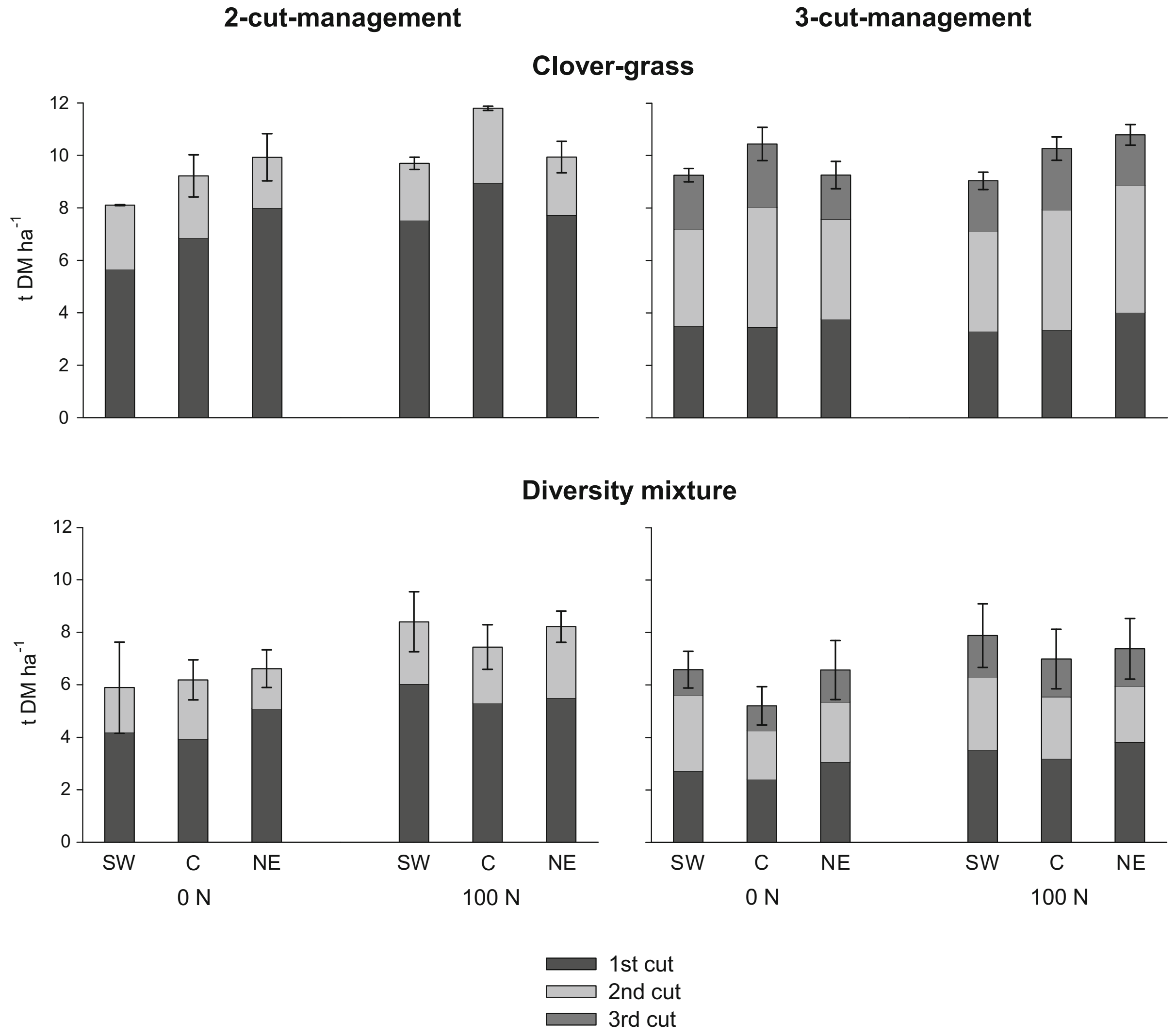

Fig. 4 Biennial mean of dry matter yield (DM) of clover-grass (CG) and a diversity-oriented grassland mixture (DG). Biomass was sampled at three different positions along the tree-grassland interface: (i) adjacent to the willows in *SW* direction, (ii) in the center of the alleys (*C*), (iii) adjacent to the willows in *NE* direction. The grassland was cut twice per year (2-cut-management) or three times per year (3-cut-management) and fertilized with 0 kg N ha^{-1} yr^{-1} (0 N) or 100 kg N ha^{-1} yr^{-1} (100 N). Whiskers show the standard error of the mean

biomass production of CG and DG more than cutting management ($P < 0.05$).

Sward composition and quality

Grasses were the predominant functional group in CG 0 N and 100 N in the 2-cut and 3-cut management (Fig. 5). The dry matter contribution of legumes in CG was lower at the position SW in all treatments. The dry matter contribution of forbs in CG was highest at the positions SW and NE being adjacent to the outer willow rows. In the 3-cut-management the total dry matter contribution of legumes was higher compared to the 2-cut-mangement. In general, legume contribution was low in the DG mixture. In the unfertilized treatment (0 N) of the 2- and 3-cut management of DG the dry matter contribution of grasses tended to be higher at the positions SW and NE along the interface and lowest for the fertilized (100 N). Contribution of forbs decreased with increased fertilization

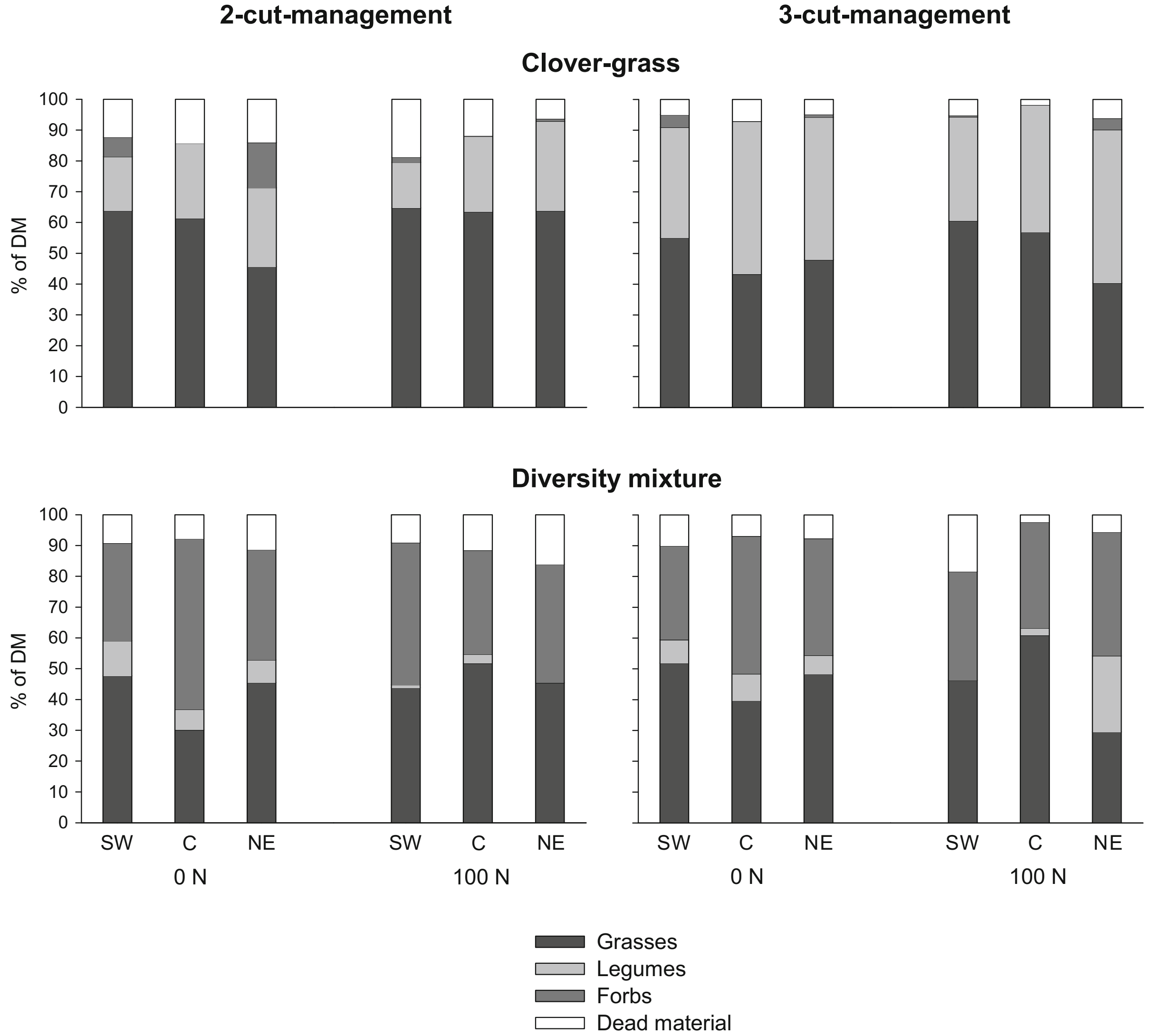

Fig. 5 Dry matter (DM) contribution of functional groups (grasses, legumes, forbs) and dead material of clover-grass (CG) and a diversity-oriented grassland mixture (DG) at three different positions along the tree-grassland interface: (i) adjacent to the willows in *SW* direction, (ii) in the center of the alleys (*C*), (iii) adjacent to the willows in *NE* direction as means of the growing seasons 2012 and 2013. The grassland was cut twice per year (2-cut-management) or three times per year (3-cut-management) and fertilized with 0 kg N ha^{-1} yr^{-1} (0 N) or 100 kg N ha^{-1} yr^{-1} (100 N)

application in all treatments of DG. Contribution of forbs in DG 0 N (2-cut and 3-cut) tended to be higher in the centre of the alley (position C).

No remarkable impact of trees on quality parameters for CG and DG mixtures along the interface was observed after the third year of establishment. There was a slight tendency for N concentration of CG to be lower at SW position compared to position C and NE. On a dry matter basis, average biennial quality values for CG were 2.3 % N, 46.6 % NDF, 37.1 % ADF, 5.6 % ADL and for DG 1.4 % N, 47.4 % NDF, 39.0 % ADF, 6.9 % ADL. N content seemed to be higher in the 3-cut-mangement for CG and DG. Unfertilized CG swards showed higher N contents than fertilized. DG samples contained slightly more ADF and ADL than CG.

Discussion

Microclimate

The competition for light is perceived as a major constraint of understory performance in multi-species temperate agroforestry systems (Chirko et al. 1996; Reynolds et al. 2007; Dufour et al. 2012), although the results are inconsistent. For example, Gillespie et al. (2000) found that edge rows received lower PAR compared to the middle rows in a red-oak-maize system. But once competition for water and nutrients was removed by root barriers to segregate tree and crop roots, shade was less important than belowground competition. It is supposed that maize as a C_4 plant responds differently to shade than cool-season grasses and legumes which are mainly C_3 plants (Reynolds et al. 2007). Forage species exhibiting the C_3 photosynthetic pathway have been shown to be more tolerant of shade in studies on temperate agroforestry systems (Lin et al. 2001; Delate et al. 2005). In our study, CG and DG at position SW were exposed to 24 % lower PPFD, with an average difference between alley and control of 902 mol m^{-2} w^{-1}. Concomitantly, mean values at position SW were 22 mol m^{-2} w^{-1}, at position C 30 mol m^{-2} w^{-1} and at position NE 26 mol m^{-2} w^{-1}; the differences between positions along the interface were more pronounced in 2013. However, this did not appear to have negative effects on the productivity of CG and DG 3 years after establishment. Other studies on light interactions have reported light reductions of 33 % upon the understory next to trees (Douglas et al. 2006a), which agrees with those measured in this study.

In addition to solar radiation trees can also influence soil moisture, soil temperature and precipitation in the alleyways (Jose et al. 2009). Guevara-Escobar et al. (2000) and Douglas et al. (2001) reported that poplars decreased the available rainfall to pasture understory and that the soil water content around trees was heterogeneous. In the present study, no differences in rainfall distribution along the interface could be observed. Volumetric soil moisture content in 35 cm depth was highest at position SW adjacent to the outer willow row, but lowest in 15 cm depth. Pollock et al. (2009) concluded that soil moisture content monitored under 2–6 years old radiata pine with three understory types of bare ground, lucerne and ryegrass/clover and under a control as open pastures were complementary in the first three or four growing seasons but this balance subsequently declined in favor of pine trees.

A further outcome of the present study was that shading lowered soil temperature in 5 cm depth at position SW and NE, both being adjacent to the outer willow row, compared to the centre of the grassland alley (position C). In a number of other studies higher soil temperature was measured as a result of greater irradiance (Jose et al. 2009).

Trees

Differences in DBH during early tree establishment between pooled outer and inner willow rows were consistent with results from a study on mixed hardwood (*Juglans* spp.) alley cropping, where tree growth responded negatively to understory (mainly grass species) in immediate proximity to the tree trunk (Burner et al. 2015). In the present experiment, the difference in growth between outer and inner willow rows was mainly related to unfavourable rainfall distribution after planting. In a site with substantial soil moisture deficit after planting understory belowground competitions could have negatively affected tree root growth which was also stated by Pollock et al. (2009) under 2–6 year *P. radiata* D.Don intercropped with different pasture species. Although no significant influence from grassland alleys on DBH of outer willow rows was confirmed in 2012, this effect was significant in 2013. Competition between trees and forage crops were also observed in a bottomland hardwood alley cropping system in central Iowa, USA, where trees (4 years) showed less growth when forage crops were incorporated compared to trees on bare ground (Delate et al. 2005). In contrast, Gamble et al. (2014) stated no influence of grassland understory on multi-rows of willows and poplar in the third year after establishment. It was proposed that alley orientation had a greater impact on tree growth during early establishment, which agrees well with the significant influence of direction on DBH in 2012 in this study.

Grassland

A key question in agroforestry research is whether microclimatic modifications by trees ameliorate or hinder the understory productivity in a young, temperate alley cropping system. In this study, no clear effect from trees on grassland productivity along the interface could be stated during early establishment. This was also reported by Delate et al. (2005), who found no differences in total forage and clover yield next to tree rows after the second year of establishment. Lin et al. (2001) also found only minor reduction of mean dry weight of seven cool-season grasses and legumes under 50 % shade. During early establishment understory is usually superior to the woody crops in temperate systems. After full maturity of trees a shift from net competitive to net facilitative effects of trees on grassland productivity can be expected (Jose et al. 2009). The interactions in temperate agroforestry systems differ from those in tropical/subtropical regions, since facilitation often increases when abiotic stress increases (Gargaglione et al. 2014). Under temperate climate conditions competitive effects might increase when environmental stress, e.g. drought, is absent.

Beside the grassland productivity sward composition and quality are important factors for the economic success of grassland based systems. In comprehensive studies on widely spaced poplar (8–11 years) and introduced pastures species the legume contribution in the sward decreased under trees (Douglas et al. 2006b). This is in accordance with the present study where dry matter contribution of legumes in CG was lower at the position SW in all treatments compared to the centre of the alleys. It is proposed that the reduction of 24 % PPFD at position SW limited white clover growth. White clover as a heliophilous plant responds sensitive to limited light quantity as previous studies showed (Ehret et al. 2015b).

The low legume contribution in DG can be explained by the initial seeding mixture where legume content (*Lotus corniculatus* L.) was only 0.3 %. Interestingly, the dry matter contribution of forbs in CG was highest at the positions SW and NE being next to the outer willow rows which is mainly related to invading segetal species (e.g. thistles, dandelion), which were well established in the adjacent outer willow rows. Weed pressure in SRC is comparatively high in the first few years after establishment and seed dispersal in the grassland alleys, especially in the areas adjacent to the outer willow rows, is very common. CG mixture showed gaps in early spring in the sward and it is proposed that segetal species used the retarded regrowth of white clover (enhanced by shading at SW and NE) to invade the edge area of the alleyways.

The influence of trees on forage quality was rather low in this experiment. There was only a tendency that N concentration in CG mixture was lower at SW position compared to position C. This might be related to the lower legumes contribution in the edge zones. Other studies on shaded forage plants showed increased crude protein values under moderate shade (Lin et al. 2001), whereas Ehret et al. (2015b) found no effect of artificial shade on crude protein and fiber contents of white clover/ryegrass mixtures. Overall, unfertilized CG swards showed slightly higher N contribution than fertilized. N fertilization induced higher productivity and increased dry matter contribution of grasses, which might cause a lower N content in the fertilized CG. DG samples contained slightly more ADF and ADL than CG which might be due to the higher amount of forbs which contain higher ADF and ADL.

Conclusion

During early establishment (until the third year) understory productivity of two grassland mixtures was not affected by shrub willow hybrids. However, sward composition of the clover-grass mixture changed along the tree-grassland interface. The dry matter contribution of legumes (i.e. white clover) was lower at SW position than in the centre of the alleys; forbs contribution in clover-grass mixture was highest at the positions adjacent to the willow rows. Sward composition of the diversity oriented grassland mixture was not affected by willows. There was no remarkable impact of trees on forage quality. Outer willows rows next to the alleyways showed slight competition effects expressed in a smaller diameter at breast height compared to inner rows. Tree shade modified the incident light on grassland understory being adjacent to the outer willow rows. Biennial mean DLI along the interface were at position SW (edge) 22 mol m^{-2} w^{-1}, at position C (centre) 30 mol m^{-2} w^{-1} and at position NE (edge) 26 mol m^{-2} w^{-1}. Accordingly, soil temperature was lower at the edge positions. There was no clear pattern in spatial variation of volumetric soil moisture content along the interface in 15 cm depth, except that moisture content was highest in 35 cm depth at SW position in both years.

Overall, the incorporated production of shrub willow hybrids and grassland has potential for an environmentally sound provision of bioenergy feedstock. By the frequent harvest of the shrub willow hybrids in 3–6 year rotations light availability for the grassland understory is modified in spatial and temporal dimensions. Therefore, understory might cope better with the tree shade than it was described for other temperate agroforestry practices, where light was a growth limiting factor. However, horizontal and vertical growth of the trees may still modify the microclimate during the life-span of alley cropping systems consisting of willows and grassland and more research is needed on long-term monitoring of competitive, complementary and facilitative effects.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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