Alley cropping of willows and grassland for bioenergy provision: productivity, tree-crop interactions and energy balance

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Preface

This thesis is submitted to the Faculty of Organic Agricultural Sciences of the University of Kassel to fulfil the requirements for the degree Doktor der Agrarwissenschaften (Dr. agr.). This dissertation is based on three papers as first author, which are published by or submitted to international refereed journals. A list of the original papers including the chapter in which they appear in this dissertation will be given on the next page. A list of other publications (e.g. contributions to conference proceedings) is given in chapter 11.

Wisdom is like a baobab tree; no one individual can embrace it. **– An African proverb**

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List of papers

Chapter 3: EHRET M, GRAß R and WACHENDORF M (2015) The effect of shade and shade material on white clover-perennial ryegrass mixtures for temperate agroforestry systems. Agrofor Syst. doi:10.1007/s10457-015-9791-0

Chapter 4: EHRET M, GRAß R and WACHENDORF M (2015) Productivity at the tree-crop interface of a young willow-grassland alley cropping system. Agrofor Syst. Submitted

Chapter 5: EHRET M, BÜHLE L, GRAß R, LAMERSDORF N and WACHENDORF M (2014) Bioenergy provision by an alley cropping system of grassland and shrub willow hybrids: biomass, fuel characteristics and net energy yields. Agrofor Syst 89:365–381

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Abbreviations

0N:	0 kg N ha^{-1} yr^{-1}
100N:	100 kg N ha^{-1} yr^{-1}
2-cut:	2-cut-management
3-cut:	3-cut-management
ADF:	Acid detergent fibre
ADL:	Acid detergent lignin
AIC:	Akaike’s information criterion
C:	Centre
CG:	Clover-grass
CH:	Combustion of hay
control:	Grassland control
CW:	Combustion of willow wood chips
DBH:	Diameter at breast height
DG:	Diversity-oriented grassland mixture
GHG:	Greenhouse gases
DLI:	Daily light integral
FAO:	Fod and Agricultural Organization of the United Nations
IFBB:	Integrated generation of solid fuel and biogas from biomass
KUP:	Kurzumtriebsplantage
LCA:	Life cycle assessment
LHV:	Lower heating value
l_N:	Normal litre
N:	Stickstoff
NDF:	Neutral detergent fiber
NE:	North-east
NIRS:	Near infrared spectroscopy
NPK:	Nitrogen, phosphorus, and potassium
OECD:	Organisation for Economic Co-operation and Development
oM:	Organic matter
PAR:	Photosynthetically active radiation
PC:	Press cake
PF:	Press fluid
PPFD:	Photosynthetic Photon Flux Density
SEM:	Standard error of the mean

SRC:	Short rotation coppice
SW:	South-west
THG:	Treibhausgase
VS:	Volatile solids
VWC:	Volumetric soil water content
W:	Intercropped with willows
W control:	Willows in a pure stand
WCD:	Whole crop digestion
XDS:	X-ray spectrometer detector system

1 General introduction

Under today's settings of rapid human population growth and climate change, agro-ecosystems and forest-ecosystems are in a state of transition. It is a global challenge to achieve efficient and productive land use while reducing greenhouse gas emissions (GHG) and conserving biodiversity (Johnson & Virgin 2010; Tscharntke et al. 2012; Soussana 2014).

The thereby induced agricultural intensification is a relevant driver for environmental degradation (Ceccarelli et al. 2014; Cumming et al. 2014). For example, agriculture, forestry and other land use are estimated to be responsible for around 17–31 % of anthropogenic GHG emissions. As the global population is predicted to reach 9–10 billion people by 2050, the demand for food will increase, and, thus, overexploitation of natural resources, food security and land availability become even more critical issues (Smith et al. 2013). There are land-use conflicts and competing interests on land for providing food, water, timber, energy, settlements, infrastructure, recreation and biodiversity (Coelho et al. 2012).

The ambition of energy policies in the EU and the U.S. to substitute fossil fuels by renewables resulted in an increased demand of biomass for bioenergy in industrialized countries. In the recent years, awareness has been growing that energy crop production caused land grabbing, rising food prices and forest degradation (Borras & Franco 2012; Erb et al. 2012; Tscharntke et al. 2012). In particular, the detrimental effects of bioenergy cropping systems evolved from annual crops (first generation) like oilseed rape, oil palm or corn, e.g. biodiversity losses, nitrate leaching, and erosion (Righelato & Spracklen 2007; Searchinger et al. 2008).

However, feedstock for energy recovery can be delivered by a multitude of crops. Karp & Richter (2011) emphasized the potential of low input perennial crops as superior to annual crops. Suggested perennial crops are willow/poplar short rotation coppices (SRC), miscanthus and different grass species. The production of biofuels from willows showed highest net energy output and lowest GHG emissions compared to annuals (Börjesson & Tuvesson 2011). Environmental benefits of bioenergy crops are much needed in combating climate change. Perennials can provide permanent crop cover, less tillage, sequester more carbon than annuals, reduce N_2O emissions and improve soil ecology (Karp & Richter 2011; Pugesgaard et al. 2014). Another advantage of cultivating perennials as bioenergy crops is that they can even grow on marginal land where food crops can not be efficiently established.

Crop yield and substantial GHG savings are among the most important factors for sustainable production of bioenergy feedstock (Whitaker et al. 2010). Beside the productivity of bioenergy cropping systems, also appropriate and efficient conversion technologies help to safeguard environmental resources. Especially perennials, which frequently have high contents of lignocellulosic substances with a complex physical structure, require an efficient conversion into useful end-products, e.g. biorefinery (Bonin & Lal 2012). However, each feedstock production and conversion has associated benefits and negative consequences. Therefore, the energy efficiency of different bioenergy production chains needs to be evaluated by using life-cycle assessment (LCA), where inputs and outputs are calculated to assess gains or offsets (Bonin & Lal 2012).

There is also a need to design landscapes that combine biomass production for food and/or fuel with biodiversity. Yields and biodiversity can coexist in agricultural systems. Intercropping, crop rotation or agroforestry systems are appropriate practices for agro-ecological intensification that comprises yield stability and environmental benefits (Tscharntke et al. 2012; Kremen & Miles 2012). Agroforestry is the integration of woody vegetation, crops/pasture and/or livestock on the same area of land (Nair 1993). This multifunctional land-use system reconciles production with protection of the environment and provides supporting and regulating ecosystem services, for example erosion control and soil enrichment (Jose 2009). Land use systems which comprise agricultural or pastoral and forest crops obtain a special ecological value (Tscharntke et al. 2012) which can contribute to a sustainable and land-use efficient production of bioenergy crops.

Beyond this background a comprehensive analysis on a young temperate agroforestry system for the provision of biogenic energy carriers was conducted in the current PhD-study. The agroforestry practice applied in this research is called “alley cropping” where shrub willow hybrids were grown in multi-rows under short rotation coppice and grassland sown as understory in the alleyways. Two types of grassland (white clover-ryegrass and a diversity oriented grassland mixture) were included in the trial, as they constitute appropriate grassland vegetation at low levels of nitrogen fertilization. The study was embedded in the project BEST – strengthening bioenergy regions which focused on the implementation of innovative strategies to combat current controversy on land use for food and bioenergy crops.

The first part of the thesis (chapters 3 and 4) aimed to identify possible competition effects between shrub willow hybrids and the two grassland mixtures. Since light seemed to be the factor most affecting the yield performance of the understory in temperate agroforestry systems, a biennial in situ artificial shade experiment (chapter 3) was established over a separate clover-grass stand to quantify the effects of shade level and material on productivity, sward composition and nutritive value. Data to possible below- and aboveground interactions and their effects on productivity, sward composition, and quality were evaluated along the tree-grassland interface within the alley cropping system over a time period of two years after system's establishment (chapter 4).

The second part of the thesis (chapter 5) assessed the potential of a young willow-grassland alley cropping system as feedstock for biofuel production. The productivity of the alley cropping system was examined on a triennial time frame and was compared to separate grassland and willow stands as controls. The energetic potential of willow wood chips and of three different conversion technologies applied to grassland as biomass feedstock (combustion of hay, integrated generation of solid fuel and biogas from biomass, whole crop digestion) were evaluated. Finally, the net energy balances of separate grassland stands, agroforestry and pure willow stands were compared regarding their efficiency.

2 Research objectives

The general objective of this study was to understand the agronomic and physiological responses of willow and grassland biomass when incorporated in a temperate alley cropping system and to evaluate the potential of this alley cropping practice for the provision of bioenergy feedstock.

Below- and aboveground interactions between willows and grassland were monitored by a biennial artificial shade experiment outside the agroforestry trial and along a tree-grassland interface within the grassland alleys of the agroforestry system. Microclimatic parameters comprised photosynthetically active photon flux density (PPFD), soil moisture, soil temperature and precipitation. Agronomic parameters comprised dry matter yield, sward composition and quality. The artificial shade experiment was set up on a white clover-perennial ryegrass sward. Experiments along the interface were based on two different grassland mixtures, i.e. white clover-perennial ryegrass and diversity oriented grassland mixture with 32 species, at two fertilizer levels and cutting frequencies measured along the interface at three different positions. Energy balances were developed for separate grassland stands, alley cropping willows and grassland and pure shrub willow stands. Hay combustion, integrated generation of solid fuel and biogas from biomass (IFBB), and anaerobic whole-crop digestion (WCD) were included as energetic conversion techniques for grassland biomass. The willows in the alley cropping system were utilized for combustion.

The specific objectives of the experiments were

(i) 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.

(ii) to monitor the effects of willows on micro-environment, productivity, sward composition and quality along the tree-grassland interface of the alleys in spatial and temporal dimensions.

(iii) to examine the productivity, energetic potential and net energy balance of an alley cropping system of grassland and willows in comparison to separate grassland and pure shrub willow stands as controls, using hay combustion, integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion as conversion techniques for grassland biomass and combustion for willow wood chips.

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

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. Longterm effects of shade on white clover-perennial ryegrass mixtures as an understory in temperate agroforestry systems need to be evaluated in future research activities.

3.1 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) agroecological 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).

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* x *S. viminalis*) x *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.

3.2 Materials and methods

3.2.1 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 Food and Agricultural Organization of the United Nations (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.

3.2.2 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.

3.2.3 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.

3.2.4 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 (VarioMAX 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, Figure 3-1).

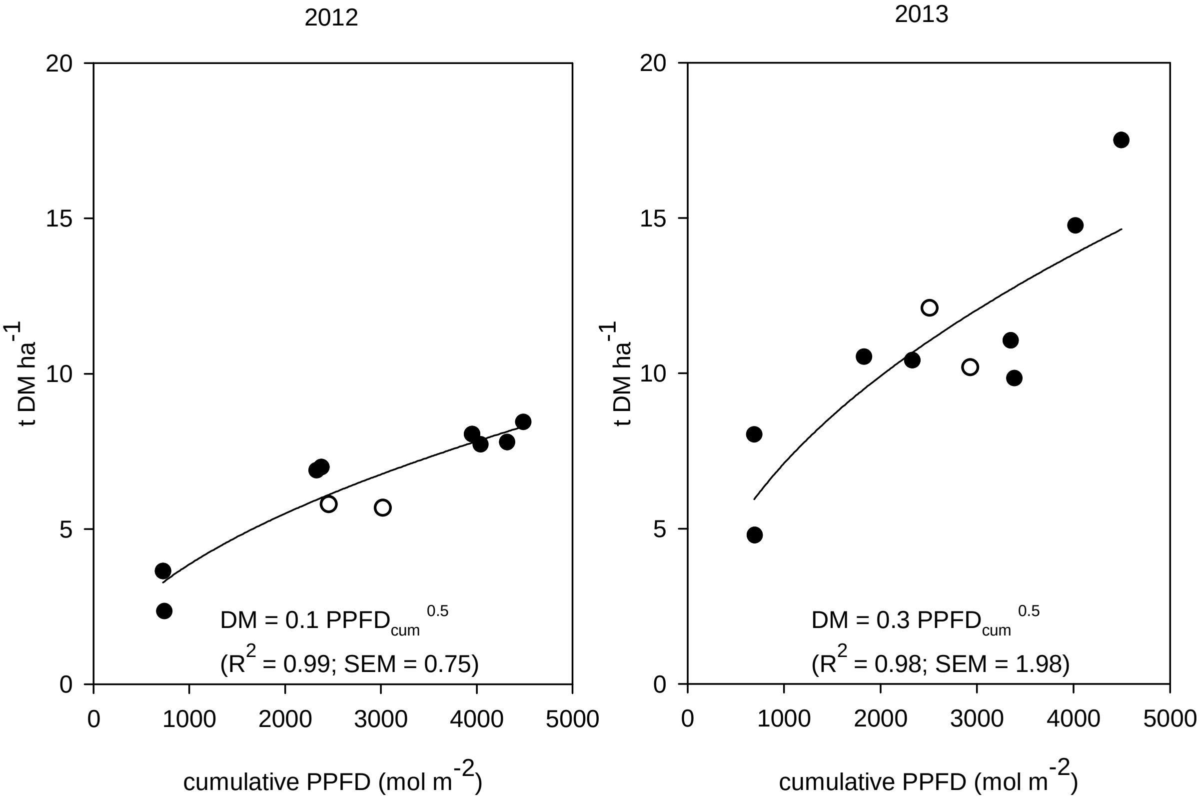

Figure 3-1 Relationship between cumulative PPFD ($PPFD_{cum}$) and annual herbage production in the growing seasons 2012 and 2013. The points of the slatted treatment are indicated as *open circles* and the shade cloth treatments as *filled circles*.

3.2.5 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).

3.3 Results

3.3.1 Microclimate

Microclimatic parameters were aggregated on a weekly basis to allow a visual discrimination among shade levels over the growing season (Figure 3-2). Shade intensities of the shade cloth, as indicated by the cloth manufacturer, were almost confirmed by PPFD measurements (Table 3-1). 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 3-1). 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 (Figure 3-2b). From the temperature profiles it becomes apparent that differences among the shade levels only occurred in the second half of the growing season (Figure 3-2b).

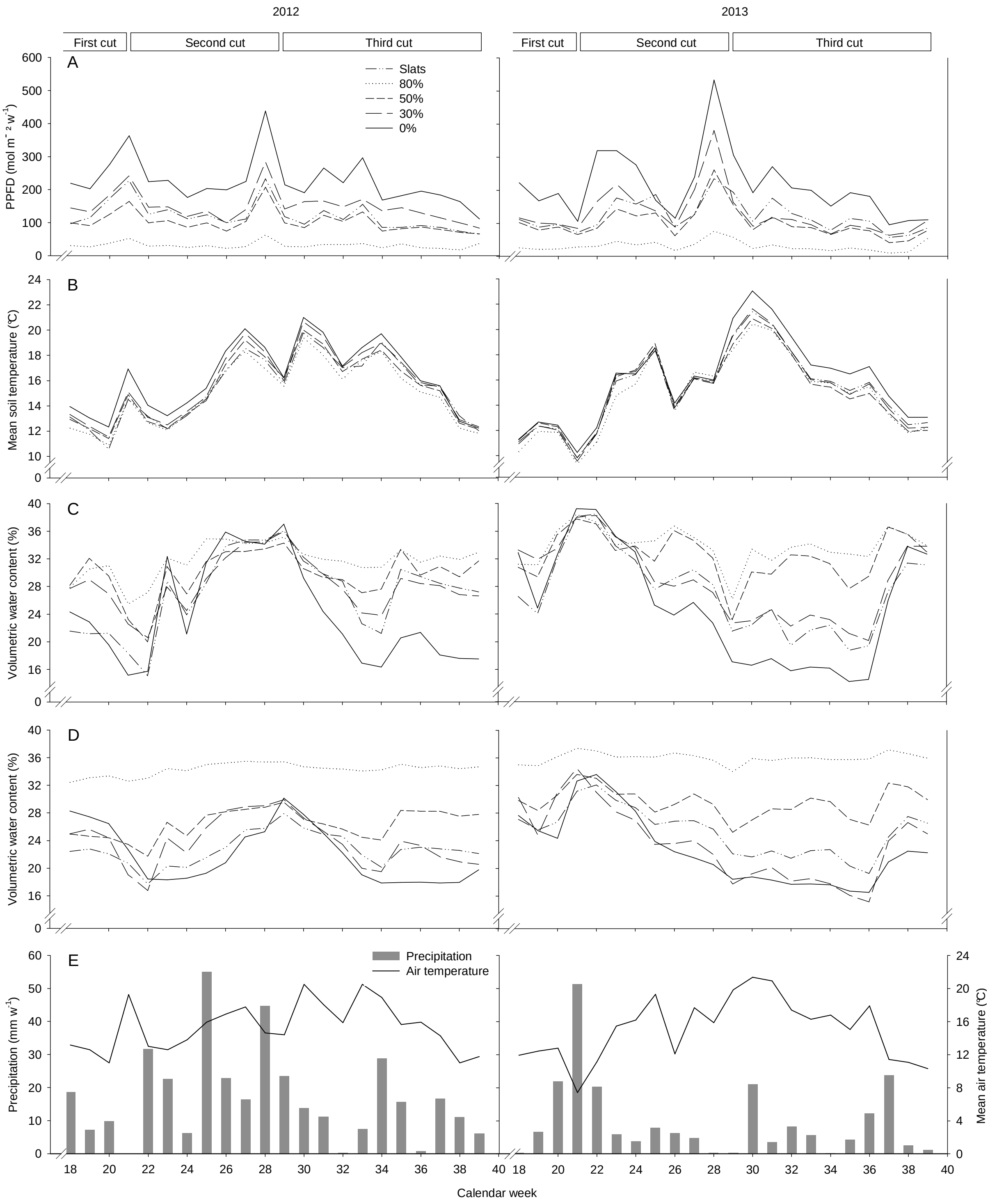

Figure 3-2 Environmental parameters measured under different levels of shading (0, 30, 50, 80 % and a slatted structure with 50 % shade). Displayed are weekly values of **a** mean photosynthetic photon flux density (PPFD), **b** mean soil temperature at 5 cm depth, mean volumetric soil moisture content 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 3-1 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. 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).

	PPFD (mol m^{-2} w^{-1})				**Soil temperature (°C)**				**Volumetric soil moisture content (%)**			
	2012		**2013**		**2012**		**2013**		**2012**		**2013**	
Shade level	**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	*	*	**

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

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 (Figure 3-2c, 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 (Figure 3-2d, e). The mean values of soil moisture for both growing seasons showed that the severe shade treatment remained near field capacity (Table 3-1). The soil moisture content under the control was 25 % reduced 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.

3.3.2 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; Figure 3-3) 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 in the following cuts of the same and the following year.

3.3.3 Sward composition

Shade reduced clover and increased grass contribution in both experimental years (Figure 3-4; Table 3-2). 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 (Figure 3-4). 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.

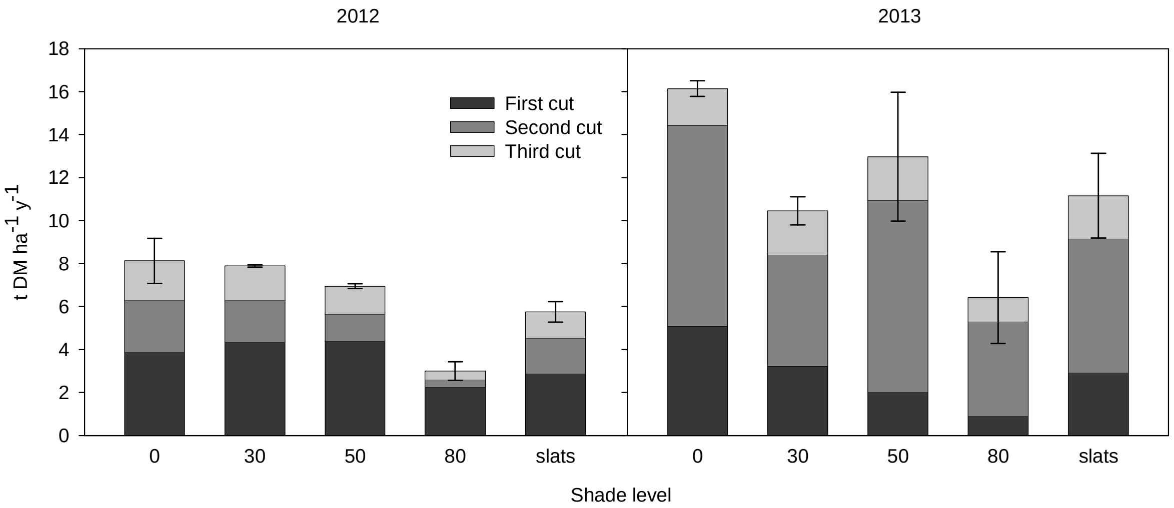

Figure 3-3 Total annual herbage production of a white clover-perennial ryegrass sward under different levels of shade cloth (0, 30, 50, and 80 %) and a slatted structure (50 %) in 2012 and 2013.

Table 3-2 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 x 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’

3.3.4 Herbage quality

There was no significant influence of shade on herbage quality, irrespective of year and cutting date (Table 3-2). 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 % 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.

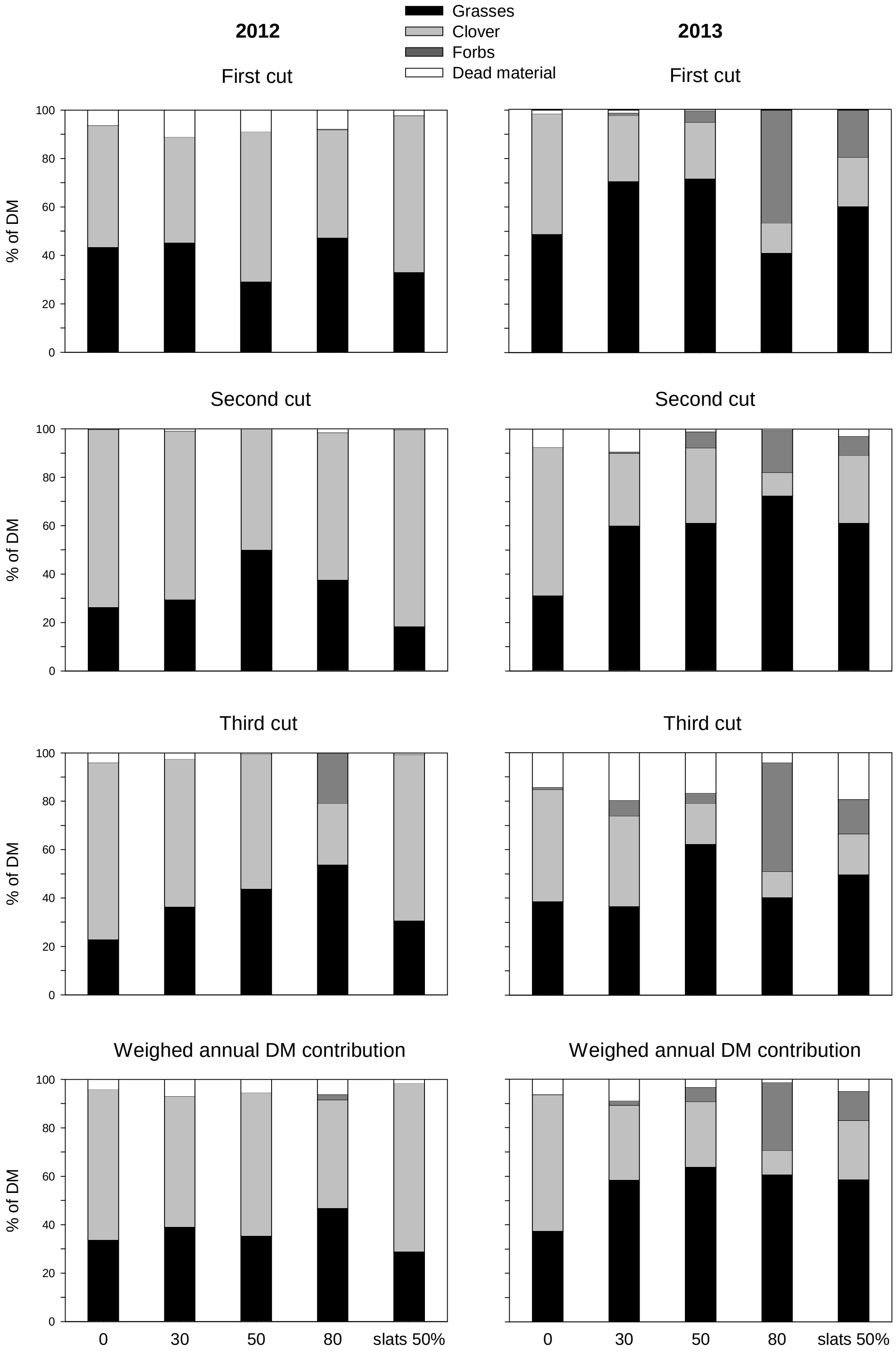

Figure 3-4 Dry matter contribution of functional groups (grasses, white clover, forbs) and dead material under different levels of shade cloth (0, 30, 50, and 80 %) and a slatted structure (50 %) in 2012 and 2013. Inter-correlation among the functional groups was low (mean correlation coefficient < 0.1) in both years.

3.4 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 favourable 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. 2006a). 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).

3.5 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.

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

Abstract Alley cropping multi-rows of shrub willow hybrids and grassland is a promising temperate agroforestry practice for an environmental 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 of understory along the interface. Biennial mean daily light integral at position south-west was 22 mol m^{-2} w^{-1}, in the center of the alley 30 mol m^{-2} w^{-1} and at position north-east 26 mol m^{-2} w^{-1}. Accordingly, soil temperature was lower at the positions south-west and north-east 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 south-west 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 to 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 south-west. 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.

4.1 Introduction

Intercropping lignocellulosic or cellulosic crops in temperate agroforestry systems shows particular promise for an environmental sound provision of bioenergy feedstock (Gruenewald et al. 2007; Gamble et al. 2014; Holzmueller & Jose 2012). Suggested lignocellulosic crops are, for example, fast-growing 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. 2013).

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. 2006b; 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, 2006b) 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. 2006b). 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. 2006a).

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 & Belseky 2008).

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 (Burner & Belseky 2008; Reynolds et al. 2007; Holzmueller & 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 & 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 & 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, (iv) Does sward composition and quality alter along the tree-grassland interface.

4.2 Material and Methods

4.2.1 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 by 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 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 (Figure 4-1a). 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-east to south-west.

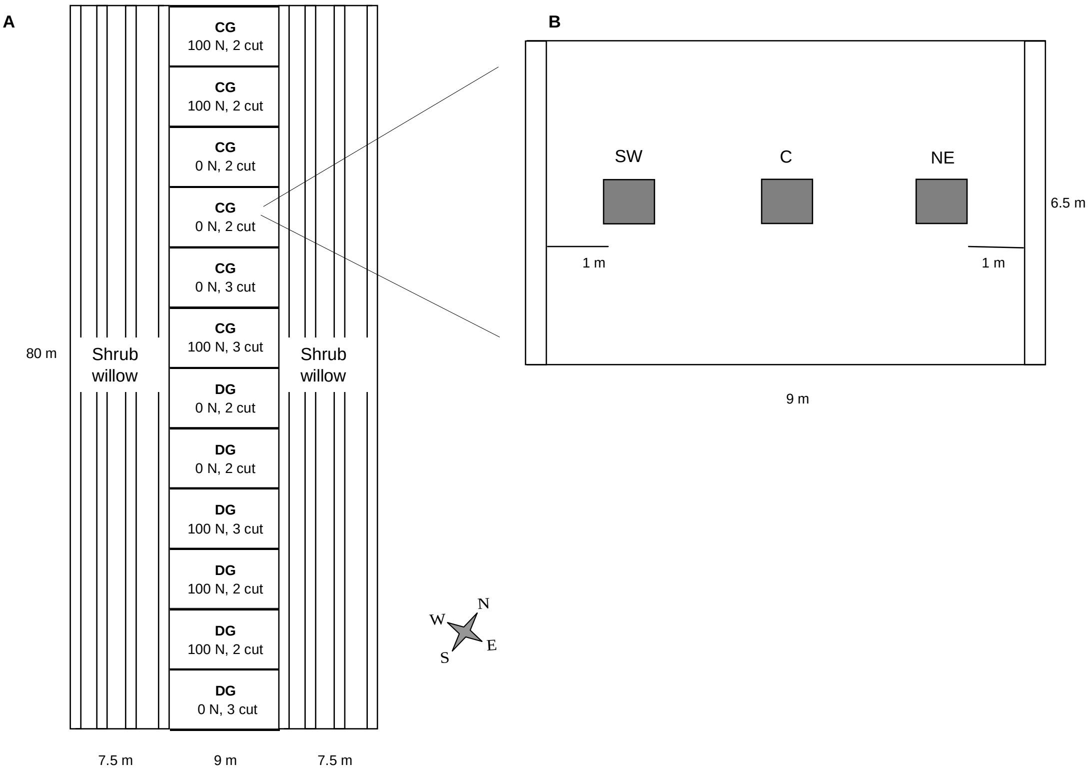

Figure 4-1 Schematic representation of the experimental design showing an alley of clover-grass (CG) and a diversity-oriented grassland mixture (DG) integrated in multi-rows of shrub willow hybrids. As experimental factors different cutting regimes and fertilization levels for CG and DG were included 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 south-west (SW) and north-east (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.

4.2.2 Microclimate

4.2.2.1 Soil moisture content, soil temperature and precipitation

Soil moisture and soil temperature recordings were started in an unfertilized clover-grass plot (CG, 0N, 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 (Figure 4-1b):

1. at the position south-west (SW) 50 cm from the outer willow row
2. at the position in the center of the alley (C)
3. at the position north-east (NE) 50 cm from the outer willow row

EC-5 soil moisture sensors were used to record volumetric soil moisture content (VWC) in 15 cm 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.

4.2.2.2 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 to 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 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.

4.2.3 Trees

Dormant stem cuttings with 3-4 buds of the willow clone (clone 'Tordis', *Salix schwerinii* x *S. viminalis* x *S. vim.*) were planted by hand using a double-row system with 1.5/0.75m spacing by a density of 12,000 trees per ha. 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. Diameter at breast height (1.30 m above ground) and stem diameter at distance above ground 0.1 m were measured with a caliper. Diameter at breast height (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. Tree height of the main shoot was measured by height pole. Ten trees per single row of willows were examined – in total 320 trees. Yield was estimated by using the allometric power equations, as high accuracies were shown for willows (Verwijst & Telenius 1999; Hartmann et al. 2014). As reference, 15 trees from the edge area and 15 trees from the centre area were harvested. Prior to that, willows were separated into five classes of different DBH. After harvest fresh matter and dry matter content was determined. Values were used for model calibration.

4.2.4 Grassland

In the alleys of the agroforestry system two grassland mixtures were established: a mixture of *Trifolium repens* L. and *Lolium perenne* L. (clover-grass, CG) and a diversity-oriented mixture with 32 species (DG). 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 in the alleys along the tree-grassland interface for each replicate: in the centre of each plot (C) and adjacent to the willow rows south-west (SW) and north-east (NE) (Figure 4-1a and b).

For the determination of fresh matter yield, samples were taken from subplots sizing 50 cm to 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 to 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 to 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 quality parameters according to standard methods.

4.2.5 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 x M, B x M x C, B x M x 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).

4.3 Results

4.3.1 Microclimate

4.3.1.1 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 4-1). 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, at position SW 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.

Table 4-1 Biennial mean cumulative transmitted photosynthetically active photon flux density (PPFD), biennial mean soil temperature (°C) and biennial mean volumetric soil moisture content (%) at 15 cm 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 south-west direction (SW), in the center of the alley (C), in north-east direction (NE) from 30th April to 30th September 2012 and 2013.

	PPFD (mol m^{-2} w^{-1})				**Soil temperature (°C)**				**Volumetric soil moisture content (%)**			
	2012		**2013**		**2012**		**2013**		**2012**		**2013**	
Interface position	**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		16.3		15.9		23.98	22.00	25.24	22.69

During the second year after the establishment of the alley cropping system (2012), weekly means of the daily light integral (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 (Figure 4-2). 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}.

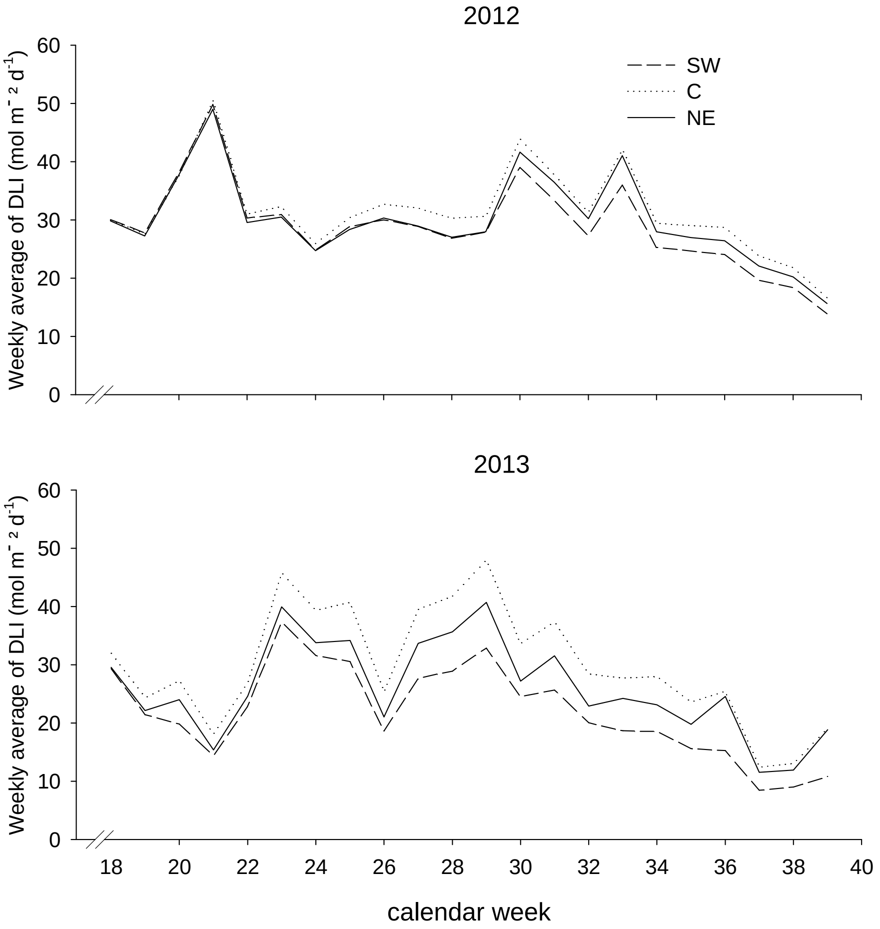

Figure 4-2 Weekly average of daily light integral (DLI) measured in a grassland plot of the alley cropping system at three different positions along the tree-grassland interface: (i) adjacent to the willows in south-west direction (SW), (ii) in the center of the alley (C), (iii) adjacent to the willows in north-east direction (NE) 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.

4.3.1.2 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 4-1).

Volumetric soil moisture content in 35 cm depth was highest at position SW along the interface in 2012 and 2013, respectively (Table 4-1). 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.

4.3.2 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 (Figure 4-3). 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 south-western and north-eastern outer 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}.

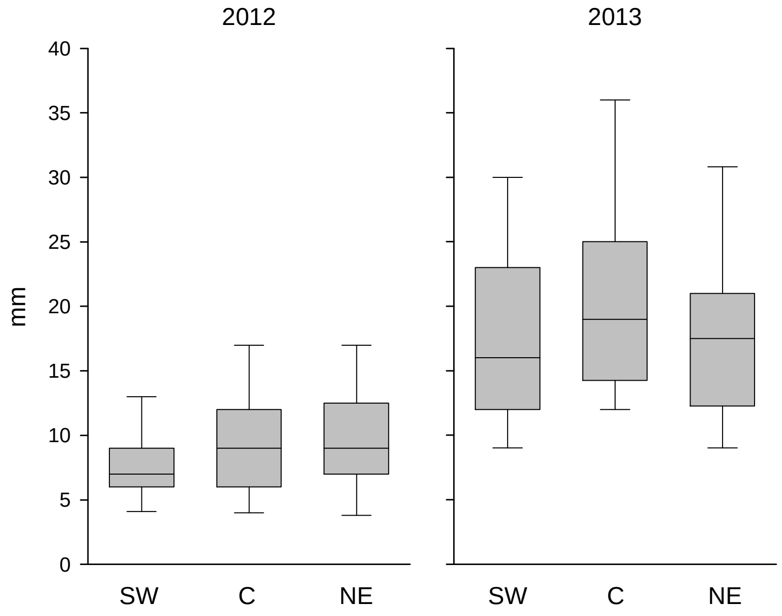

Figure 4-3 Mean of diameter at breast height [mm] of intercropped shrub willow hybrids in the year 2012 and 2013 in the south-western edge row (SW) adjacent to the grassland alleys, in the center row (C), in the north-eastern edge row (NE) adjacent to the grassland alleys. Willows were established in the year 2011. Whiskers show the standard error of the mean.

4.3.3 Grassland

4.3.3.1 Productivity

The impact of outer willow rows on productivity of CG and DG plots was not confirmed until the third year after establishment (Figure 4-4). 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 biomass production of CG and DG more than cutting management ($P < 0.05$).

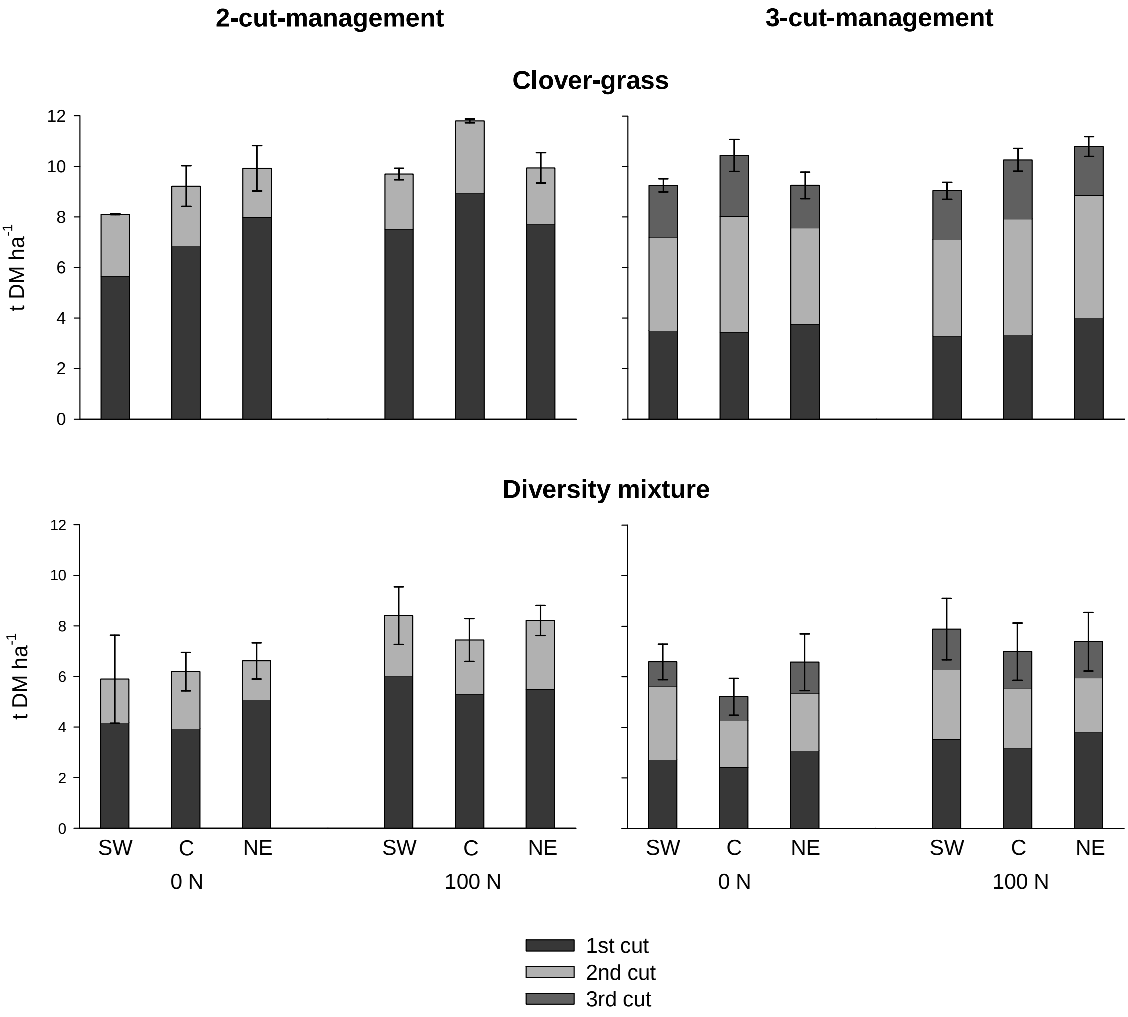

Figure 4-4 Biennial mean of dry matter yield of clover-grass (CG) and a diversity-oriented grassland mixture (DG). Biomass was sampled at three different positions along the tree-grassland interface: (i) adjacent to the willows in south-west direction (SW), (ii) in the center of the alleys (C), (iii) adjacent to the willows in north-east direction (NE). 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.

4.3.3.2 Sward composition and quality

Grasses were the predominant functional group in CG 0N and 100N in the 2-cut and 3-cut management (Figure 4-5). 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.

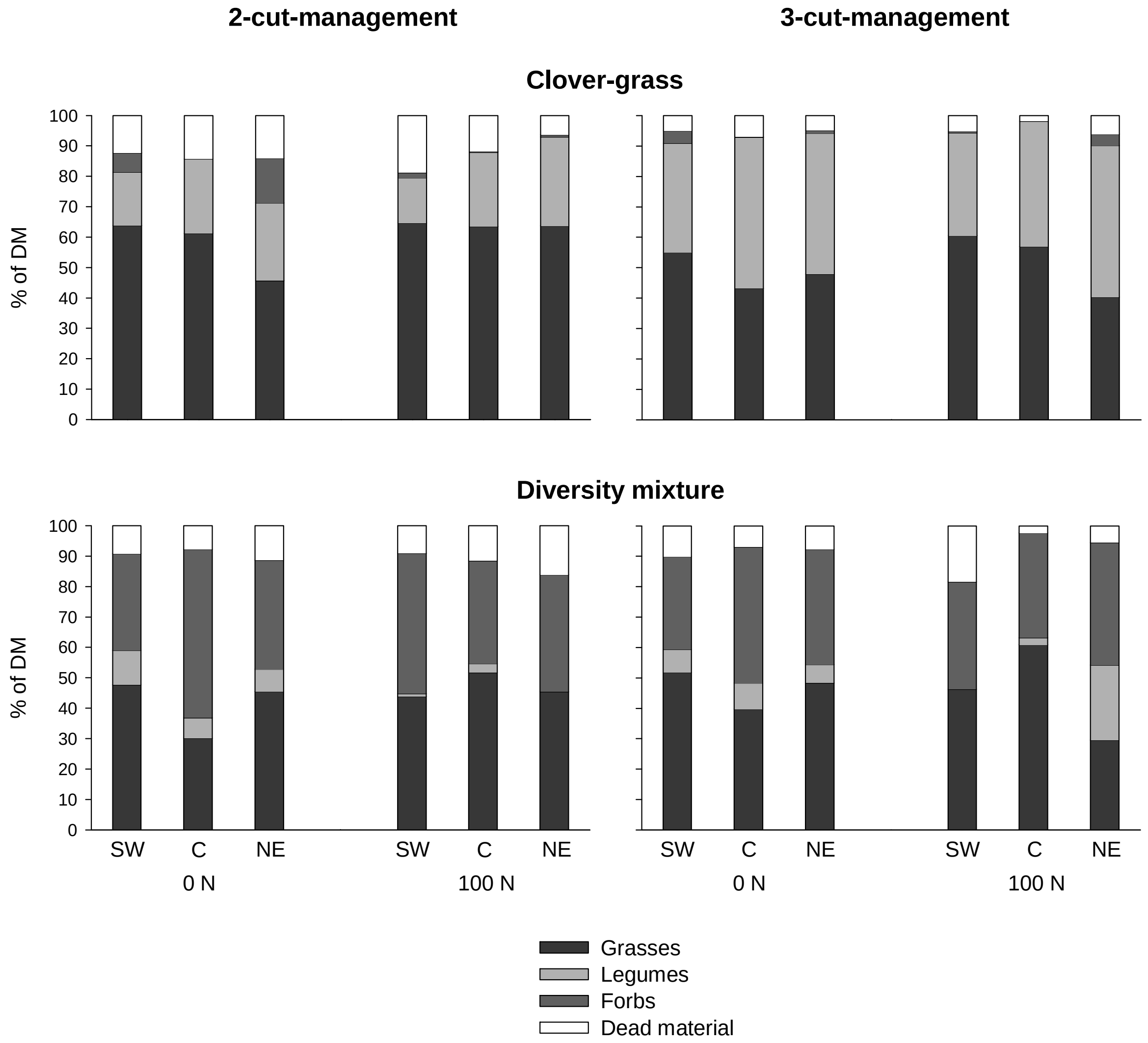

Figure 4-5 Dry matter contribution of functional groups (grasses, legumes, forbs) and dead material of clover-grass (CG) and a diversity-oriented grassland mixture (DG) at three different positions along the tree-grassland interface: (i) adjacent to the willows in south-west direction (SW), (ii) in the center of the alleys (C), (iii) adjacent to the willows in north-east direction (NE) 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).

In general, legume contribution was low in the DG mixture. In the unfertilized treatment (0N) 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 (100N). Contribution of forbs decreased with increased fertilization application in all treatments of DG. Contribution of forbs in DG 0N (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.

4.4 Discussion

4.4.1 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 below-ground competition. It is supposed that maize as a C4 plant responds differently to shade than cool-season grasses and legumes which are mainly C3 plants (Reynolds et al. 2007). Forage species exhibiting the C3 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 19 % 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 three years after establishment. Other studies on light interactions have reported light reductions of 33 % upon the understory next to trees (Douglas et al. 2006 b), 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 yr old radiate 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).

4.4.2 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 *Pinus 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.

4.4.3 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 to those in tropical/subtropical regions, since facilitation often increases when abiotic stress increases (Gargalione 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. 2006a). 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 19 % 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. 2015).

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. (2015) found no effect of artificial shade on crude protein and fiber contents of white clover-ryegrass mixtures. 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.

4.5 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 south-west 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 daily light integrals 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 environmental 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.

5 Bioenergy provision by an alley cropping system of grassland and shrub willow hybrids: biomass, fuel characteristics and net energy yields

Abstract In the temperate zone, alley cropping is promoted as a climate change-resilient agroforestry practice for the provision of biogenic energy carriers. However, little information is available on the potential of such cropping systems as feedstock for biofuel production. In a field trial in Central Europe, the triennial performance of alley cropping systems was assessed. The systems consisted of clover-grass, a native diversity-oriented grassland mixture and multirows of willows. They were compared to a willow and grassland control adjacent to the trial area. Three different conversion technologies were applied to grassland feedstock and analyzed for relevant quality parameters. Net energy balances were calculated to determine the potential of the cropping systems and the associated controls as providers of biogenic energy carriers. The grassland control had the highest triennial yield (18 t DM ha^{-1}), whereas pure willow stands were less productive with 7 t DM ha^{-1}. Alley cropping was intermediate with 12 t DM ha^{-1} on average. Net energy yield of the clover-grass based systems was highest in the grassland control for all conversion technologies, whereas values of the diversity-based systems in the control and the alley cropping system achieved similar values. This study only investigated the first 3 years after establishment, when growth rates of shrub willows were still low. Thus, more research is needed to evaluate the long-term performance of agroforestry systems with shrub willows and herbaceous crops.

5.1 Introduction

The Organization for Economic Cooperation and Development (OECD) aims to halve the global emissions of CO_2 by 2050, compared to the level in 2000. In order to reach this target, the replacement of fossil fuels with renewable energy resources has to be envisioned, with a particular role of bioenergy (IEA 2013). However, the increase and intensification of biomass production for energy conversion on agricultural land has already shown adverse impacts on agroecosystems, e.g. biodiversity losses, nitrate leaching, and erosion (Schulze and Koerner 2012; Righelato and Spracklen 2007). Natural forests are also at risk, as they do not have the capacity to sustainably meet the future demand for timber, wood fuel and material utilization (Morhart et al. 2014). In several Northern European countries, especially in Sweden, Germany and the UK, the implementation of short rotation coppice (SRC), i.e. fast-growing trees on agricultural areas, are discussed as an alternative approach for sustainable wood production (Mitchell et al. 1999).

Under today’s agricultural frameworks, farmers and landowners face many challenges whilst they are seeking to make their farms and forests productive, cost-effective and environmentally friendly (Workman et al. 2003). Mixed cropping systems might offer an appropriate option to fulfill environmental demands, by an increase in diversity and yield stability compared to single-cropped systems (Costanzo and Barberi 2014). Agroforestry systems represent such mixed cropping systems and consist of a mix of trees and arable crops or grassland within the same area of land (Nair 1993). Agroforestry is perceived as a climate change-resilient cropping system for farmers linking climate change mitigation with adaptation (Mbow et al. 2014; Nguyen et al. 2013). Their multifunctional structure provides supporting and regulating ecosystem services, for example erosion control and soil enrichment, and also provides a variety of products, for example fodder, food, fuel, biomass or genetic resources (Jose 2009). The World Agroforestry Center (2014) promoted agroforestry as an integrated food and energy system which can address food and energy demand by developing food and multifunctional biofuel crops. Barbieri and Valdivia (2010) reported that municipalities with a high proportion of bioenergy crops on their territories are not only interested in a diversity of production systems to meet the local year-long demand, but that they are also interested in the aesthetic and recreational values of bioenergy crop landscapes.

In contrast to traditional agroforestry systems like orchards or the Spanish *dehesas*, alley cropping is a type of agroforestry system which is adapted to the temperate zone, with a high degree of mechanization (Long and Nair 1999). Trees are planted in rows and crops are planted in the alleyways, which facilitates their management by machinery and enhances productivity, whilst still providing various ecosystem services (Quinkenstein et al. 2009). Mainly fast growing woody species such as willow (*Salix* spp.) or poplar (*Populus* spp.) are incorporated in temperate alley cropping systems. As fast-growing trees are managed in short rotations, the competition for light between the trees and the food/forage crops in the alleys is reduced (Reynolds et al. 2007; Holzmueller and Jose 2012).

For the production of bioenergy feedstock, perennial crops, e.g. willows and grasses, are emphasized as being environmentally superior to annual crops (Karp and Richter 2011) due to their ability to produce large biomass yields with relatively low input (Albaugh et al. 2014). Willows, for instance, had the highest net energy output and the lowest greenhouse gas emissions when compared to wheat, rape seed, and sugar beet (Börjesson and Tufvesson 2011). In many low-input agroecosystems grasses are intercropped with legumes since legumes have an importance as a primary source of nitrogen in agriculture (Thomsen and Haugaard-Nielsen 2008). In this perspective, clover-grass is a commonly used grassland mixture in low-input temperate agroecosystems due to high dry matter yields in unfertilized pastures and the ability to be a soil improving ground cover (Thomsen and Haugaard-Nielsen 2008). The biomass of clover-grass provides a suitable biogas substrate due to its low lignin content as it is cut three times or more frequent per growing season (Gissén et al. 2014). Contrary, material from high-diversity grassland cut only two times per year has high mineral concentrations and is usually senescent with high lignin and cellulose content (Khalsa et al. 2014). The material is hardly suitable for economically efficient biogas production, as it leads to low methane yields (Richter et al. 2009). Alternatively, such material could serve as a feedstock for combustion, but without any pre-treatment its high element concentrations would cause ash slagging (K, Mg), corrosion (Cl, S) and emissions (Cl, S, N) (Jenkins et al. 1998; Obernberger et al. 2006). To overcome these difficulties, the integrated generation of solid fuel and biogas from biomass (IFBB, Wachendorf et al. 2009) was developed. The main element of this conversion procedure is the mechanical dehydration after hydrothermal conditioning of the ensiled biomass, which produces a solid fibrous fraction for thermal use (press cake, PC) and a liquid fraction with easily fermentable constituents for biogas production (press fluid, PF). The fuel quality of the mechanically dehydrated whole crop silage is improved in comparison to the untreated biomass because of the partial elution of organic and mineral compounds which are detrimental to combustion (Bühle et al. 2012a).

The present study examined an agroforestry system of grassland (clover-grass and a diversity-oriented grassland mixture) and fast growing willows in an in situ experiment in Germany, West-Central Europe. Hay combustion, IFBB, and anaerobic whole-crop digestion were included as experimental factors, as these techniques represent major energetic conversion techniques for grassland biomass. The willows in the alley cropping system were utilized for combustion. Mineral fertilizer was included in the experiment to estimate the effects of recycling biogas slurry, which is generated as a by-product both in the IFBB and anaerobic whole-crop digestion, on the grassland. Two types of grassland were included in the trial, as they constitute appropriate grassland vegetation at low levels of nitrogen fertilization.

The objectives of this paper were to: (1) examine the productivity of an alley cropping system of grassland and willows in comparison to separate grassland and pure shrub willow stands as controls; (2) to evaluate the energetic potential of willow wood chips and of three different conversion technologies applied to grassland as biomass feedstock (combustion of hay, integrated generation of solid fuel and biogas from biomass, whole crop digestion); (3) to determine the effects of grassland type (clover-grass mixture, diversity-oriented grassland mixture) and fertilizer level (0 and 100 kg nitrogen ha^{-1} $year^{-1}$) on productivity and energetic potential and (4) to compare the net energy balances of separate grassland stands, agroforestry and pure shrub willow stands.

5.2 Materials and methods

5.2.1 Description of the site and the agronomic systems

The study was conducted at the field trial area of the joint research project BEST (Strengthening Bioenergy regions) in Lower Saxony, Germany (51°39’83’’N and 9°98’75’’E, 325 m a.s.l.), from March 2011 to January 2014. The climate of this site was characterized by an average temperature of 9.2 °C and an annual precipitation of 642 mm (period of 1991–2010, Hartmann et al. 2014). The predominant soil type was classified as a stagnosol according to the FAO World Reference of Soil Resources (2006), and consisted of sedimentary deposits from sandstone, siltstone and claystone (Hartmann et al. 2014). The preceding crop grown on the experimental area was winter barley.

Three adjacent cropping systems were established: grassland as a control, shrub willow in short rotation as a control, and an agroforestry system of both grassland and shrub willow (Figure 5-1). Control plots of pure grassland (0.06 ha) and shrub willow stands (0.6 ha) were planted on the same field with three replicates of each. The agroforestry system consisted of alternating multi-rows of fast-growing willows in a short rotation cycle (3 years) and grassland sown in the alleyways, with three replicates of each. The alley cropping system covered a total of 0.7 ha. The grassland alleyways were 9 m wide and 80 m long. Grassland plot dimensions were 9 m wide and 6.5 m long, for a total of 12 plots (six plots per grassland mixture) in each alleyway. The willow rows were 7.5 m wide and 80 m long. This pertains to a land use proportion of 45 % willows and 55 % grassland.

5.2.2 Experimental design and cultivation measures

Within the grassland control and the grassland alleyways of the agroforestry system, two types of grassland mixtures were established: a grassland mixture of *Lolium perenne* L. and *Trifolium repens* L. (clover-grass, CG) with a clover proportion of 31 %; and a diversity-oriented grassland mixture with 32 species, consisting of 43 % grasses and 41 % non-leguminous forbs (DG). They were sown by tillage drilling in March 2011. CG and DG were split into sub-plots, measuring 9 m by 6.5 m, with different cutting regimes and fertilization levels: (i) two cuts per year which is later referred to as the conversion technologies ‘combustion of hay’ (CH) and ‘Integrated generation of solid fuel and biogas from biomass’ (IFBB), (ii) three cuts per year which is later referred to as the conversion technology ‘whole crop digestion’ (WCD). The fertilization levels applied were 0 and 100 kg nitrogen ha^{-1} year^{-1} (NPK 2-cut, 60-40; NPK 3-cut, 40-30-30).

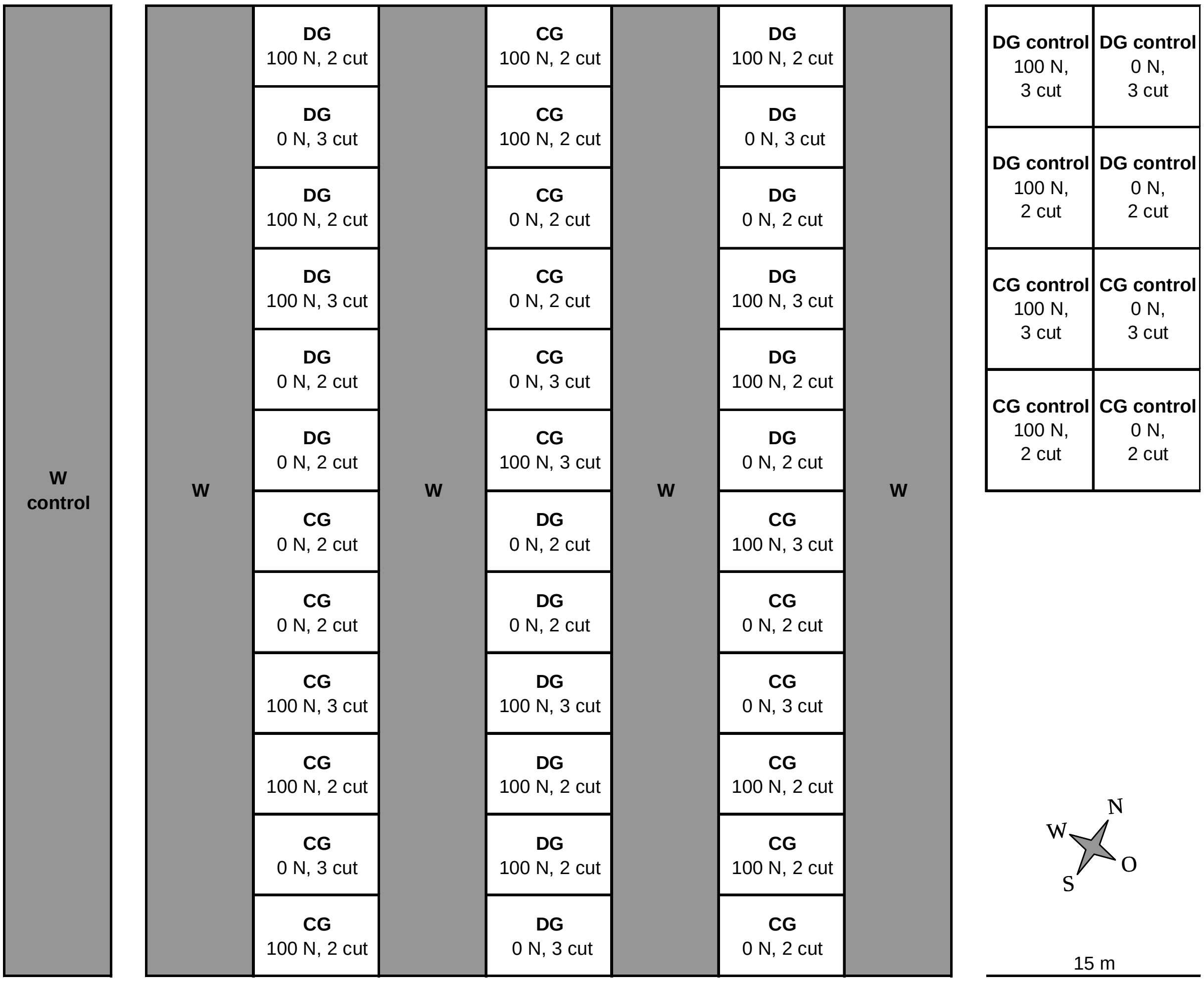

Figure 5-1 Schematic representation of the experimental design showing clover-grass (CG) and a diversity-oriented grassland mixture (DG) in a separate stand (control) and intercropped with willows (W) in an agroforestry system and of willows in a pure stand (W control). As experimental factors different cutting regimes and fertilization levels for CG and DG were included in the split-plot alleys of the agroforestry system and in the control: (i) two cuts per year which is later referred to as the conversion technologies ‘combustion of hay’ (CH) and ‘Integrated generation of solid fuel and biogas from biomass’ (IFBB), (ii) three cuts per year which is later referred to as the conversion technology ‘whole crop digestion’ (WCD). The fertilization levels applied were 0 kg N ha^{-1} year^{-1} (0 N) or 100 kg N ha^{-1} year^{-1} (100 N).

Shrub willows within the control and the agroforestry system were willow clone ‘Tordis’ ((*Salix schwerinii* x *S. viminalis*) x S. vim.), and were planted by hand as dormant stem cuttings with 3–4 buds in March 2011. In future a three-year-rotation of the willows is intended. The ‘double row’ system was applied, as it is used in commercial SRC plantations, and is essential for mechanical harvesting. Alternating inter-row distances were 0.75 and 1.5 m, with a within-row spacing of 0.75 m, to yield a planting density of 12,000 trees per hectare. No herbicides and no fertilizers were applied. In the first and second years weed management was carried out manually using hoes and lawn mowers. Field operations applied to the cropping systems, including soil preparation, sowing/planting, maintenance and harvest, are shown in detail in Table 5-1 and Table 5-2.

Table 5-1 Field operation data for combustion of hay (CH), integrated generation of solid fuel and biogas from biomass (IFBB), and whole crop digestion (WCD), applied on grassland biomass at a farm-field distance of 5 km and a field size of 4 ha based on mean of all grassland treatments accumulated over 3 years (KTBL 2014).

Machinery	**Ø fuel diesel consumption (l ha^{-1})**		
	WCD	**IFBB**	**CH**
Cultivator, harrow, 2.5 m, 83 kW	33.7	33.7	33.7
Gras seed drills, 2.5 m, 83 kW	13.5	13.5	13.5
Field roller, 6 m; 83 kW	4.4	4.4	4.4
Mulcher, 3 m; 83 kW	30.3	30.3	30.3
Pasture harrow, 9 m, 83 kW	2.0	2.0	2.0
Mowed material conditioner, 3.1 m; 83 kW	34.8	26.7	26.7
Rotary tedders and turners, 8.5 m, 83 kW			42.0
Rotary windrower, 6.5 m; 83 kW	20.9	15.5	15.5
Selfloading trailer, 28 m³, 7 t; 83 kW	48.6	45.3	
Ensiling, wheeled loader, 13.5 t, 105 kW, 4 m³	9.2	9.2	
Round baler, 1.5 m, 320 kg/bale, 67 kW			18.1
Bale transport, front loader, dumper, 2 x 8 t, 1750 daN, 67 kW			15.8
Fertilizer spreader, 1.5 m³, 67 kW	4.5	3.8	3.8
Total	201.9	184.4	202.0

5.2.3 Assessment of aboveground biomass

Aboveground biomass of grassland was determined in the control and in the alleyways of the agroforestry system during the growing seasons of 2011, 2012 and 2013. At each harvest date, subplots of a 0.25 m^2 area were sampled at 50 mm stubble height and herbage fresh mass was recorded. Samples of 100 to 200 g from each sub-plot were dried at 105 °C for 48 h, and weighed to determine herbage dry matter content. Triennial dry matter yield over the period of investigation (2011–2013) was calculated as the sum of all cuts from each year. 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. For the estimation of symbiotically fixed dinitrogen, a model was used for N fixation in clover-grass, as described by Høgh-Jensen et al. (2004):

$$N_{fix} = DM_{legume} * N\% * P_{fix} * (1 + P_{root+stubble} + P_{transsoil} + P_{immobile})$$

where DM_{legume} was the aboveground biomass of legumes, N% was the concentration of N in the dry matter of the legume, and P_{fix} was fixed N_2 as proportion of total N in the shoot dry matter of the legume. The variables $P_{root+stubble}$, $P_{transsoil}$, $P_{immobile}$ (Høgh-Jensen et al. 2004) were fixed N_2 in the root and stubble as proportion of totally fixed shoot N at the end of the growing period, below-ground transfer of fixed legume N at the end of the growing period, and fixed N_2 immobilized in an organic soil pool at the end of the growing period as proportion of fixed shoot N, respectively.

Table 5-2 Field operation data for combustion of shrub willow, at a farm-field distance of 5 km and a field size of 4 ha (KTBL 2014).

Machinery	**Ø fuel diesel consumption (l ha^{-1} yr^{-1})**
Cultivator, harrow, 2.5 m, 83 kW	33.7
Planting, double row, 3m, 102 kW	14.0
Hoeing machine, 9 m; 67 kW	7.2
Harvester, 9 m, 67 kW	39.3
Forest rotary tiller, 160 kW	25.0
Total	119.2

Aboveground biomass of the willows in the control and in the rows of the agroforestry system were determined in January 2013 and 2014 by using regression models. This is called a model-based sampling approach (West 2009). Initially, total height, diameter at breast height (DBH, 1.30 m), and diameter at stem height at 0.10 m above soil level were recorded for 10 trees per row, in total 320 trees. Then, measured trees from all rows of the experiment were sorted into five classes of different DBH (0–0.9, 0.9–1.8, 1.8–2.7, 2.7–3.6, and 3.6–4.5 cm).

Six trees per class (three from the edge, three from the center area) were selected randomly for harvesting. Overall, 15 trees from the edge area and 15 trees from the centre area were selected from the whole field experiment and cut at a stump height of 0.10 m. The proportion of willows located in edge rows vs interior rows was 50–50 %. Willows were cut by loppers and fresh weight was measured in the field. After chopping the material a sub-sample was oven-dried at 105 °C until constant weight, and weighed to determine the dry matter yield. Based on the biomass yields of the harvested trees and their total height, diameter at breast and at 0.10 m above soil level height, regression models were developed and applied to all trees investigated; for total height, diameter at breast and at 0.10 m above soil level height. The biomass yield per hectare was estimated by using this regression method and a site-specific allometric power equation, as high accuracies with this method have been shown for willows in previous studies (Verwijst and Telenius 1999; Hartmann et al. 2014):

$y = ax^b$

where y was the dry matter yield of the willows, x was the breast height diameter, and a (8.42), b (1.23) were the determined regression factors. The coefficient of determination R^2 was 0.91.

5.2.4 Conversion technologies

In order to assess different options for energetic use of the grassland biomass, three conversion technologies were considered; ‘Combustion of hay’ (CH) and the ‘Integrated generation of solid fuel and biogas frombiomass’ (IFBB) were conducted with biomass from the two-cut management system, whereas biomass from the three-cut management system was used for ‘Whole crop digestion’ (WCD). The biomass harvested for energy conversion consisted of mixed samples from each replicate of the experiment. The conversion procedure for the willow biomass is explained later in this chapter (‘‘Combustion of willow wood chip (CW)’’ section). The general framework of the studied conversion technologies for grassland and willow biomass is illustrated in Figure 5-2. Machinery data that were used to calculate the energy balance can be found in Table 5-1 and Table 5-2.

5.2.4.1 Combustion of hay (CH)

Producing hay is a state of the art technology. However, the use of the dried grassland biomass in conventional combustion units is still challenging and not frequently practiced. The main reason for the low level of practical implementation is the high mineral content of the biomass, which is detrimental to its thermal use (Bühle et al. 2014). In this study, grassland biomass was harvested with a finger-bar mower at a stubble height of 50 mm. Dried samples were investigated for combustion-relevant constituents.

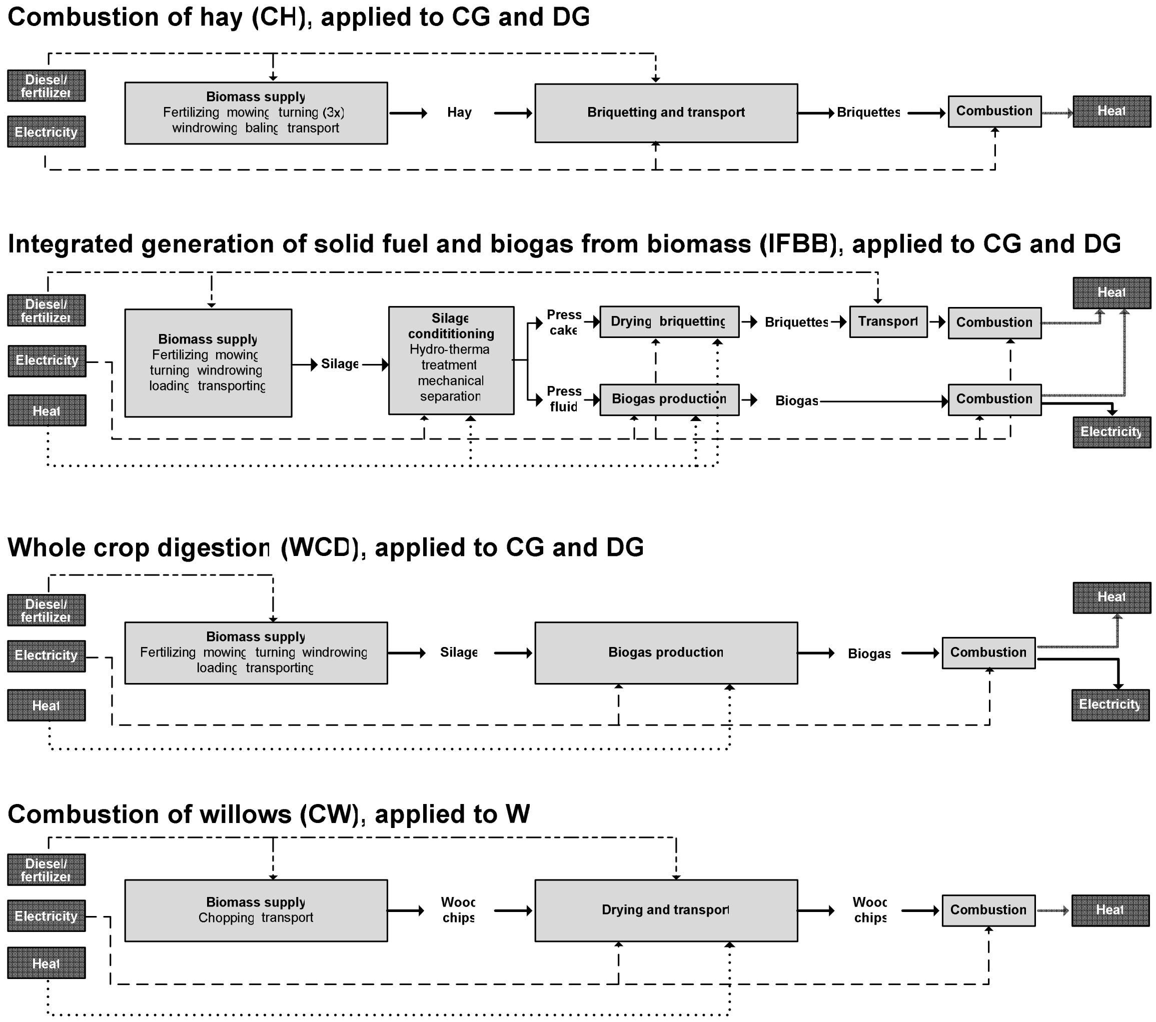

Figure 5-2 General framework of the studied conversion technologies for grassland biomass grown in a separate stand as control and in an agroforestry system intercropped with willows. The conversion technologies applied to clover-grass (CG) and a diversity-oriented grassland mixture (DG) comprise: combustion of hay (CH), integrated generation of solid fuels and biogas from biomass (IFBB), and whole crop digestion (WCD). The conversion technology applied to the woody biomass of willows (W) was combustion (CW).

5.2.4.2 Integrated generation of solid fuel and biogas from biomass (IFBB)

The IFBB technology aims to efficiently produce a high quality fuel from lignocellulosic biomass (Wachendorf et al. 2009). After harvesting with a finger-barmower at a stubble height of 50 mm, the herbage was windrowed and wilted for two hours in the field. Approximately 20 kg of the herbage was chopped into 50 mm pieces, compacted and ensiled in 60 L polyethylene barrels without any additives, for a minimum period of 3 months. After the ensiling period, the silage was mashed with water (ratio 1:4) at 40 °C for 15 min and separated by a conical screw press into a solid fraction (press cake) for thermal use, and a liquid fraction (press fluid) to be used as a biogas substrate. The press cake was analyzed for combustion relevant constituents (see ‘‘Chemical biomass analyses’’ section), whilst the press fluid was investigated for its methane potential (see ‘‘Whole crop digestion (WCD)’’section).

5.2.4.3 Whole crop digestion (WCD)

Whole crop digestion is the most commonly applied system to convert wet conserved grassland biomass into electricity and heat. It is especially suitable for organic substrates with a high proportion of easily digestible compounds. The method for conservation of the biomass was the same as for IFBB (‘‘Integrated generation of solid fuel and biogas from biomass (IFBB)’’ section). Processing of the silage was conducted by anaerobic digestion in batch experiments. The fermentation of the substrates took place in 20 L polyethylene containers. The containers were filled with 8 kg fresh matter of an inoculum from digested, active slurry, and with 400 g of whole crop grassland silage. Fermentation time was 35 days. Methane volumes were measured under laboratory conditions and converted to standard conditions (273.15 K, 101.325 kPa) (Richter et al. 2009).

5.2.4.4 Combustion of willow wood chip (CW)

The combustion of wood chip is a common conversion technology which is well established in many industrialized countries. However, the use of woody biomass from short rotation coppice as fuel or in the pulp and paper industry is a relatively new practice. *Salix* spp. and *Populus* spp. are especially well adapted to the temperate climate and thereby have good potential as bioenergy carriers (Rowe et al. 2011). Data relating to the cultivation machinery used can be found in Table 2. For the fresh harvested willows a moisture content of 50 % was assumed (Fiala and Bacenetti 2012). Data for fuel characteristics were based on Kaltschmitt et al. (2009) (Table 5-6).

5.2.5 Chemical biomass analyses

Representative samples of 200–300 g from each grassland treatment, and the IFBB press cake, 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, Hahn, Germany). Samples were analyzed for C, H, and N using an elemental analyser (VarioMAX CHN Elementar Analysesysteme GmbH, Hanau, Germany). Content of K, Na, Mg, Ca, Cl, S, and P were determined by using x-ray fluorescence analysis. The lower heating value (LHV) of hay and press cake was calculated from the concentrations of C, H, and N with the empiric equation for biofuels from Friedl et al. (2005). Data related to the chemical analyses of the feedstock for combustion purposes are described in Table 5-6.

5.2.6 Energy balance

The assessment of the energy balance for the agroforestry system focused on the following conversion technologies applied to grassland biomass: (1) the combustion of hay, (2) the integrated generation of solid fuel and biogas from biomass, (3) the whole crop digestion; and for willows (4) the combustion of willow wood chip was conducted. Figure 5-2 shows the system boundaries of the conversion technologies as considered for the energy balance, which included establishment, cultivation, transport of the grassland and woody biomass, and the conversion of biomass into energy (heat, electricity). Inputs (diesel, fertilizer, electricity, heat) were taken into account during the whole process chain. Detailed information about the energy input for field operations is presented in Table 5-1 and Table 5-2. The net energy yield per hectare was calculated as the difference between energy input and energy output for all cropping systems and treatments. Furthermore, the net energy yield of the agroforestry system was compared to the net energy yields of separate grassland stands (CG control, DG control) and pure willow stands (W control). For a better comparison of the cropping systems, the functional unit was normalized to 1 ha for grassland control, 1 ha for shrub willow control, and 1 ha for the agroforestry system with a composition of 55 % grassland and 45 % shrub willow. The distance from farm to field was assumed to be 5 km. The energy balance of the cropping systems was based on a time frame of 3 years. Energy inputs for establishment of the cropping systems and the site restoration from willow short rotation coppice to arable land was included in the energy balance as a sixth of the whole field operation data, assuming a lifespan of the cropping systems of 18 years. Further framework assumptions are given in Table 5-3.

5.2.7 Statistical analyses

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 analysed statistically. 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-grass 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 x M, B x M x C, B x M x 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).

Table 5-3 Framework assumptions for the net energy balance.

Parameter	**Units**
Silage losses	12 %
Degree of efficiency combined heat and power plant, electrical	35 %
Degree of efficiency combined heat and power plant, thermal	50 %
Degree of efficiency heat plant, thermal	85 %
Hay losses	36 %
Wood chip losses	10 %
Thermal capacity oM	2.1 kJ kg^{-1} K^{-1}
Thermal capacity ash	0.75 kJ kg^{-1} K^{-1}
Thermal capacity water	4.19 kJ kg^{-1} K^{-1}
Δ T silage for anaerobic digestion	28.7 K
Δ T silage for mashing	31.7 K
Δ T mash water	15 K
Heat input dryer	1.1 kWh kg^{-1} water
Electricity input anaerobic digestion	9.05 % of output
Electricity input biomass dosing	0.37 kWh t^{-1} FM silage
Electricity input mashing	3.5 kWh t^{-1} FM silage
Electricity screw press	41 kW t^{-1} DM silage
Electricity input drying	50.8 kW t^{-1} DM press cake
Electricity input briquetting	84.79 kW t^{-1} DM press cake
Electricity input combustion	0.3 % of lower heating value

5.3 Results

5.3.1 Biomass

Triennial grassland productivity of CG was on average 32 % higher than that of DG (Figure 5-3). The dry matter yield of the different grassland mixtures in the control and in the alleys differed remarkably (Table 5-4). Cutting management did not affect dry matter yield, whereas N fertilizer significantly ($P < 0.05$) increased the yield by 121 %, irrespective of the cutting management. The effect of N fertilizer was more pronounced in DG (+138 %) than in CG (+108 %). White clover contributed 29 % (0 N, unfertilized) and 31 % (100 N, fertilized) to the average total annual DM yield of CG mixture. DG only contained minor seed portions of the legumes birdsfoot trefoil (*Lotus corniculatus* L.) or black medick (*Medicago lupulina* L.). Due to the white clover content in CG, approximately 219 kg atmospheric N ha^{-1} was biologically fixed in the unfertilized CG mixture.

It is remarkable that the yield of agroforestry systems including unfertilized DG (DG-W agroforestry) was similar to unfertilized DG grown as a separate stand (DG control), although the proportion of grassland in the agroforestry system was only 55 %. However, separate grassland swards had the highest yield (18 t DM ha^{-1} on average), whereas pure willow stands were least productive with 7 t DM ha^{-1} on average, after the first rotation. Agroforestry systems were intermediate with 12 t DM ha^{-1} on average. In all cutting managements and fertilizer treatments the contribution of willows to the overall yield of the agroforestry system was only 20 %. Comparing the dry matter yield of willows in the control with that of the agroforestry system, the willow incorporated in the agroforestry system achieved 1 t DM ha^{-1} less than the control after the first rotation. The growth parameter DBH was significantly ($P < 0.05$) lower in the rows within the edge area than those within the center area in winter 2013; however, there was no significant difference in DBH of the trees grown in the edge and center areas in winter 2014.

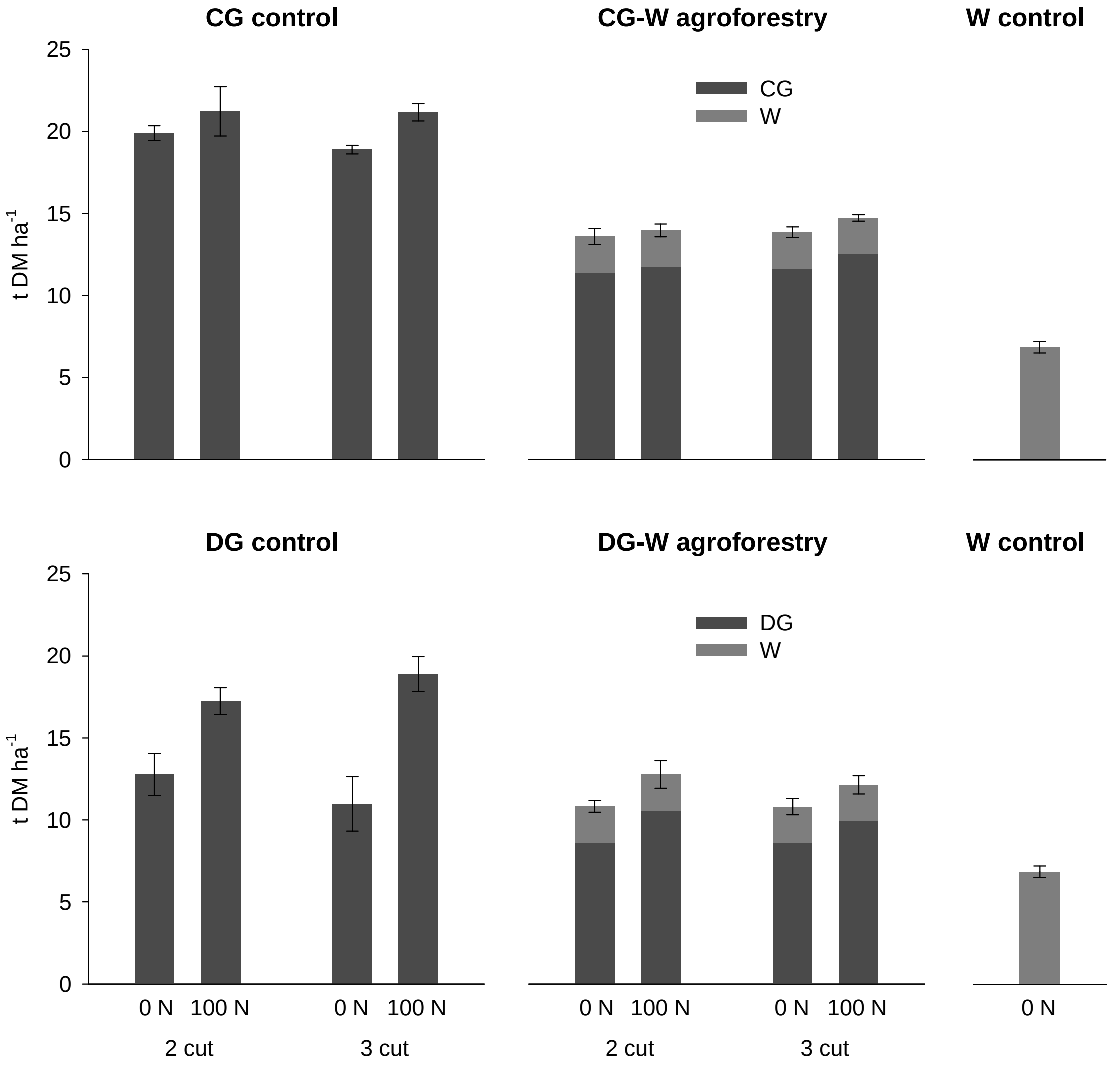

Figure 5-3 Triennial dry matter yield of clover-grass (CG) and a diversity-oriented grassland mixture (DG) in a separate stand (control) and intercropped with willows in an agroforestry system (CG-W, DG-W) and of willows in a pure stand (W control) after the third year after establishment. The grassland was cut twice per year (2 cut) or three times per year (3 cut) and fertilized with 0 kg N ha^{-1} year^{-1} (0 N) or 100 kg N ha^{-1} year^{-1} (100 N). Whiskers show the standard error of the mean.

Table 5-4 ANOVA table for triennial dry matter yields (t ha^{-1}). Yields were accumulated for the years 2011 to 2013.

Source	F-value	Level of significance
Grassland mixture (M)	25.03	**
Cutting frequency (C)	4.59	NS
Nitrogen fertilizer (N)	45.52	**
M x C	4.24	NS
M x N	6.25	NS
C x N	0.50	NS

NS not significant
* P < 0.05; ** P < 0.01; *** P < 0.001

5.3.2 Methane yields and fuel qualities

Biomass-specific methane yields of the IFBB press fluids did not differ between the grassland mixtures or fertilizer levels (Table 5-5). Area-specific methane yields of the press fluids differed between CG (1,700 m^3 ha^{-1}) and DG (1,000 m^3 ha^{-1}). Fertilization only increased methane yield in DG press fluids by 136 %. Methane content in the biogas from the IFBB press fluids was lowest in CG 100 with 51 vol.%, whereas values of the other treatments were all around 60 vol.%. No differences were observed for the methane content of the WCD treatments. Both biomass-specific and area specific methane yields of WCD were lower in DG than in CG (by 93 and 72 % respectively). N fertilizer significantly increased area-specific methane yields of DG WCD by 585 m^3 ha^{-1}.

Table 5-5 Triennial biomass-specific methane yield [l_N kg^{-1} VS], area-specific methane yield [m^3 ha^{-1}] and methane content in biogas [vol.%] produced from silages of two different alley cropped grassland mixtures. Anaerobic digestion was conducted using either IFBB press fluids or whole crop silages (WCD). Grasslands were clover grass (CG) and a diversity-oriented grassland mixture (DG), both fertilized with 0 kg N ha^{-1} $year^{-1}$ (0) or 100 kg N ha^{-1} $year^{-1}$ (100). The standard error of the mean describes the difference in methane yield between the three sampling years.

Grassland mixture	IFBB			WCD		
	Biomass specific methane yield (l_N kg^{-1} VS)	Area specific methane yield (m^3 ha^{-1})	Methane content in biogas (vol. %)	Biomass specific methane yield (l_N kg^{-1} VS)	Area specific methane yield (m^3 ha^{-1})	Methane content in biogas (vol. %)
	M ± SEM §	M ± SEM	M ± SEM	M ± SEM	M ± SEM	M ± SEM
CG 0	316 ± 16	1701 ± 231	61 ± 4	286 ± 20	4830 ± 605	59 ± 4
CG 100	314 ± 32	1715 ± 220	51 ± 4	285± 9	5103 ± 618	56 ± 3
DG 0	312 ± 14	880 ± 84	60 ± 5	260 ± 22	3303 ± 393	60 ± 4
DG 100	317 ± 10	1202 ± 132	61 ± 5	271 ± 11	3888 ± 434	58 ± 5

§ mean ± standard error of the mean ‘SEM’

The lower heating value of the press cake was slightly higher than that of hay (Table 6). The press cake from the IFBB procedure contained less ash and minerals compared to the unprocessed hay. The hydrothermal conditioning pre-treatment within the IFBB procedure caused a mass flow of minerals into the press fluid. Solid fuels (hay, IFBB press cake) from DG mixture had lower N content than CG. Fuel characteristics of beech were compared with those of willows and grassland biomass (Table 5-6), which shows that woody biomass provides a fuel with a higher heating value and lower levels of ash and mineral contents.

Table 5-6 Fuel characteristics of hay and IFBB press cakes produced from two alley-cropped grassland mixtures (clover-grass (CG) and a diversity-oriented grassland mixture (DG)), both fertilized with 0 kg N ha^{-1} year^{-1} (0) or 100 kg N ha^{-1} year^{-1} (100). Mean values are shown over the three experimental years 2011, 2012 and 2013. Fuel characteristics of willows are based on analyses of Hartmann et al. (2014) (K, S, Ca) and Kaltschmitt et al. (2009) (LHV, ash, Cl, N). Fuel characteristics of beech are listed as a reference for comparison (Kaltschmitt et al. 2009).

	Lower heating value (MJ/kg DM)	**Ash (% DM)**	**Cl (% DM)**	**K (% DM)**	**N (% DM)**	**S (% DM)**	**Ca (% DM)**
Hay							
CG 0	17.08	8.16	0.42	2.52	1.91	0.19	0.92
CG 100	17.04	7.93	0.29	2.51	1.71	0.18	0.78
DG 0	16.92	8.33	0.42	2.02	1.20	0.20	1.27
DG 100	16.89	7.65	0.41	1.96	1.01	0.16	0.98
IFBB (press cake)							
CG 0	17.92	4.66	0.04	0.39	1.19	0.10	0.63
CG 100	17.81	4.31	0.04	0.39	0.94	0.09	0.46
DG 0	17.59	5.24	0.04	0.38	0.88	0.08	0.90
DG 100	17.63	4.87	0.04	0.38	0.79	0.07	0.76
Willow wood chips							
	18.40	2.00	< 0.001	0.26	0.54	0.04	0.37
Beechwood							
	18.40	0.50	< 0.001	0.15	0.22	0.02	0.29

5.3.3 Net energy balance

The energy output, consisting of heat and electricity, was highest in the IFBB procedure (44 MWh ha^{-1} on average) for both grassland mixtures (CG, DG) and cropping systems (grassland control, agroforestry, Figure 5-4). 80 % of the energy output produced by IFBB press cakes was heat output. Lowest energy outputs were obtained from WCD (28 MWh ha^{-1} on average), whereas CH was intermediate (37 MWh ha^{-1} on average). For WCD, total energy output consisted of similar proportions of heat and electricity output. In contrast, energy output from CH consisted exclusively of heat from the direct combustion of solid fuels. N fertilization increased energy output by 23 % for all conversion technologies considered. Energy output for CG was 41 % higher than for DG mixtures. Pure willow stands achieved lower energy outputs compared to CG control and CG-W agroforestry systems, however, they were on a similar level to unfertilized DG-based grassland and agroforestry systems.

In general, the energy input by diesel and fertilizer was low compared to the overall energy turn-over. Highest energy inputs were observed for the IFBB procedure, which was mainly due to the high energy demand for the drying of the press cake. The electricity input was also highest for IFBB.

With 39 MWh ha^{-1}, CH achieved the highest triennial net energy yield, followed by WCD (27 MWh ha^{-1}), and IFBB with a yield of 26 MWh ha^{-1}. Combustion of willow wood chip achieved a net energy yield of 23 MWh ha^{-1} after the third year of establishment.

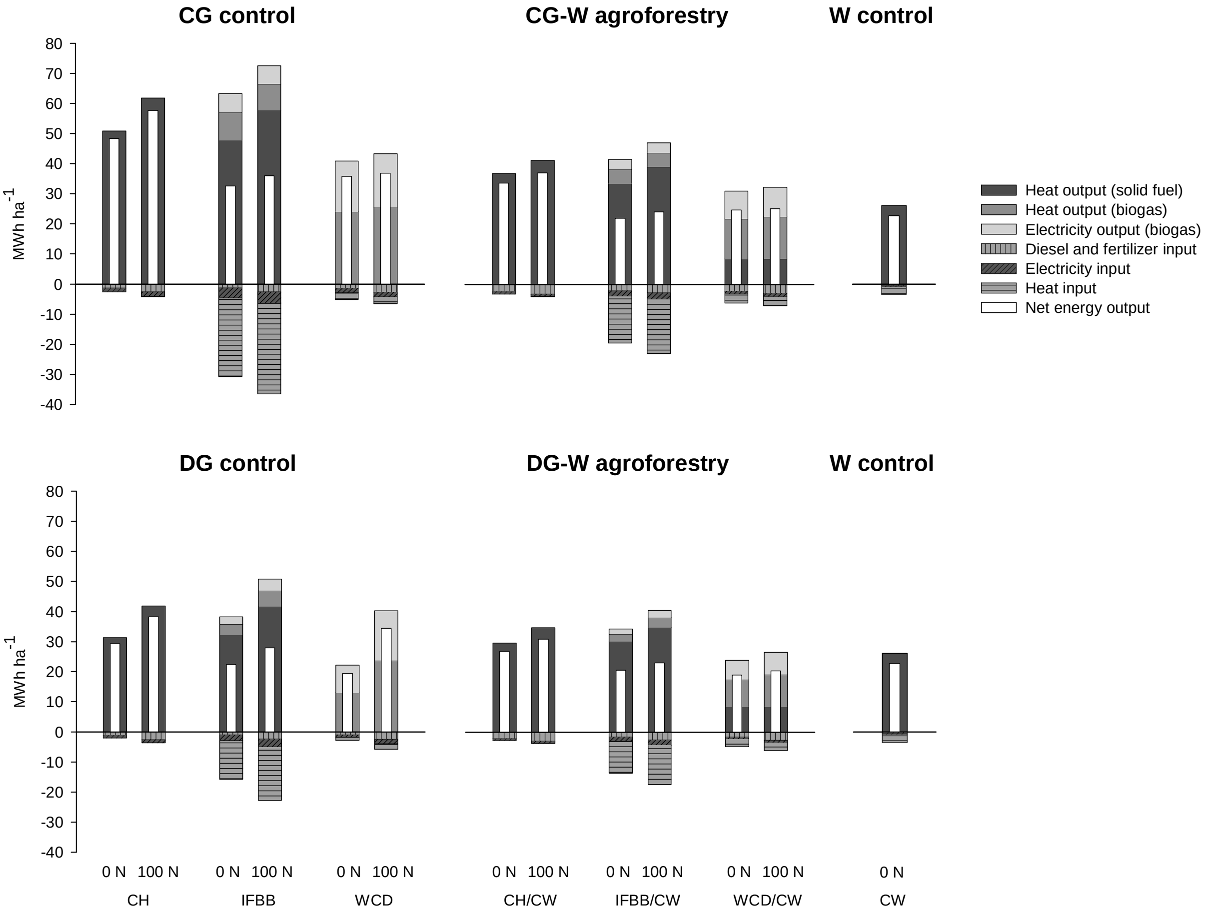

Figure 5-4 Triennial energy input, output and net energy yields of clover-grass (CG) and a diversity-oriented grassland mixture (DG) in a separate stand (control), in an agroforestry system with clover-grass (CG-W) and a diversity-oriented grassland mixture (DG-W) intercropped with willows; and of willows in a pure stand (W control) after the third year after establishment. Two levels of nitrogen fertilizer were applied to the grassland: 0 kg N ha^{-1} year^{-1} (0 N) and 100 kg per ha^{-1} year^{-1} (100 N). Willows were not fertilized (0 N). Three conversion technologies were applied to the grassland biomass: combustion of hay (CH), integrated generation of solid fuels and biogas from biomass (IFBB) and whole crop digestion (WCD). Willows were combusted as wood chips (CW).

5.4 Discussion

5.4.1 Biomass

Alley cropping is becoming an increasingly popular agroforestry type in the temperate zone. As pointed out by Holzmueller and Jose (2012), alley cropping offers potential to provide biomass-based energy carriers. However, little information is available on the productivity of perennial herbaceous and woody crops over time and across a broad range of site conditions.

Therefore, it was a major goal of this study to examine the productivity of alley cropping systems consisting of grassland and willows under moderate European climate conditions. The triennial yield performance of an alley cropping system of grassland and shrub willow in the first rotation was compared with that of pure stands of grassland and shrub willow hybrids of the same age and within comparable conditions. While the grassland control yielded highest with 18 t DM ha^{-1}, yield of willow control was lowest (7 t DM ha^{-1}), and average yield of agroforestry systems was intermediate with woody biomass contributing only 20 % of the overall yield of 12 t DM ha^{-1}. It is well documented that shrub willow hybrids have low growth rates, especially in the first few years of establishment, whereas values can increase up to 10 t DM ha^{-1} year^{-1} after the first rotation (Aylott et al. 2008; Dimitriou et al. 2012; Stork et al. 2014; Wilkinson et al. 2007). Extremely low rainfall in the year of establishment may have further reduced growth (Hartmann et al. 2014). Furthermore, it is documented that a cut-back of willow clones in the first year of establishment enhances the productivity (Bullard et al. 2002). This practice was not applied on the willows in the study presented. Yield performance of the willows in the control and the agroforestry system may have also been modified by a higher cutting density and a biennial harvest cycle (Bullard et al. 2002). Weed management in the early years of establishment is crucial for the success of SRC. Probably, mowing herbaceous competition is ineffective in plantations of fast-growing species (Coll et al. 2007). Given to the low yields of willows after the third year of establishment an integrated weed management, as recommended by Morhart et al. (2013) would have improved the performance.

Comparing the yields of willows based on one hectare, we found that willows incorporated in agroforestry systems achieved slightly lower yields than in a pure stand, whereas yields of alley cropped grassland was not different from pure swards. Similarly, Gamble et al. (2014) reported that in the first 2 years after establishment the herbaceous alley crops showed no evidence of competition in a willow alley cropping system. Gruenewald et al. (2007)

investigated the productivity of an alley cropping system with black locust and alfalfa on a reclaimed mine-site in North-East Germany. Although root systems competed for the same resources in the topsoil layer, black locust was shown to exert only a minor influence on alfalfa yields under the prevailing growth conditions.

In this study, triennial grassland productivity of CG was on average 132 % higher than in DG. The application of fertilizer to grassland induced a pronounced yield increase in DG, whereas in CG the effect was minor. This was not surprising, as the seed mixture of CG consisted of white clover and perennial ryegrass which are among the most productive grassland species under temperate European climate conditions (Frame and Newbould 1984; Peyraud et al. 2009). Cultivars used for each of these species had recently been recommended by the official German agricultural authorities for the specific site conditions. Seed mixtures like DG are usually used to enhance floristic diversity, and are, thus, composed of species which are generally not improved by breeding, but are sampled in nature and multiplied by the seed producer. Forbs species, which made up 41 % of the seed mixture, are especially known to establish very slowly and to remain less productive (DeHaan et al. 2010). In contrast to CG, where white clover contributed 29 and 31 % to the average total annual DM yield with 0 and 100 N, respectively, DG only contained minor seed portions of birdsfoot trefoil (*Lotus corniculatus* L.) or black medick (*Medicago lupulina* L.). Their DM contribution in the swards was negligible. This explains the low N fertilizer effect in CG, as approximately 219 kg atmospheric N ha^{-1} was biologically fixed by white clover in the unfertilized treatments, which was estimated according to Høgh-Jensen et al. (2004), who found an N fixation of 41 kg ha^{-1} per t DM of white clover.

5.4.2 Methane yields and fuel qualities

WCD was conducted for grassland which was harvested three times per year. This is considered as the appropriate number of cuttings for anaerobic digestion, since the biomass-specific methane yield declines with the increased maturity of plants at lower cutting frequencies (Herrmann et al. 2013; King et al. 2012; Melts et al. 2014). Irrespective of N fertilization, biomass-specific methane yield of CG was 107 % higher than that of DG. One reason may be the high white clover content of CG, which is known to provide highly digestible biomass (Khalsa et al. 2014). Furthermore, CG contains less forbs than DG, which have particularly low digestibility after flowering (Prochnow et al. 2006; Richter et al. 2009). Contrary to CG, DG contains many secondary grasses which have not been improved through breeding programs, and subsequently quickly decline in digestibility in comparison to perennial ryegrass (Frame 1990). Although press fluid was produced from grassland which was cut twice a year and concomitantly had a higher lignification compared to biomass from a three cut regime, biomass-specific methane yield was 39 l_N kg^{-1} VS higher than in WCD from grassland cut three times per year. This proves that large parts of easily digestible organic substances, like sugar and proteins, are transferred into the press fluid, making it an effective substrate for biogas digestion (Bühle et al. 2012a). Methane content of biogas was similar for IFBB and WCD, but the area-specific methane yield from WCD was three times higher than from IFBB. This was not surprising, as only 20 % of the organic matter was transferred into the press fluid (data not shown). The fact that the area-specific methane yield from CG was 144 % that from DG was simply a consequence of CG’s higher DM yield, as the biomass-specific methane yield in CG was only 104 % higher and the biogas methane content was the same for both substrates.

Solid fuels from grassland biomass are known to be a difficult substrate for combustion (Bühle et al. 2014; Hensgen et al. 2012) which are improved by increasing maturity of the plants (McEniry et al. 2012). Therefore in the present study only biomass from the 2-cut system was considered for combustion. Consistent with studies from Bühle et al. (2014) and Hensgen et al. (2012), mineral contents of the raw material (i.e. hay) was higher than other substrates, for example willow wood chip and beech wood. However, after hydrothermal pre-treatment, the press cake contained lower concentrations of the constituents which cause corrosion or slagging (K, Cl; Bühle et al. 2014) and increase the risk of emissions (N; Hensgen et al. 2012). Furthermore, the heating value of PC was slightly higher than the raw material, making it an appropriate fuel for established wood burners. By blending the PC from grassland biomass with material from willows, for example wood chip or sawdust, an even more appropriate fuel could be produced. In agroforestry systems, as considered in the present study, briquettes from grassland biomass (PC) were produced annually and wood chip from willows triennially. This could contribute towards a permanent biofuel provision at regional level.

5.4.3 Net energy balance

The IFBB conversion technology had a higher electricity and heat input than WCD, CH, and CW, which is caused by the heat used for hydrothermal conditioning and drying of press cakes. These results are consistent with the findings of Richter et al. (2010) and Bühle et al.

(2012b); however, in the present study a WCD scenario was chosen with complete waste heat utilization. In practice, biogas plants usually have a waste heat recovery of 20 or 50 % (FNR 2005). Therefore, different scenarios of waste heat recovery (e.g. 50, 20, 0 %) should be included in a more comprehensive energy balance, which would result in a decrease of the total net energy yield of WCD.

Diesel and fertilizer input represented only a small amount in all cropping systems and treatments, but were somewhat higher in the fertilized treatments. Considering the similar methane yield and fuel quality after IFBB-conversion of CG and DG biomasses, the difference in energy balance between the two sward types is obviously caused by the varying dry matter yield per hectare. As CH represented the highest net energy yield in comparison to IFBB, WCD, and CW, in the control and in the agroforestry system, it seemed to be the preferable conversion technology for grassland biomass. However, the low fuel quality for combustion is not considered in these energy balances, but would render this scenario hardly viable, as the costs for repairs and reinvestments of combustion technology may be very high. Only large scale heating plants can appropriately utilize hay as fuel, although the revenues are low which makes it economically unprofitable.

Net energy yields of agroforestry systems were clearly lower compared to pure grassland systems, which was not surprising considering the low yields of willows. However, this study only covered the establishment phase of the trees and, as found by Stork et al. (2014), it can be expected that their growth will increase over the coming years, reaching full productivity possibly after the first or second rotation. As this will eventually affect both energy input and output figures in various ways, it requires a re-evaluation after each rotation and, finally, across the total agroforestry lifespan. To provide a more holistic framework of the cropping systems this should, apart from the energetic considerations, also include economic and ecological analyses. Such agroforestry systems may have a potential for the diversification of income sources and product lines for farmers and landowners, as well as provide additional ecosystem services (e.g. soil quality, biodiversity), as found by Benjamin et al. (2000) and Jose (2009).

5.5 Conclusions

During the first 3 years following establishment, the performance of different alley cropped agroforestry systems was tested. Due to the low yield of shrub willow biomass, yield performance of agroforestry systems was lower than that for pure grassland stands, irrespective of the grassland seed mixture or fertilization, but was higher than that for pure willow stands. Among the agroforestry variants (including strips of unfertilized willows) those with alley cropped clover-grass mixtures out-yielded those with native diversity-oriented seed mixtures, and systems with fertilized grasslands always yielded higher. Considering the net energy yields, the same ranking among the cropping systems, grassland mixtures and fertilizer levels was found. The comparison of three different energetic conversion techniques for the grassland biomass revealed highest net energy yields for hay combustion, whereas the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion performed similarly. However, due to the low fuel quality of hay, its direct combustion cannot be recommended as a viable conversion technique, whereas IFBB fuels were of a similar quality to wood chip from willow. Overall, this study only covers the first 3 years after establishment, when growth rates of shrub willows are still low. Thus, more research is needed to evaluate the long-term performance of agroforestry systems with shrub willows and herbaceous biomass crops.

6 General discussion

Feedstock from mixed perennial cropping systems is becoming increasingly popular for energy recovery in the temperate zones, as these land use systems comprise yield stability and environmental benefits (Karp & Richter 2011; Tscharntke et al. 2012; Kremen & Miles 2012). Agroforestry systems which are based on perennial woody and herbaceous crops represent such mixed cropping systems. They are considered as an alternative agro-ecological approach to produce biomass-based energy carriers. Agroforestry has a long history in the provision of lignocellulosic biomass in the temperate as well as in the tropical zones. But until now, little information is available on the combined production of perennial herbaceous and woody biomass over time and across a broad range of site conditions in the temperate zones. Therefore, it was a major goal of this dissertation to examine the productivity, the tree-crop interactions and the energetic potential of an agroforestry practice of multi-rows of willows under short rotation coppice intercropped with two grassland mixtures in the alleys under temperate climate conditions. To better understand the opportunities and the constraints for the development of agroforestry in the temperate zones, this chapter deals, in a first step, with a historical overview of temperate and tropical agroforestry systems and aims to delineate future needs for boosting agroforestry in Europe. In a second step, the chapter discusses the major findings of this dissertation and their contribution to agroforestry research. Further, it gives recommendations for future research activities on alley cropping willows and grassland, as an example of a modern agroforestry practice adapted to the temperate zones.

6.1 Historical and future perspectives of agroforestry practices

Agroforestry is an ancient land use practice that farmers have used in the temperate and the tropical zones. In Europe, forest clearance, burning the slash and cultivating arable crops for varying periods on the cleared area by the sequential or simultaneous integration of trees was the cornerstone for agroforestry (Nair 1993; Smith 2010). Archeological records of oldest temperate agroforestry system were found in Spain and dates the copper age in c. 2500 BC (Eichhorn et al. 2006). During Middle Age, early agroforestry practices began to decline in Europe, when crop rotation was introduced and soil fertility was relying less on leaf litter nutrient cycling from woods. With the invention of chemical fertilizers during the 19th century, the incorporation of trees on agricultural land was further pushed back in Europe (Eichhorn et al. 2006). In the U.S., Native Americans and European settlers practiced subsistence farming using agroforestry approaches. Concomitantly to the developments in Europe, e.g. industrialization and separation of forest and agricultural sector, there was a decline of agroforestry in the U.S. during the last two centuries. It is reported that in the U.S. agroforestry practices survived into the mid of the 20th century (Lassoie et al. 2009). In Europe, agroforestry was still widely spread in Finland up to the end of the 19th century and it was disseminated in few areas in Germany until the late 1920s (Nair 1993). Therefore, some historical agroforestry practices were still maintained in a traditional manner in the temperate zones (Eichhorn et al. 2006; Lassoie et al. 2009). In particular, in the 20th century there has been a significant regression in the use of agroforestry systems across Western Europe. Eichhorn et al. (2006) identified seven basic causes for the decline of agroforestry practices in Europe:

- Increasing mechanization induced removal of scattered trees
- Post-war demand for increased productivity through monocultures
- Reduction in agricultural work force
- Shift from small, fragmented land holdings to larger single farms
- Policy regimes that favoured single crop systems over mixed cropping
- Wooded areas ineligible for subsidy payments (removal of trees to maximize subsidy income)
- Stricter quality requirements for dessert fruit resulting in intensification of orchard production

Not only in the temperate zones, also in the tropics agroforestry had a long history. In Central America many societies imitated forest structures by planting various trees and crops in multi-stories on small-scale production units since ancient times (Oelbermann et al. 2004). Asia and Africa have also a unique heritage of traditional agroforestry systems (Nair 1993). By the end of the 19th century the in Myanmar originated “taungya” system which is seen as a forerunner to agroforestry found increasingly interest among colonial foresters. The idea of the “taungya” system was to set up forest plantations by unemployed or landless workers. In return for performing forestry tasks, the workers would be allowed to cultivate the land between the rows of tree seedlings to grow agricultural crops. This practice became more and more widespread in Asia and Africa. More than hundred years, from the 1856 to the mid-1970s, extensive research was done on the “taungya” systems, but the focus was only on the establishment of high value timber products (e.g. teak, *Tectona grandis* L.F.). Farms, the welfare and rights of the farmers, the production of the integrated agricultural crops and its potential as a land use system were barely considered by the science community. Certainly, some claimed that local farmers were exploited while establishing cheap forest plantations (King 1987; Nair 1993).

Many circumstances in the 1970s added to the general acceptance of agroforestry as a land use system that is applicable to both farm and forest. Among other circumstances, these were e.g. a re-assessment of forestry policies by the FAO; the deteriorating food situation in many areas of the developing world; the increasing spread of tropical deforestation and ecological degradation; the energy crisis of the 1970s; a reawakening of scientific interest in both intercropping and farming systems. The term “agroforestry” first coined in 1977 (Lundgren 1982). Since the mid-1970s the World Agroforestry Center (ICRAF, International Council for Research in Agroforestry) promotes agroforestry practices in developing countries. Since the 1980s and 1990s research moved at a global scale and in the late 1990s a strong science culture was built on advances in agroforestry. During this time modern agroforestry systems, which comprise increased productivity and environmental conservation, has been implemented and studied in the U.S., in Europe, in New Zealand and the temperate regions of Australia (Smith 2010).

Since the 21st century when concerns on dependence on fossil fuels and global climate change have been raised, the production of biofuels and energy from woody and herbaceous biomass has become important. In this context, agroforestry has gained a renewed interest as an integrative sustainable land use practice (Lassoie et al. 2009; Jose 2009; Gruenewald et al. 2007). However, FAO (2013) stated in a guide for decision-makers that agroforestry is often constrained by legal, policy and institutional frameworks in both tropical and temperate zones. Currently, there are limited federal incentives that help farmers to adopt agroforestry practices in their management regimes. Policies are required that assist the adoption of agroforestry and acknowledge its contribution to national development. Furthermore, FAO (2013) explicated that there is a need for a better communication between sectors and the mainstreaming of agroforestry in national policies.

Nevertheless, temperate agroforestry seems to be in transition. Recent examples from the U.S. and Europe showed positive trends towards agroforestry into mainstream. Lassoie et al. (2009) reported from a significant progress in building a research-education-application infrastructure and in developing a national agroforestry policy. In Europe, progress could be accomplished by the foundation of the European Agroforestry Federation (EURAF) in 2011.

Since its foundation, EURAF achieved that incentives for the support of agroforestry have been introduced to the Common Agricultural Policy. Agroforestry practices are listed as Ecological Focus Areas and farmers can receive greening payments in pillar I (Reg.(EU) 1307/2013). The set-up of agroforestry systems can be supported through national or regional Rural Development Programs in pillar II (Reg.(EU)1305/2013) (Anonymous 2015). Furthermore, increased research activities on traditional and modern temperate agroforestry practices could be observed in Europe.

Although progress has been good, specific challenges still face the development of European agroforestry. Farmers are still reluctant and risk-averse to preserve or to adopt agroforestry practices on their farms. Among others one reason might be that the maintenance of traditional agroforestry was perceived as a burden due to the lack of mechanization (Eichhorn et al. 2006). A monetary reason might be that agroforestry demands high initial investment costs; while benefits are purchased until the trees become productive. Subsidies during the years of establishment of agroforestry systems might be an incentive for farmers (Nerlich 2013). To make the management of agroforestry systems profitable, the focus should be upon the economic value of the trees and a clearly defined market for the tree product should be developed (Eichhorn et al. 2006). A major constraint to a wider applicability of agroforestry is the limited awareness among farmers and landowners (Smith 2010). In a survey with 260 participating farmers across 14 sample areas in seven European countries between 2003 and 2004, only 33 % of the interviewees could define agroforestry correctly as an association of trees with crops or livestock. The survey showed also that 31 % of the farmers fear possible crop yield losses, the complexity of work (21 %) and difficulties with mechanization (17 %) (Graves et al. 2009).

To sum up, future needs for boosting European agroforestry will include building an infrastructure for research, development and innovation; to coordinate education, exchange and dissemination activities; to establish extension and advisory services; to promote agroforestry in the general public and to continue working on national agroforestry policies and legislation.

6.2 Alley cropping − a promising temperate agroforestry practice

Alley cropping or growing a crop between rows of trees might be a convenient agroforestry practice in certain agricultural production zones to improve total light energy capture and productivity per unit land (Burner & Belseky 2008; Reynolds et al. 2007; Holzmueller & Jose

2012). In contrast to traditional agroforestry systems like orchards or the Spanish *dehesas*, alley cropping is a type of agroforestry system which is adapted to the temperate zone, with a high degree of mechanization (Long and Nair 1999). As trees are planted in rows and crops in the alleyways, their management is facilitated by machinery and enhances productivity, whilst still providing various ecosystem services (Quinkenstein et al. 2009).

6.2.1 Grassland as understory for temperate alley cropping systems

The competition for light between understory and overstory species is perceived as a major constraint that can affect understory growth in temperate agroforestry systems (Chirko et al. 1996; Reynolds et al. 2007; Dufour et al. 2012). Therefore, it is a common practice in agroforestry research to evaluate the shade tolerance of the understory species. In the first study of this dissertation an unfertilized white clover-perennial ryegrass sward was exposed to different levels of artificial shade and shade material over two succeeding growing seasons. The belowground competition on water and nutrients between trees and grassland was excluded (chapter 3). In a concomitant study, the effects of willows on white clover-perennial ryegrass and a diversity oriented grassland mixture were analyzed at three positions (SW, C, NE) along a tree-crop interface within the alleys of the adjacent newly established agroforestry system (chapter 4). Two different fertilizer levels (0 and 100 kg N ha^{-1} yr^{-1}) and two cutting managements (2 and 3 cuts per year) were included as experimental factors in the grassland alleys.

The analysis of the artificial shade experiment has shown that the mean biennial DM yield observed for clover-grass growing under shade cloth and slats of 50 % PPFD was reduced by 4 and 7 t ha^{-1}, respectively, compared with the control in full sunlight with an overall biennial yield of 24 t ha^{-1}. In the study along the tree-grassland interface of the adjacent young alley cropping system no clear effects of trees on clover-grass productivity were observed over the two growing seasons, but the incident light on understory was on average 19 % lower at position SW and 10% lower at NE compared to the non-shaded control. Considering the sward composition of clover-grass it was shown in both studies that the contribution of white clover decreased by increased shade. It is proposed that the sward composition responds earlier than the overall sward productivity to changes of microclimate induced by trees/artificial shade. There is also evidence that ryegrass is more susceptible to reduced radiation than other cool-season grasses. It seemed to be in both studies that non-leguminous forbs (mainly segetal species) profited from the decline of grasses when shade increased. This is in accordance with other studies emphasizing other cool season grasses like cocksfoot or brome grass are more shade tolerant than perennial ryegrass (Devkota et al. 2009; Lin et al. 1999; Van Sambeek et al. 2007). For example, cocksfoot has been referred to as one of the most shade tolerant temperate pasture species on long-term, especially, in the areas adjacent to trees (Varella et al. 2011). Although the outcome of the artificial shade experiment showed that clover-grass can perform well under low to medium shade, it is suggested to seek for species or varieties with broader amplitudes of light requirements. A participatory plant breeding program launched by French agroforesters and the project AGFORWARD aims to select shade tolerant durum wheat varieties for temperate agroforestry systems. This seems to be a forward-looking approach to combat light competition between understory and overstory under temperate climate conditions (pers. comm.).

The diversity oriented grassland mixture was only analyzed along the tree-grassland interface and showed lower biennial yields at position C compared to SW and NE in three of four treatments. One of the most important outcomes regarding DG was that in the unfertilized treatments of DG the dry matter contribution of grasses tended to be higher at the positions SW and NE and in correlation to this, the contribution of forbs tended to be higher in the centre of the alley. To gain insight on the possible effects of tree shade on the complex sward composition of DG containing 32 species, thereof 43 % grasses and 41 % non-leguminous forbs, an artificial shade experiment under exclusion of belowground competition might be conducted in future research activities.

Beside plant available radiation artificial shade/shade of trees influenced soil temperature in both studies. Shading lowered soil temperature in 5 cm depth under soil. In a number of other studies lower soil temperature was measured as a result of lower irradiance (Jose et al. 2009). The impact of shade on soil moisture content was significant in the artificial shade experiment, whereas no clear tendencies could be stated in the context of the study along the tree-grassland interface of the young alley cropping system.

Overall, the understory crop must show persistence and cope with the effects of shade from trees including intra-seasonal and annual fluctuation of PPFD. Therefore, the effect of shade on different positions along the interface within the grassland alleys should be evaluated in a long-term perspective. Due to a lack of randomization the effect of shade on positions along the tree-grassland interface could not be tested statistically in this dissertation. A sufficient randomization should be implemented in the set-up of future research activities. The experimental design of both experiments did not enable interpretation of the various microclimatic effects on plant growth, as they showed also complex interactions. Therefore, one focus of future research should be in disentangling the below-ground interactions and in the evaluation of competitiveness of clover-grass and diversity oriented mixture and willows in a long-term perspective, as the root system of grassland occupies a niche similar to that of the shallow rooting willows (Heinsoo et al. 2009; Kutschera 1960).

6.2.2 Potential of willow-grassland alley cropping for bioenergy production

Crop yield is among other factors the most determining for the success and the sustainability of bioenergy cropping systems (Whitaker et al. 2010). In this dissertation, the triennial yield performance of a young alley cropping system after the first rotation was compared with that of pure stands of grassland and willows. Separate grassland swards had the highest yield (18 t DM ha^{-1} on average), whereas pure willow stands were least productive with 7 t DM ha^{-1} on average, after the first rotation. Alley cropping was intermediate with 12 t DM ha^{-1} on average (chapter 5). Considering the different grassland mixtures the triennial productivity of clover-grass was on average higher than that of the diversity-oriented mixture, as clover-grass is among the most productive grassland species under temperate climate conditions (Frame and Newbould 1984; Peyraud et al. 2009). The willow yield after three years was very low and influenced the performance of the alley cropping system by contributing only 20% of the overall yield of 12 t DM ha^{-1}. After full establishment of willow SRC a yield increment is expected in the coming rotations. Assuming an annual growth rate of established willows of 10 t DM ha^{-1} yr^{-1} (Dimitriou et al. 2012; Stork et al. 2014) and a dry matter yield of 10 t DM ha^{-1} yr^{-1} for grassland mixtures (mean of CG and DG), the alley cropping system would achieve a triennial yield of 30 t DM ha^{-1} after the second rotation (when applying a 3-year rotation cycle). Consequently, willow biomass contribution would increase to 45% of the overall yield.

Beside crop yield, the efficiency of the conversion technology is another important factor of sustainable bioenergy cropping systems. In this dissertation, three different conversion technologies were applied to grassland biomass and analyzed for their net energy output. Whole crop digestion was conducted for grassland harvested three times per year. This is considered as the appropriate number of cuttings for anaerobic digestion, since the biomass-specific methane yield declines with the increased maturity of plants at lower cutting frequencies (Herrmann et al. 2013; King et al. 2012; Melts et al. 2014). Hay combustion and IFBB was applied to grassland harvested two times per year which had a higher lignification compared to biomass from a three cut regime. Combustion was applied to willow wood chips. Solid fuels from grassland biomass are known to be a difficult substrate for combustion (Bühle et al. 2014; Hensgen et al. 2012). If processed by the IFBB technology, solid fuels showed improved combustion properties compared to the untreated raw material (i.e. hay) which is consistent with studies from Bühle et al. (2014) and Hensgen et al. (2012). In view of the predicted global shortfall of woody biomass (Nabuurs et al. 2006) briquettes from grassland biomass produced annually and wood chip from willows produced triennially in agroforestry systems could contribute towards a permanent biofuel provision at regional level by fulfilling several ecosystem services.

Aiming to identify the most energy saving production systems the current dissertation conducted energy balances on different conversion technologies for willows and for the two grassland mixtures and the different cropping systems (i.e. pure grassland systems, pure willow SRC, agroforestry system). For comparability of the different cropping systems the dry matter yields, fuel characteristics, methane yields obtained from comprehensive field and laboratory studies were included in the energy balances. The same field operation data and framework assumptions were utilized for calculations, as these are also important for the comparability of the systems. The net energy yield of the agroforestry system was lower in comparison to pure grassland systems. This was mainly related to the low overall yield of the willows. The net energy yield for agroforestry systems would increase when willows achieve higher DM yields. This would be in favor of the agroforestry system and SRC single stand as they represent low input systems. The comparison of the three different energetic conversion techniques for grassland biomass revealed highest net energy yields for hay combustion, whereas the IFBB and WCD performed similarly. However, the low fuel quality of hay was not considered in the assumptions made for the energy balances. In the present dissertation a WCD scenario was chosen with complete waste heat utilization. In practice, biogas plants usually have a waste heat recovery of less than 50 % (FNR 2005); this would remarkably lower the net energy output of WCD. Therefore, different scenarios of waste heat recovery (e.g. 50, 20, 0 %) should be included in a more comprehensive energy balance, which would result in a decrease of the total net energy yield of WCD. In a nutshell, the findings of energy balances are strongly dependent on the assumptions made (Bühle et al. 2012). To provide a more holistic framework of the cropping systems this should, apart from the energetic considerations, include an assessment on GHG savings, carbon sequestration, humus balance, land use aspects and biodiversity during the life-span of those systems.

7 Conclusions

Based on the assessment of a white clover-perennial ryegrass sward under different artificial shade levels and materials, based on the monitoring of the interactions along the tree-grassland interface within the grassland alleys, and based on the net energy balances of an alley cropping system of two grassland mixtures and willows in comparison to separate grassland and pure willow stands as controls, the following conclusions result from this research:

(i) The artificial shade experiment showed that shade by 80 % reduced white clover-perennial ryegrass productivity on average by 50 % compared to a non-shaded control. White clover as a heliophilous plant responded negatively to increasing shade, whereas non-leguminous 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 showed 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.

(ii) Tree shade modified spatially the incident light on grassland understory along the tree-grassland interface with lowest radiation adjacent to the willows. Accordingly, soil temperature was lower on the understory adjacent to the willows than in the centre of the alleys. The effect increased in the third year after establishment. There was no clear pattern of distribution of volumetric soil moisture content along the interface. Grassland productivity along the interface was not affected by shrub willow hybrids during early establishment. Sward composition of white clover-perennial ryegrass mixture changed along the interface, as legumes (i.e. white clover) contributed higher dry matter yields in the centre of the alleys than when being adjacent to the willows. Non-leguminous forbs contribution (mainly segetal species) was higher adjacent to the willow rows than in the centre. Sward composition of the diversity oriented grassland mixture was not affected by willows. There was no remarkable impact of trees on herbage quality.

(iii) Due to the low yield of shrub willow biomass, yield performance of agroforestry system was lower than that for pure grassland stands, irrespective of the grassland seed mixture or fertilization, but was higher than that for pure willow stands. Among the agroforestry variants (including rows of unfertilized willows) those with alley cropped clover-grass mixtures out-yielded those with native diversity-oriented seed mixtures, and systems with fertilized grasslands always yielded higher. Considering the net energy balances, the same ranking among the cropping systems, grassland mixtures and fertilizer levels was found. The comparison of three different energetic conversion techniques for the grassland biomass showed highest net energy yields for hay combustion, whereas the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion performed similarly. However, due to the low fuel quality of hay, its direct combustion cannot be recommended as a viable conversion technique, whereas IFBB fuels were of a similar quality to wood chip from willow. This study only covers the first 3 years after establishment, when growth rates of shrub willows are still low. Long-term effects within willow-grassland alley cropping systems under temperate climate conditions need to be considered in future research.

8 Summary

The demand for biomass for bioenergy has increased rapidly in industrialized countries in the recent years. Biogenic energy carriers are known to reduce CO_2 emissions. However, the resource-inefficient production of biomass often caused negative impacts on the environment, e.g. biodiversity losses, nitrate leaching, and erosion. The detrimental effects evolved mainly from annual crops. Therefore, the aim of modern bioenergy cropping systems is to combine yield stability and environmental benefits by the establishment of mixed-cropping systems. A particular emphasis is on perennial crops which are perceived as environmentally superior to annual crops. Agroforestry systems represent such mixed perennial cropping systems and consist of a mix of trees and arable crops or grassland within the same area of land. Agroforestry practices vary across the globe and alley cropping is a type of agroforestry system which is well adapted to the temperate zone, with a high degree of mechanization. Trees are planted in rows and crops are planted in the alleyways, which facilitates their management by machinery.

This study was conducted to examine a young alley cropping system of willows and two grassland mixtures for bioenergy provision under temperate climate conditions. The first part of the thesis identified possible competition effects between willows and the two grassland mixtures. Since light seemed to be the factor most affecting the yield performance of the understory in temperate agroforestry systems, a biennial in situ artificial shade experiment was established over a separate clover-grass stand to quantify the effects of shade. Data to possible below- and aboveground interactions among willows and the two grassland mixtures and their effects on productivity, sward composition, and quality were monitored along a tree-grassland interface within the alleys. In the second part, productivity of the alley cropping system was examined on a triennial time frame and compared to separate grassland and willow stands as controls. Three different conversion technologies (combustion of hay, integrated generation of solid fuel and biogas from biomass, whole crop digestion) were applied to grassland biomass as feedstock and analyzed for its energetic potential. The energetic potential of willow wood chips was calculated by applying combustion as conversion technique. Net energy balances of separate grassland stands, agroforestry and pure willow stands evaluated their energy efficiency.

Results of the biennial artificial shade experiment showed that severe shade (80 % light reduction) halved grassland productivity on average compared to a non-shaded control. White clover as heliophilous plant responded sensitively to limited radiation and its dry matter contribution in the sward decreased with increasing shade, whereas non-leguminous forbs (mainly segetal species) benefited. Changes in nutritive quality could not be confirmed by this experiment. Through the study on interactions within the alleys of the young agroforestry system it was possible to outline changes of incident light, soil temperature and sward composition of clover-grass along the tree-grassland interface. Nearly no effects of trees on precipitation, soil moisture and understory productivity occurred along the interface during the biennial experiment. Considering the results of the productivity and the net energy yield alley cropping system had lower than pure grassland stands, irrespective of the grassland seed mixture or fertilization, but was higher than that for pure willow stands. The comparison of three different energetic conversion techniques for the grassland biomass showed highest net energy yields for hay combustion, whereas the integrated generation of solid fuel and biogas from biomass (IFBB) and whole crop digestion performed similarly. However, due to the low fuel quality of hay, its direct combustion cannot be recommended as a viable conversion technique, whereas IFBB fuels were of a similar quality to wood chip from willow.

9 Kurzfassung

9.1 Einleitung

Vor dem Hintergrund einer stetig wachsenden Weltbevölkerung und der Folgen der Klimaveränderung befinden sich Agrar- und Wald-Ökosysteme im Wandel. Es wurde zu einer globalen Herausforderung, effiziente und gleichsam produktive Landnutungssysteme zu entwickeln, die weniger klimarelevante Treibhausgase (THG) ausstoßen und die Biodiversität erhalten (Johnson & Virgin 2010; Tscharntke et al. 2012; Soussana 2014).

Mit einer zunehmenden Intensivierung der Landwirtschaft sind vielfältige Umweltbelastungen verbunden (Ceccarelli et al. 2014; Cumming et al. 2014). Zum Beispiel tragen die Land- und Forstwirtschaft sowie andere Landnutzungsformen mit 17–31 % am meisten zur Emission klimarelevanter THG bei. Die Weltbevölkerung wird auf geschätzte 9–10 Milliarden im Jahr 2050 wachsen, wodurch die Nachfrage von Nahrungsmitteln steigen wird und sich Bereiche wie Ressourcenübernutzung, Nahrungsmittelsicherheit und Landverfügbarkeit verschärfen werden (Smith et al. 2013). Die Folgen werden Landnutzungskonflikte und unterschiedliche Nutzungsinteressen für die Bereitstellung von Nahrungsmitteln, Wasser, Holz, Energie, Siedlungen, Infrastruktur, Erholungsgebiete und Biodiversität sein (Coelho et al. 2012).

Das Bestreben der europäischen und US-amerikanischen Energiepolitik, fossile Brennstoffe zunehmend durch erneuerbare Energien zu ersetzen, führte zu einem gestiegenen Bedarf an Biomasse für die Bioenergieproduktion in den Industrienationen. In den letzten Jahren konnte beobachtet werden, dass der wachsende Energiepflanzenanbau für „Land Grabbing“ (ausländischer Landerwerb), steigende Lebensmittelpreise und Waldzerstörung mitverantwortlich ist (Borras & Franco 2012; Erb et al. 2012; Tscharntke et al. 2012). Die negativen Auswirkungen des Energiepflanzenanbaus in Form von Verlust an Biodiversität, Stickstoffauswaschung und Erosion entstanden hauptsächlich durch den Anbau einjähriger Kulturen („first generation“), wie zum Beispiel Raps, Ölpalme oder Mais (Righelato & Spracklen 2007; Searchinger et al. 2008).

Grundsätzlich steht der Landwirtschaft ein breites Spektrum an Kulturarten für die Produktion von Bioenergieträgern zur Verfügung. Unterschieden wird dabei zwischen ein- und mehrjährige Kulturen. Karp & Richter (2011) stellten das Potential von extensiv bewirtschafteten mehrjährigen Kulturen gegenüber den einjährigen Kulturen als vorteilhaft dar. Geeignete mehrjährige Kulturen sind schnell wachsende Hölzer wie Pappeln und Weiden, die in sog. Kurzumtriebsplantagen (KUP) angelegt werden, Miscanthus und verschiedene andere Grassarten. Die Produktion von Biokraftstoffen aus Weide zeigten den größten Netto-Energieertrag und die geringsten THG Emissionen im Vergleich zu einjährigen Kulturen (Börjesson & Tuvesson 2011). Mehrjährige Kulturen tragen zu einer dauerhaften Bodenbedeckung, reduzierten Bodenbearbeitung gesteigerten Kohlenstoffspeicherung, geringeren Emission von N_2O und einer Verbesserung der Bodenökologie im Vergleich zu einjährigen Kulturen bei (Karp & Richter 2011; Pugesgaard et al. 2014). Ein weiterer Vorteil mehrjähriger Energiepflanzen liegt darin, dass sie auf marginalen Standorten angebaut werden können, wo Nahrungspflanzen nicht wirtschaftlich angebaut werden können.

Die Ertragsleistung und die Einsparung von THG-Emissionen gehören zu den wichtigsten Faktoren eines nachhaltigen Bioenergiepflanzenanbaus (Whitaker et al. 2010). Neben der Produktivität eines Systems unterstützen angepasste und effiziente Konversionstechnologien den Ertrag an Nutzenergie und damit die Schonung von Umweltressourcen. Mehrjährige Kulturen sind reich an Lignocellulose, wodurch es einer Vorbehandlung und einer effizienten Konversionstechnologie bedarf, wie zum Beispiel der Bioraffinerie (Bonin & Lal 2012). Jedoch beinhaltet jede Produktionskette und Konversionstechnologie von Biomassen Vorteile und Nachteile. Um die Energieeffizienz der verschiedenen Bereitstellungsketten für Bioenergie zu bewerten, wird die Ökobilanzierung angewandt, um die Umweltwirkungen von Produkten während des gesamten Lebensweges systematisch zu analysieren (Bonin & Lal 2012).

Eine weitere Herausforderung der Bioenergieproduktion besteht darin, Landschaften so zu strukturieren, dass die pflanzliche Erzeugung für Nahrung und/oder Brennstoff mit den Anforderungen an die Biodiversität vereint wird. Produktivität und Biodiversität können nebeneinander bestehen. Mischkulturen, Fruchtfolgen oder Agroforstsysteme sind geeignete Maßnahmen zur so genannten agrar-ökologischen Intensivierung, die Ertragsstabilität mit positiven Umweltwirkungen verbindet (Tscharntke et al. 2012; Kremen & Miles 2012).

Agroforstwirtschaft bedeutet den Anbau von Gehölzen und Kulturpflanzen und/oder Viehhaltung auf der gleichen landwirtschaftlichen Nutzfläche (Nair 1993). Diese multifunktionale Landnutzungsform vereint Produktion mit Ökologie und Umweltsicherung und stellt unter anderem unterstützende und regulierende Ökosystemdienstleistungen bereit, wie zum Beispiel Erosionsschutz und Bodenanreicherung (Jose 2009). Landnutzungssysteme, die Landwirtschaft oder Viehhaltung und Wald kombinieren, haben einen speziellen ökologischen Wert (Tscharntke et al. 2012), der auch zu einem nachhaltigeren und flächeneffizienteren Bioenergiepflanzenanbau beitragen kann.

Ausgehend von diesen Aspekten wurde in der vorliegenden Dissertation eine umfassende Analyse eines jungen Agroforstsystems für die Bereitstellung von Bioenergieträgern unter gemäßigten Klimabedingungen durchgeführt. Die hier angewandte Agroforstmethode war der so genannte Feldstreifenanbau, auch „alley cropping“ genannt, in dem Reihen schnellwachsender Weidenklone im Kurzumtrieb im Wechsel mit Grünlandstreifen angelegt wurden. Zwei verschiedene Grünlandansaaten (Weißklee-Deutsches Weidelgras-Mischung, diversitätsorientierte Mischung mit 32 Arten) wurden ausgewählt, da sie geeignete Grünlandarten bei geringer Düngung darstellen. Die Studie war Teil des Verbundprojektes „BEST – Bioenergieregionen stärken“, das regional angepasste Konzepte und innovative Systemlösungen zur Produktion von Biomasse zur Bioenergiegewinnung untersuchte.

Der erste Teil der Arbeit (Kapitel 3 und 4) hatte zum Ziel, mögliche Konkurrenzeffekte zwischen Weidenklonen und den zwei Grünlandansaaten zu ermitteln. Da das Licht der begrenzende Faktor für die Ertragsleistungen der Unterkultur in gemäßigten Agroforstsystemen zu sein scheint, wurde ein zweijähriges künstliches Schattierungs-Experiment mit einem Weißkleegrasbestand unter Feldbedingungen durchgeführt (Kapitel 3), um die Auswirkungen von Schattenstufen und Schattierungsmaterial auf den Ertrag, die botanische Bestandeszusammensetzung und die Qualität zu quantifizieren. Des Weiteren wurden Untersuchungen zu möglichen unter- und oberirdischen Interaktionen und deren Auswirkungen auf den Ertrag, die botanische Bestandeszusammensetzung und die Qualität entlang eines Baum-Grünland-Gradienten über einen Zeitraum von zwei Jahren durchgeführt (Kapitel 4).

Der zweite Teil der Arbeit bewertete das Potential eines jungen Agroforstsystem aus Grünland und Weiden für die Bereitstellung von Bioenergieträgern. Die Produktivität des Agroforstsystems wurde drei Jahre lang untersucht und mit Grünland und Weiden als Kontrollen verglichen. Das energetische Potential von Hackschnitzeln aus Weidenholz und von drei verschiedenen Konversionstechnologien für Grünlandbiomasse (Heuverbrennung, Integrierte Festbrennstoff- und Biogasproduktion aus Biomasse, Ganzpflanzenvergärung) wurde bewertet. Schließlich wurden die Netto-Energiebilanzen für die Grünlandkontrolle, das Agroforstsystem und die Weidenkontrolle erstellt und bezüglich ihrer Effizienz verglichen.

9.2 Forschungsziele

Ziel dieser Arbeit war es, pflanzenbauliche und physiologische Eigenschaften von Weiden und Grünland im Mischanbau in einem Agroforstsystem der gemäßigten Breiten zu verstehen und das Potential des Agroforstsystems für die Bioenergiebereitstellung zu bewerten.

Unter- und oberirdische Interaktionen zwischen Weiden und Grünland wurden jeweils in einem zweijährigen künstlichen Schattierungsexperiment außerhalb der Agroforstfläche und entlang eines Baum-Grünland-Gradienten in den Grünlandstreifen innerhalb des Agroforstsystems untersucht. Die mikroklimatischen Parameter umfassten die photosynthetisch aktive Strahlung (PPFD), die Bodenfeuchte, die Bodentemperatur und den Niederschlag. Die pflanzenbaulichen Parameter umfassten den Trockenmasseertrag, die botanische Bestandeszusammensetzung und die Qualität der Grünlandbiomasse. Das künstliche Schattierungsexperiment wurde über einem Weißklee-Deutschen Weidelgras-Bestand errichtet. Die Versuche entlang des Baum-Grünland-Gradienten wurden auf zwei verschiedenen Grünlandbeständen (Weißklee-Deutsches Weidelgras-Mischung und eine diversitätsorientierte Mischung mit 32 Arten) mit zwei unterschiedlichen Düngestufen und Nutzungsintensitäten ausgeführt. Die mikroklimatischen und pflanzenbaulichen Parameter wurden an drei verschiedenen Positionen entlang des Gradienten gemessen.

Für die Grünlandkontrolle, das Agroforstsystem aus Weiden und Grünland und die Weidenkontrolle wurden Energiebilanzen erstellt. Die Heuverbrennung, Integrierte Festbrennstoff- und Biogasproduktion aus Biomasse (IFBB) und Ganzpflanzenvergärung wurden als experimentelle Faktoren betrachtet, da diese Verfahren gängige Konversionstechnologien für Grünlandbiomasse sind. Für die Verwertung der Weiden des Agroforstsystems wurde die Verbrennung von Hackschnitzeln unterstellt.

Die spezifischen Ziele der Untersuchungen waren

(i) die Auswirkungen von Schattenstufen und Schattierungsmaterial (Beschattungsnetze und eine Lattenkonstruktion) auf Produktivität, botanische Bestandeszusammensetzung und Qualität eines Kleegrasbestandes in einem zwei-jährigen künstlichen Schattierungsversuch zu quantifizieren.

(ii) die Auswirkungen von Weiden auf Mikroklima, Produktivität, botanische Bestandeszusammensetzung und Qualität entlang eines Gradienten in den Grünlandstreifen in raumzeitlichen Dimensionen zu ermitteln.

(iii) die Produktivität eines Agroforstsystems aus Grünland und Weiden im Vergleich zu den Grünland- und Weidenkontrollen zu untersuchen; das Energiepotential von Weidenhackschnitzel und drei verschiedenen Konversionstechnologien für Grünlandbiomasse zu bewerten; die Netto-Energiebilanzen von Grünlandkontrolle, Weidenkontrolle und Agroforstsystem aus Grünland und Weiden zu vergleichen.

9.3 Schlussfolgerungen

Basierend auf den Untersuchungen eines Weißklee-Deutschen Weidelgras-Bestandes unter unterschiedlichen Schattierungsstufen und –materialien und der Interaktionen entlang eines Baum-Grünland-Gradienten in den Grünlandstreifen, sowie den Netto-Energiebilanzen des Agroforstsystems aus zwei Grünlandansaaten und Weiden im Vergleich zur Grünland- und Weidenkontrolle, resultierten nachstehende Schlussfolgerungen aus dieser Studie:

(i) Das künstliche Schattierungsexperiment zeigte, dass der Schattenwurf zu Ertragsminderungen von 50 % in der 80%igen Schattenvariante, verglichen mit der Kontrolle, führte. Weißklee als heliophile Pflanze reagierte negativ auf eine steigende Beschattung, während die Kräuter profitierten. Auswirkungen auf die Qualität des Kleegrasbestandes konnten im zweijährigen Versuch nicht nachgewiesen werden. Obwohl es das Versuchdesign nicht ermöglichte, die verschiedenen Auswirkungen des Mikroklimas auf das Pflanzenwachstum zu erklären, zeigten die Ergebnisse, dass es praktikabel ist, einen Kleegrasbestand als Unterkultur in einem Agroforstsystem der gemäßigten Breiten Zentraleuropas unter leichten bis mittleren Schatten zu bewirtschaften.

(ii) Der Schattenwurf der Bäume beeinflusste das einfallende Licht auf die Grünlandunterkultur entlang des Gradienten, was sich in einer geringeren Einstrahlung neben den Bäumen zeigte. Dementsprechend war die Bodentemperatur unter dem Grünland direkt neben den Bäumen geringer als in der Mitte der Grünlandstreifen. Es gab kein klares Verteilungsmuster der Bodenfeuchte entlang des Gradienten. Die Grünlandproduktivität entlang des Gradienten war nicht beeinträchtigt durch den Schattenwurf der angrenzen Bäume während der frühen Etablierungsphase des Agroforstsystems. Die botanische Bestandeszusammensetzung des Kleegrasbestandes änderte sich entlang des Gradienten. Der Ertragsanteil der Leguminosen (i.e. Weißklee) war in der Mitte des Grünlandstreifens höher als an den Rändern neben den Weiden. Der Kräuteranteil im Kleegrasbestand war höher an den Rändern als in der Mitte der

Streifen. Die botanische Zusammensetzung der diversitätsorientierten Grünlandmischung war nicht durch die Weiden beeinträchtigt. Effekte der Bäume auf die Grünlandqualität wurden nicht festgestellt.

(iii) Bedingt durch die geringen Ertragsleistungen der Weiden waren die dreijährigen Gesamtertragsleistungen der Biomassen im Agroforstsystem niedriger als die der Grünlandkontrollen, unabhängig von der Grünlandmischung und der Düngestufe, aber dennoch höher als die der Weidenkontrolle. Innerhalb der Varianten im Agroforstsystem erzielten diejenigen mit Kleegras als Unterkultur einen höheren Ertrag als jene mit der diversitätsorientierten Mischung. Die gedüngten Grünlandstreifen erzielten generell höhere Trockenmasseerträge. Die Netto-Energiebilanzen der einzelnen Systeme folgten der gleichen Reihenfolge wie der der Gesamtertragsleistungen. Der Vergleich der drei unterschiedlichen Konversionstechnologien für Grünlandbiomasse zeigte die höchsten Netto-Energieerträge für die Heuverbrennung, wobei sich IFBB und Ganzpflanzenvergärungen ähnlich verhielten. Jedoch kann die Heuverbrennung aufgrund der niedrigen Brennstoffqualität nicht als geeignete Konversionstechnologie empfohlen werden. IFBB-Brennstoffe hingegen wiesen eine ähnliche Qualität wie die Hackschnitzel der Weiden auf. Die Studie umfasste einen Zeitraum von drei Jahren nach der Systemetablierung, währenddessen die Wachstumsraten der Weiden niedrig waren. Langzeitauswirkungen im Agroforstsystem aus Weiden und Grünland unter gemäßigten Klimabedingungen müssen in zukünftigen Forschungsfragen berücksichtigt werden.

9.4 Zusammenfassung

Der Bedarf an Biomasse für die Bioenergiegewinnung in den Industrienationen ist in den letzten Jahren schnell angestiegen. Biogenen Energieträgern wird ein erhebliches Potenzial zur Einsparung von fossilen Ressourcen und CO_2–Emissionen zugesprochen. Der Anbau von Biomasse hat jedoch auch negative Auswirkungen auf die Umwelt, wie zum Beispiel der Verlust an Biodiversität, Nitratauswaschungen und Bodenerosion verursacht. Die nachteiligen Auswirkungen entstanden meist durch den Anbau von einjährigen Kulturen. Daher ist es das Ziel von modernen Bioenergiepflanzensystemen, Ertragsicherheit mit Ökologie und Umweltsicherung in Form von Mischanbau zu vereinbaren. Ein spezielles Augenmerk wurde hierbei auf mehrjährige Dauerkulturen gelegt, die aus umweltschutz-fachlicher Sicht den einjährigen Kulturen überlegen sind. Agroforstsysteme sind eine Form des mehrjährigen Mischanbaus und bestehen aus Bäumen und ackerbaulichen Kulturen oder Grünland auf der

gleichen Landparzelle. Agroforstliche Bewirtschaftformen unterscheiden sich weltweit. Eine für die gemäßigten Breiten angepasste Bewirtschaftungsform ist der Feldstreifenanbau, wobei ein hoher Grad an Mechanisierung möglich ist. Bäume werden in Reihen angepflanzt und die Unterkultur wird in den Gassen dazwischen angelegt, was den Einsatz von Maschinen erleichtert.

Das Ziel der Studie war die Untersuchung eines jungen Agroforstsystems aus zwei verschiedenen Grünlandmischungen und Weiden für die Bioenergiebereitstellung unter gemäßigten Klimabedingungen. Der erste Teil der Arbeit ermittelte mögliche Konkurrenzeffekte zwischen Weiden und Grünland. Da Licht derjenige Faktor zu sein schein, der die Ertragsleistung der Unterkulturen in einem Agroforstsystem der gemäßigten Breiten am meisten beeinflusst, wurde ein 2-jähriges künstliches Schattierungsexperiment mit einem Kleegrasbestand durchgeführt, um die Auswirkungen von Schattenwurf zu quantifizieren. Unter- und oberirdische Interaktionen zwischen Weiden und Grünland und deren Auswirkungen auf Produktivität, botanische Bestandeszusammensetzung und Qualität wurden entlang eines Gradienten in den Grünlandstreifen erhoben. Im zweiten Teil der Studie wurde die Produktivität des Agroforstsystems über einem dreijährigen Zeitraum untersucht und mit den jeweiligen Grünland- und Weidenkontrollen verglichen. Drei verschiedene Konversionstechnologien (Heuverbrennung, IFBB, Ganzpflanzenvergärung) wurden bei der Grünlandbiomasse angewandt und auf das energetische Potential hin untersucht. Auch für Hackschnitzel aus Weiden wurde das Potential für die thermische Verwertung errechnet. Des Weiteren wurden Netto-Eenergiebilanzen für Agroforst, Grünland- und Weidenkontrolle erstellt.

Die Ergebnisse aus dem 2-jährigen Schattierungsversuch zeigten, dass die Grünlandproduktivität bei starkem Schatten (80 %) im Durchschnitt 50 % geringer war als die nicht-schattierte Kontrolle. Der Ertragsanteil von Weißklee war am höchsten im vollen Sonnenlicht und sank mit steigender Schattierung. Gleichzeitig stieg der Ertragsanteil der Kräuter mit steigender Schattierung. Auswirkungen auf die Qualität des Kleegrasbestandes konnten nicht nachgewiesen werden. Durch die Untersuchung der Interaktionen innerhalb des Baum-Grünland-Gradienten war es möglich, Änderungen im Lichteinfall, der Bodentemperatur und der botanischen Bestandeszusammensetzung von Kleegras angrenzend an die Weiden festzustellen. Keine Baumeffekte traten bei Niederschlag, Bodenfeuchte und Grünlandproduktivität entlang des Gradienten während des zweijährigen Untersuchungszeitraumes auf. Hinsichtlich der Ergebnisse zu Produktivität und Netto-Energieertrag lieferte das Agroforstsystem niedrigere Erträge im Vergleich zur Grünlandkontrolle, unabhängig von Grünlandmischung und Düngestufe, lieferte jedoch höhere Erträge als die Weidenkontrolle. Der Vergleich der drei unterschiedlichen energetischen Konversionsverfahren für Grünlandbiomasse zeigte höchste Netto-Energieerträge für Heuverbrennung, während die Integrierte Erzeugung von Festbrennstoff und Biogas aus Biomasse (IFBB) und Ganzpflanzenvergärung ähnlich abschnitten. Aufgrund der geringen Brennstoffqualität des Heus kann jedoch dessen direkte Verbrennung nicht als praktikable Konversionstechnologie empfohlen werden, während IFBB-Brennstoffe eine, ähnlich den Hackschnitzel aus Weide, gute Qualität aufwiesen.

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