Above-ground interactions and yield effects in a short rotation alley-cropping agroforestry system

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Summary

Alley-cropping systems (ACSs) with energy wood production combine short rotation coppice (SRC)-strips and crop alleys, which are arranged in parallel on the same arable field. They offer the possibility to produce energy wood and food simultaneously, while enhancing structural diversity, a fundamental condition for biodiversity. Thus, ACSs are well-adapted to the present context of increasing global population, in which the biomass production for energy purposes on arable land is criticized, as it is not considered as a priority for land use ("food vs. fuel").

By establishing an ACS with SRC-strips, the growing conditions are modified within the agricultural field due to the interactions between the tree and crop components, especially at the tree/crop interface. The main purpose of this thesis was to study these modifications, as a result of the above-ground interactions, and simultaneously, the yield effects on both, the tree and crop components, in the ACS, which was established in 2008 at the Julius Kühn-Institute in Wendhausen (Lower Saxony, Northern Germany). Furthermore, this work aimed at determining whether the whole ACS was positively or negatively influenced by these interactions. This was achieved by comparing its productivity with the productivity of the sole-cropping systems (SCSs) with only a crop or a tree component.

The ACS examined in this study consisted of nine poplar SRC-strips and eight crop alleys. Half of the SRC-strips were harvested in winter 2010/11 and all of them in winter 2013/14. Before and after the harvest, in 2013 and 2014, the microclimate, the solar radiation, the yields and yield components of the tree (poplar) and crop (winter wheat and barley) components were recorded in the ACS, for the different tree rows and at several distances from the SRC-strips. These measurements were also carried out in two SCSs: an adjacent crop open field and a SRC plantation. Additionally, different arrangement designs of the ACS were assessed: two alley widths (narrow, 48 m; wide, 96 m), two rotation cycles of the SRC-strips (3- and 6-year) and two SRC-strip designs (SRC, only energy wood; combined, combination of energy and timber wood).

The growing conditions were changed the most at the tree/crop interface and in 2013, when the trees were the tallest. During this year, the lowest wind velocities were measured next to the SRC-strip on the leeward side (wind-sheltered area), especially in the narrow alley, and the highest wind velocities on the windward side (wind-exposed area). However, differences of air temperature and relative humidity between these areas and the middle of the crop alleys were observed only on sunny days. In 2014, no wind velocity reduction was detected behind the SRC-strips and almost no differences in the air temperature and relative humidity between the different measurement points were observed. Next to the SRC-strips, the incoming solar radiation was reduced up to approximately 20 m into the crop alleys in 2013 and up to approximately 5 m in 2014. High leaf ground coverage was also noticed in the vicinity of the strips, especially on the leeward side, and mainly up to 8 m into the crop alleys, during autumn 2012 and 2013.

The yield of cereals (winter wheat and barley) was reduced next to the SRC-strips (values below the alley mean were observed up to 10 m into the crop alley), mainly due to a reduced number of ears per square meter. This effect was attributed to the high leaf ground coverage during the emergence of the crop. The shadow cast on the crop next to the SRC-strip delayed the phenological development of the plants, which remained small, developed grains with lower thousand grain and hectoliter weights than in the middle of the alley. The grain moisture contents were higher than the alley mean up to 10 m into the alley. More aphids, but also more aphid mummies and slightly more beneficial insects were observed in the direct vicinity of the SRC-strips. The outer rows of the SRC-strips (windward and leeward) showed higher shoot numbers and larger diameters, which resulted in higher wood yields in both rotation cycles. These effects came about mainly by an increased light and space availability. The middle rows of the combined design showed a high yield in the 6-year rotation cycle and a quite low one in the 3-year rotation cycle, whereas the middle rows of the SRC design showed low yields in both rotation cycles.

In general, higher wood yields were recorded in the SRC-strips than in the SRC-control field and with the SRC design than with the combined design. On average, the winter wheat yield was slightly higher in the open field and in the wide alleys than in the narrow alleys, whereas the winter oilseed rape yield was mostly higher in the wide alleys than in the narrow alleys and in the open field. From 2009 to 2014, higher aggregated biomass and energy yields were observed in the ACS (grain + wood) than in the open field, but the highest ones were achieved in the SRC-control field. In the SRC-strips, better results were achieved in the 6-year than in the 3-year rotation cycle, and more generally, in systems with winter wheat than with winter oilseed rape.

These results show that ACSs with energy wood can contribute to the "sustainable intensification" of agriculture: the yields observed in these systems were similar to the ones observed in the open field, meanwhile the structural diversity was enhanced on the field and potentially the biodiversity. Furthermore, these data can be used to improve ACS productivity. The width of the SRC-strip should be reduced to maximize the proportion of outer rows. At the same time, the crop alley width should be in a balanced relation to the total agroforestry field to limit the proportion of competition zones with lower productivity for the annual crops. The strip number, orientation and length must be adapted to the local wind directions in order to reach optimum wind protection, and properly selected to ensure structural diversity. The rotation cycle length should be selected to reach maximum wood biomass while keeping trees small to reduce the shading effect (3 to 4 years).

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Abbreviations

°C	Degree Celsius
3y-RC	3-year rotation cycle
6y-RC	6-year rotation cycle
ACS	Alley cropping system
AIC	Akaike Information Criterion
α	Regression coefficient
β	Regression coefficient
BBCH	Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie
B_{Asp}	Biomass production of the aspen
B_{Comb}	Biomass production of combined design
B_{SRC}	Biomass production of SRC design
CAP	European common agricultural policy
cm	Centimeter
Cont.	SRC-control field
d	Day
DBH	Diameter at breast height
DM	Shoot dry mass
dt	Deciton
EC	Soil apparent electrical conductivity
EC_{25}	Soil apparent electrical conductivity corrected to 25°C
EFA	Ecological Focus Area
EN	Ear number per m^2
EU	European Union
FB	Fava bean
Fig.	Figure
g	Gram
γ	Intercept
GHG	Greenhouse Gas
GJ	Gigajoules
GPS	Global Positioning System
GW	Total grain weight
h	Tree height
hL	Hectoliter
ha	Hectare

k	Number of estimated parameters
kg	Kilogram
km h^{-1}	Kilometer per hour
L	Leeward zone of crop alley
L_{SRC}	Biomass production of leeward rows of SRC design
L_{Comb}	Biomass production of leeward rows of combined design
m	Meter
MC	Moisture content
mm	Millimeter
mS m^{-1}	Millisiemens per meter
M	Middle zone of crop alley
M_{Comb}	Biomass production of middle rows of combined design
M_{SRC}	Biomass production of middle rows of SRC design
Ma	Maize
n	Sample size
ND	No data
no.	Number
nEC_{25}	Normalized soil apparent electrical conductivity corrected to 25°C
OF	Open field
OSR	Winter oilseed rape
pET	Potential evapotranspiration
R^2	Correlation coefficient
RH	Relative air humidity
σ	Standard deviation
SB	Summer barley
SE	Standard error of the mean
SRC	Short rotation coppice
SCS	Sole-cropping system
t	Ton
t_{emp}	Air temperature
TGW	Thousand grain weight
ε	Residuals
W	Windward zone of field
W_{SRC}	Biomass production of windward rows of SRC design
W_{Comb}	Biomass production of windward rows of combined design
WB	Winter barley
WW	Winter wheat
Y	Raw yield measured by the harvester
Y 14%	Yield corrected to 14% grain moisture

1 Introduction

1.1 Definitions of alley-cropping agroforestry systems and short rotation woody crops

Agroforestry was defined by Nair (1993) as the deliberate combination of crop/animal production and trees in a spatial mixture. In this system, there must be a positive or a negative form of interaction between the different components, i.e. wind protection or competition, and at least two outputs, i.e. wood and crop production. There are many types and various forms of agroforestry, which Nair (1985) categorized in three main groups, based on their components:

Agrisilviculture Combination of crops (including shrubs/tree crops) and trees (for instance the alley-cropping system (ACS)).

Silvopastoralism Combination of pasture/animals and trees.

Agrosilvopastoralism Combination of crops, pasture/animals and trees.

Arrangements of components can vary in time or space and can have productive (crop, wood or meat production) and protective (for instance erosion control or soil moisture conservation) roles (Nair, 1985). A special form of *agrisilviculture* is the ACS, where woody species are arranged in hedges and agricultural crops in alleys between the hedges (Nair, 1993). ACSs can be differentiated by their wood production purposes, i.e. energy or timber (Grünewald and Reeg, 2009). Energy wood is mainly cultivated in the form of short rotation coppice (SRC)-strips, whereas timber wood is produced in the form of single tree rows.

Agroforestry systems in Europe can be divided into two categories: the agroforestry systems of Northern Europe and the agroforestry systems of the Mediterranean area (Eichhorn et al., 2006). The systems in Northern Europe are characterized by a limitation of light, whereas the systems in Southern Europe are often limited by water availability. In Germany, agroforestry has already been used for a long time, in the form of hedges (shelterbelts) or orchards (fruit trees) combined with crop or animal production (Grünewald and Reeg, 2009). In these systems, hedges were established to delimit fields or pastures, but can also be beneficial for wind protection. They are cut generally every seven to twelve years, and the wood is used for heat production (Knauer, 1993). However, these structures tend to disappear. Between 1880 and

2012, 45 % of the hedge banks and field walls were cut down, which represents 2.5 million kilometers (Müller, 2013).

SRC plantations are characterized by highly productive and fast-growing tree species, high planting densities (around 10,000 trees per hectare) and full-mechanized harvest (Knust, 2009). The harvest occurs in short rotation cycles (2-5 years). The main output of such plantations are wood chips used for heat production. Coppicing is the action of cutting trees to their base and thus create the re-growth of the shoots out of the stump (Blake, 1983; Sennerby-Forsse et al., 1992). This process should increase the final biomass production (Auclair and Bouvarel, 1992a) and intrinsic growth performance (Herve and Ceulemans, 1996). According to Sennerby-Forsse et al. (1992), the species and/or clones of willows (*Salix* spp.), poplars (*Populus* spp.), locust trees (*Robinia* spp.), eucalyptus (*Eucalyptus* spp.), alders (*Alnus* spp.) and birches (*Betula* spp.) show good coppicing ability. Around 40,000 hectares across Europe (Pecenka, 2015) and 6,000 hectares in Germany (Wirkner, 2015) were cultivated with SRC in 2015. In Germany, most of these plantations are situated in the state of Brandenburg, due to the strong engagement of some energy suppliers (Strohm et al., 2012).

1.2 Agroforestry with energy wood in the political, environmental and economic context

1.2.1 Energetic political context in Europe and Germany

Greenhouse gas (GHG) concentrations in the atmosphere, such as carbon dioxide, have increased since 1750, largely due to human activity (fossil fuel and net land use change emissions) (IPCC, 2013). At the same time, the fossil fuels resources are assumed to strongly deplete in the next decades (Shafiee and Topal, 2009). In this context, there is a clear need of alternative energy resources producing less GHG emissions (Karp and Shield, 2008), such as renewable energies (Edenhofer et al., 2011). The European Union (EU) has set the *20-20-20 targets* for 2020: 20 % reduction of GHG emissions (from 1990 levels), to reach 20 % of renewable energies in the share of final energy consumption and 20 % increase of energy use efficiency (European Commission, 2010). The German government aims at even more ambitious targets such as the increase of the share of renewable resources in the final electricity consumption to 60 % by 2035, and to 80 % by 2050 (BMUB, 2014). As a renewable energy source, besides solar and wind energies, biomass has a great potential to help fulfilling these energetic political objectives (McKendry, 2002).

Valentine et al. (2012) listed the different potential biomass sources for the production of bioenergy (grain of food crops, crop residues, non-food crops or lignocellulosic perennial crops). They suggested that the cultivation of perennial energy crops such as *Miscanthus*, poplars or willows in short rotation coppice (SRC) would reduce land use competition compared to other bioenergy crops as they do not compete directly with food, do not need much input, reduce

GHG emissions efficiently and show high output to input energy ratios at low mitigation costs (Federal Ministry of Food and Agriculture, 2007).

However, the debate on the cultivation of biomass and bioenergy crops on arable land is still ongoing (Hertel et al., 2013), especially in the present context of a fast-growing world population (United Nations et al., 2015). As suggested by Holzmueller and Jose (2012) for the North Central Region of the United States and by Grünewald and Reeg (2009) for Germany, agroforestry including perennial bioenergy woody crops is a way of cultivating energy wood for renewable energy production whilst producing food or fodder. Moreover, Reisner et al. (2007) showed the real potential to cultivate agroforestry systems in Europe. Notably the following trees could be productively grown on 56 % of the European arable land: the walnut trees (*Juglans* spp.), the wild cherry tree (*Prunus avium*), poplars (*Populus* spp.), the stone pine (*Pinus pinea*) and the holm oak (*Quercus ilex*).

1.2.2 Environmental benefits of alley-cropping systems in Northern Germany

In Northern Germany and especially in Brandenburg, 30 to 40 % of the arable land is susceptible to wind erosion (Richter and Gentzen, 2011). Wind erosion can be controlled by windbreak hedges, such as short rotation coppice (SRC)-strips, as it reduces wind speed (Brandle et al., 2004). As a matter of fact, several windbreak rows reduce wind erosion more than just one row (Stoeckeler, 1962). Tree strips increase water infiltration and water storage, which may reduce runoff and soil loss (Anderson et al., 2008), also thanks to the mechanical reinforcement of slopes, notably by poplar roots (Jose, 2009). Palma et al. (2007) found out that agrisilvicultural systems could reduce soil loss when trees are introduced in intensive crop rotations systems. Furthermore, agroforestry systems can contribute to air quality improvement by removing carbon dioxide and producing oxygen (Jose, 2009).

As a consequence of wind breaking and modified incoming solar radiation (i.e. tree shading), the microclimate in alley-cropping systems (ACS) differ from the microclimate in a crop open field (Brandle et al., 2004). In the sheltered area of hedges and tree strips, higher temperature and air humidity, as well as reduced evaporation, could be observed (Cleugh, 1998). This contributes to conserve soil water moisture (Tsonkova et al., 2012), which can be advantageous where water is a limiting factor. However, as trees in SRC plantations can evaporate up to 90 % of the incoming precipitations (Strohm et al., 2012), they should thus not be planted on sites experiencing very low rainfall ($>$ 300 mm during the growing period) (Petzold et al., 2010).

Due to the new tree structural element in the ACS, habitat diversity is increased compared to an open landscape (Tsonkova et al., 2012). This might enhance biodiversity, especially in small SRC structures (Baum et al., 2009), such as SRC-strips, and more generally in ACSs (Tsonkova et al., 2012). Moreover, SRC-strips can contribute to habitat connectivity for arthropods and bring ecosystem services by providing habitats for beneficial insects (Glemnitz et al., 2013).

As a consequence of the greater structural diversity, Stamps and Linit (1997) suggested that agroforestry systems could help to increase insect diversity and thus reduce pest problems on the crop field. Furthermore, Gruss and Schulz (2008) observed an increased breeding birds population, several years after the establishment of an SRC, suggesting that the same can be expected in ACS with SRC-strips.

In ACSs, carbon is sequestered and stored in the soil (Quinkenstein et al., 2009), which contributes to reduce GHG emissions and increase soil fertility. However, Jose (2009) precised that the carbon sequestration potential of agroforestry systems varies depending on many factors, e.g. the type of system, geographical location and management practices. Concerning ACSs with energy wood production, the electricity production with poplar wood chips from SRC produces less GHG emissions than the electricity production from biogas (Strohm et al., 2012). Furthermore, nitrate leaching is reduced by the presence of the SRC-strips (Dimitriou et al., 2009) and more generally in agroforestry systems (Palma et al., 2007), which limits water pollution. More generally, tree species cultivated in agroforestry systems can enhance soil physical, chemical and biological properties by adding significant amount of above- and below-ground organic matter and by recycling nutrients (Jose, 2009).

1.2.3 Economic benefits of alley-cropping systems in Northern Germany

Many authors reported higher productivity in alley-cropping systems (ACSs) than in sole-cropping systems (SCS, with only one component, tree or crop) (Dupraz and Liagre, 2008; Graves et al., 2007). One indicator to compare the productivity between those two systems is the Land Equivalent Ratio (LER), developed by Mead and Willey (1980). If this ratio is greater than 1, the ACS is more productive than the SCS. In the review of Tsonkova et al. (2012), the LERs of ACSs in different studies ranged between 0.98 and 2.40. These results show the great potential of increasing productivity with such systems. This is notably explained by the longer growing season of trees than annual crops, which increases nutrient use efficiency in agroforestry systems (Jose, 2009).

The production of energy wood contributes to the decentralization of energy supply: in rural areas, it offers the possibility of self-energetic supply, as well as an income diversification for the farmer (Grünewald et al., 2007). Strohm et al. (2012) found out that the production of wood chips was even more profitable than arable crops on marginal sites, where the yields of arable crops are low.

Even though agroforestry systems and ACSs with energy wood entail many advantages, most of the agroforestry fields in Germany remain experimental.

1.2.4 Restraints and barriers for adopting alley-cropping systems in Northern Germany

Kröber et al. (2008) assumed that other energy crops than fast-growing trees, i.e. maize for biogas production or rape/wheat for biofuel production, are preferred by farmers because the cultivation techniques for these crops are already well-known. The long-term cultivation of trees on fields under lease agreements can also be a problem (Strohm et al., 2012). A customer for the wood chips, such as a biomass power plant, but also suppliers for planting material and tree harvester have to be available in the close area of the plantation. This is rarely the case in Germany, because the whole supply chain for wood chip is not yet well-developed (Strohm et al., 2012). Furthermore, in the last years, the prices for wood chips were not competitive with the ones of some arable crops, and thus the wood chips production on arable land was not profitable enough (Kröber et al., 2008). Faasch and Patenaude (2012) concluded from their analysis that SRC plantations are not a viable an alternative in Germany under the current investment conditions: without subsidies and by medium market prices, the short rotation coppice (SRC) cultivation is only profitable on at least moderate site conditions.

Another constraint for a larger adoption of alley-cropping systems (ACSs) in the land use is the potential crop yield reduction (Seiter et al., 1999), especially in the competition zone at the tree/crop interface, resulting from the introduction of trees on the agricultural field (Thevathasan and Gordon, 2004). Moreover, the need for additional management that require trees (planting, pruning, harvest, etc.) is also presented as a barrier (Seiter et al., 1999). Further restraints such as the difficulty to work with machines between trees, the tree stump removal after the last rotation cycle and the interference of roots with drainage were named by Doyle and Waterhouse (2008). More generally, the lack of technical knowledge (e.g. choice of tree species, weed control, management) perceived among farmers and advisers (Doyle and Waterhouse, 2008), but also the fear for enhancing weeds and rodents on the field and the lack of certainty about ecosystem services (Jose, 2009) represent additional constraints for the adoption of agroforestry systems.

Institutional factors can also explain the low implementation of agroforestry in temperate regions (Doyle and Waterhouse, 2008). Already 10 years ago, Dupraz et al. (2004) pointed out that the adoption of this system in Europe was limited by clear regulations: agroforestry systems can be illegal in some countries, as they are not recognized as an arable system. However, the political situation has evolved since, and the new agricultural policy in Europe may be a chance to increase the attractiveness of agroforestry for farmers.

1.2.5 New European Common Agricultural Policy 2014-2020: a chance for a better integration of alley-cropping systems in Germany?

In the European Union (EU), the Common Agricultural Policy (CAP) provides subsidies for each cultivated hectare, in the form of the *basic payments*. The cultivation of trees on the arable land is accepted in the form of short rotation coppice (SRC), which is considered as a *permanent crop*, and as a result, stays *agricultural land* eligible for basic payments (European Parliament and Council, 2013c). However, during the cultivation time, the trees have to be harvested in a maximal rotation cycle of 20 years (DirektZahlDurchfV, 2014). In Germany, SRC-plantations/-strips are not considered as *landscape features*, because they are used as a crop (AgrarZahlVerpflV, 2014) and they are not qualified as forest (BWaldG, 1975). Only some genera and species are allowed for SRC in Germany: all the species of the genera *Salix*, *Populus*, *Robinia*, *Alnus* and *Betula*, as well as *Fraxinus excelsior*, *Quercus robur*, *Quercus petraea* and *Quercus rubra*, (DirektZahlDurchfV, 2014).

In the CAP, agroforestry is defined as “a land use system in which trees are grown in combination with agricultural crops on the same lot of land” (European Parliament and Council, 2013a). However, as the maximum tree density per hectare is limited to 100 (article 9 of Delegated Commission (2014)), ACS with SRC-strips cannot be considered as agroforestry systems, because the tree density in these systems is above this limit. As a consequence, each SRC-strip and each crop alley must be registered separately for obtaining basic payments. Moreover, the minimum size of each SRC-strip is limited to 0.3 ha, just like each agricultural parcel (European Parliament and Council, 2013b). Thus, the implementation of an alley-cropping system (ACS) with SRC-strips on a farm is in accordance with the CAP and the field remains eligible for basic payments, but, until now, no particular measure was foreseen to make the establishment more attractive to farmers (e.g. grants to reduce the establishment costs).

From 2015, in the frame of the new CAP reform, each farm that receives basic payments should respect “agricultural practices which are beneficial for the climate and the environment” (article 43 of the regulation No 1307/2013, European Parliament and Council (2013c)). In this context, it is mandatory to implement ecological focus areas (EFAs) on the farm agricultural land (5 % from January 1st 2015 and should increase to 7 %), which are expected to be beneficial for the climate and the environment. The list of features considered as EFAs (article 46 of regulation No 1307/2013, European Parliament and Council (2013c)) contains: “the hectares of agroforestry that receive, or have received subsidies for their establishment” (Article 44 of Regulation (EC) No 1698/2005(2) and/or Article 23 of Regulation (EU) No 1305/2013 (European Parliament and Council, 2013a)). This measure was supposed to promote the integration of agroforestry in the EU. However, each member state of the EU can decide to implement the article 23 of Regulation (EU) No 1305/2013 in the rural development program, and thus to fund or not the establishment of agroforestry fields. In Germany, this article was not activated in any Federal Land for the period 2014-2020 (Blossey, 2015). For this reason, agroforestry systems cannot be funded until the next CAP period (from 2020), and as a consequence, agroforestry systems cannot be considered as EFA in Germany so far. Meanwhile, if some conditions are fulfilled (only use of listed tree species in DirektZahlDurchfV (2014), as well as no use of fertilizer and pesticides), SRC-strips/plantation with a minimum size of 0.3 ha (minimum size of agricultural fields) can count as EFA with a factor of 0.3 (article 46 of European Parliament and Council (2013c)). This means that one hectare of SRC-strip/plantation is considered only as 0.3 ha for the EFA calculation. All these conditions for subsidies are summarized in table 1.1.

Table 1.1. *Conditions for subsidies in Germany when establishing trees on arable land (EFA: ecological focus area).*

Production purposes	Timber	Energy (SRC)
Conditions for basic payments	Maximum of 100 tree per hectares (i.e. the field is considered as an agroforestry system)	Rotation cycle of maximum 20 years, minimum size of 0.3 ha for each plantation/strip, respect of the genera list
Further subsidies	Do not exist in Germany because no subsidies foreseen for agroforestry systems, as defined by the article 23 of regulation 1305/2013	Depends on the Federal State
Conditions for the eligibility as EFA (since 2015)	Do not exist in Germany because no subsidies foreseen for agroforestry systems, as defined by the article 23 of regulation 1305/2013	No fertilizer, no pesticide and respect of the species list
Factor for calculation of EFA	1	0.3

Faasch and Patenaude (2012) recommended to improve subsidy sufficiency, efficiency and consistency in order to promote the cultivation of SRC in Germany. Similar recommendations can be made for a larger adoption of ACSs in Germany. Further activities of the different stakeholders (researchers, politicians, farmers) are necessary in order to adapt the national legislation.

1.3 Above- and below-ground interactions in alley-cropping systems

Interactions occur when two organisms attempt to use the same resource at the same time (Jose et al., 2004) and are defined in agroforestry as the effect of one component of the system on the performance of another component and/or the whole system (Nair, 1993).

In agroforestry systems, interactions can take place at the below- and above-ground levels, influencing the system positively or negatively. The productivity of the system is the net result of these positive and negative interactions among the components (Jose et al., 2004). The crop yield in agroforestry systems will only increase if the positive effects are greater than the negative ones (Cannell et al., 1996). According to the same authors, this objective can be reached, if the trees utilize resources (e.g. water, light, nutrients) that the crop does not acquire. In the competition zone situated at the tree/crop interface and which can be as large as one to two times the strip height (Nuberg, 1998), the negative interactions are numerous. The potential interactions that take place in alley-cropping system (ACS) with energy wood at the below- and above-ground levels and that will be described in this section[1] are presented in fig. 1.1.

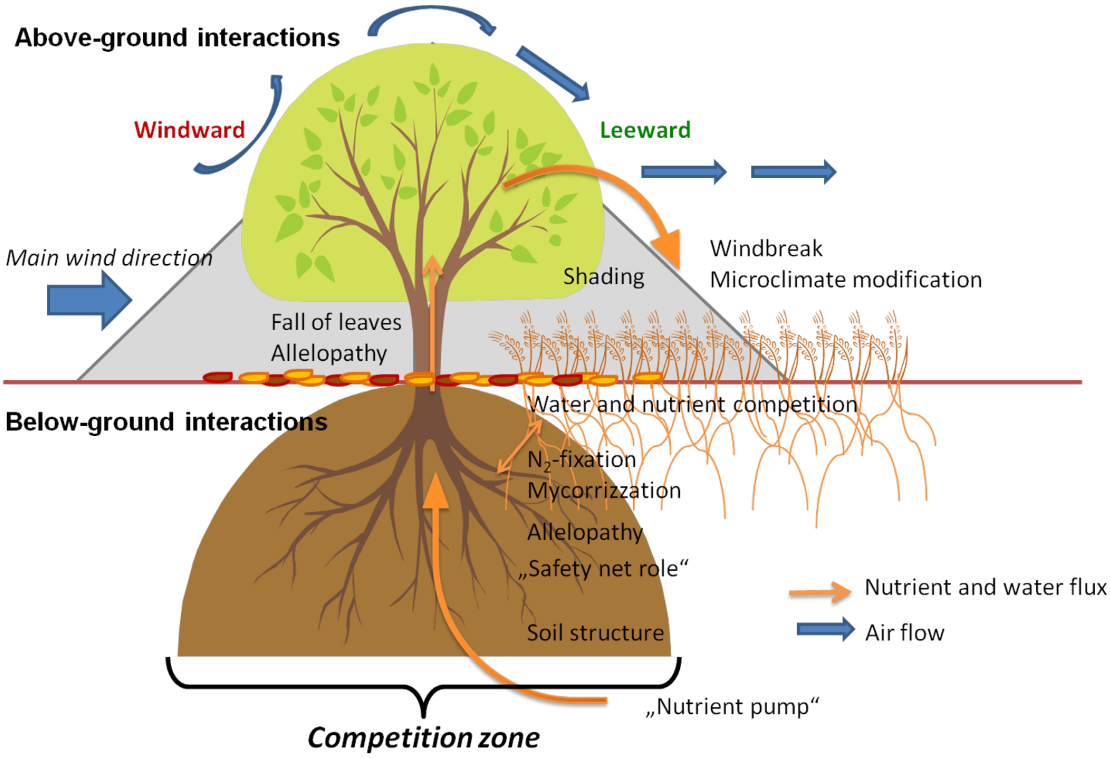


Figure 1.1. *Above- and below-ground interactions occurring in alley-cropping systems.*

1.3.1 Below-ground interactions

Negative below-ground interactions, such as water and nutrient competition, can influence the whole system productivity. They are mostly due to the proximity of roots in the same soil strata (Van Noordwijk et al., 2006). In temperate regions, the below-ground competition for

[1]Even though a lot of references reporting about silvoarable systems (with single tree rows) exists, it was here focused on studies about ACS with energy wood, short rotation coppice (SRC) plantations, shelterbelts, windbreak rows and hedges in temperate regions, and if possible with poplars. Given the different structure of both systems (silvoarable systems with single tree rows and alley-cropping systems with SRC-strips) and the different effects on climatic conditions, design, tree species, etc., it would not be precise, to describe all possible effects in both systems.

water, already observed by Gillespie et al. (2000), seems to be an important driving force of productivity in ACS and will reduce productivity in regions where this resource is a limiting factor for plant growth (Jose et al., 2004). According to these authors, competition for nutrients can also be expected where no fertilization occurs on the crop field. Some trees such as oaks, hornbeams and also poplars can be more competing with crops because of their horizontal and shallow root system (Röser, 1995), but with increasing age, the roots will probably use different sets of nutrients horizons (Thevathasan and Gordon, 2004). Furthermore, allelochemicals can be released through root exudation (Jose et al., 2004) and can delay or even suppress the growth of other plants in the near environment (allelopathy) (Kohli et al., 2008). The negative allelopathic effects of poplar leaves were already reported by Singh et al. (2001) and could be extended to roots.

As a positive interaction, trees can act as "nutrient pumps" and bring nutrients, but also water, from the subsoil to the topsoil, making these resources available for the crops cultivated in agroforestry systems (Van Noordwijk et al., 2006). The latter authors defined some conditions in order to guarantee this effect: a high amount of roots and mycorrhiza in deep soil layers, which should contain a high amount of available nutrient, and a water content that should allow for the diffuse transport to the roots. Van Noordwijk et al. (2006) precised that if roots are developing under the crop alley, they could act as a "safety net": catch leached nutrients and bring them again to the topsoil through litter fall. Besides, poplars are able to fix nitrogen (Wühlisch and Chauhan, 2011) and thus do not require nitrogen fertilization, meanwhile they can rapidly take up and make use of this nutrient (Cooke et al., 2005). Therefore, they rooting system can potentially act as a safety net.

Mycorrhiza produce some proteins which, combined with sugar from root exudates, forms the glycoprotein *glomalin*. This latter is involved in the formation of soil aggregates and thus improve soil structure (Hoorman et al., 2009). Poplars can develop both, ectomycorrhizal and arbuscular associations, which are influenced by environmental conditions (Karlinski et al., 2010), and notably reduced by fertilization (Baum and Makeschin, 2000). Moreover, it was shown that the inoculation of ectomycorrhiza fungi and the ectomycorrhiza associated bacteria enhanced growth of willows and thereby contributed to remediation of metal-contaminated sites, as more elements were accumulated in the wood biomass (Zimmer et al., 2009). As a result, the presence of poplars or willows trees influence the soil physical and chemical properties. Further studies in poplar short rotation coppice (SRC) plantations in Germany have shown that the bulk density was increased in the upper soil layers under SRC, already few years after planting (Schmitt et al., 2010). Walter et al. (2015) observed no general trend of soil organic carbon stock change by SRC establishment on cropland or grassland but the organic carbon density in the first soil centimeters was significantly higher under SRC compared to cropland soils.

1.3.2 Above-ground interactions

Kort (1988) defined the effects of windbreak rows being mostly on snow distribution, reduction of wind damage, modification of the microclimate and long-term soil retention. Windbreaks can indeed create a consequent wind speed reduction on the agricultural fields as they increase the surface roughness (Brandle et al., 2004). When the air flow is approaching the windbreak, some passes through and the remaining part circles around or over the trees. Cleugh (1998) and Brandle et al. (2004) described that around the windbreak, the air flow starts to slow down already between 2 and 5 h (where h is the height of trees) at the *windward* side of the strip (wind-exposed area). Directly at the *leeward* side (wind-protected area) behind the windbreak, a *quiet zone* extends until 10 h (with the highest wind reduction), and further until 20 h (with only a slight wind reduction) (Cleugh, 1998; Brandle et al., 2004). Röser (1995) also concluded from his review of German literature on windbreaks, that the limit of the quiet zone on the leeward side lies between 15 to 25 h, but reaches 30 h at some places.

According to Cleugh (1998), Brandle et al. (2004), McNaughton (1988) and Grace (1988), the air temperature and humidity are expected to be higher up to 8 h (h: tree height) on the leeward than on the windward side during the day. Cleugh (1998) described the microclimate modification being also the consequence of the tree shading, and especially the trapping of long-wave radiation and turbulent exchanges of heat, water vapor and carbon dioxide. According to Röser (1995), on the leeward side, the carbon dioxide might be at saturation in the night hours and not enough delivered during the day hours, leading to reduced concentrations available for the plant. Brandle et al. (2004) reported that the soil temperature is increased on the leeward side except in the shaded zone. Moreover, in the direct vicinity of the windbreak, the rainfall might be slightly less or more than in the open field, whereas snow can have less detrimental effects and notably be stopped. Windbreaks might also protect against advective frost (very cold wind forming ice spikes on leaves). According to Nuberg (1998), the soil moisture might be higher in the shaded leeward side because of reduced soil water evaporation.

The extend of the shade into the crop alley depends on the windbreak orientation, height, latitude, time of the year and day, etc. (Nuberg, 1998). The amount of biomass produced under trees depends on the fraction of incident photosynthetically active radiation that is intercepted, and the efficiency of the plant to convert the radiation by photosynthesis (Ong and Huxley, 1996). Generally, the filtered light under deciduous trees is rich in orange, yellow, green and infra-red, which are photosynthetically less active and more involved in cell elongation than red and blue light rays (Krueger, 1981), which can lead to greater leaf area index. However, Jose et al. (2004) reported that the competition for light was minor in several alley-cropping systems.

The leaves that fall on the adjacent crop field also influence the system: they can enhance soil organic carbon, but might also have a negative allelopathic effect, that inhibits seed germination and growth of crop plants (Singh et al., 2001), and generally reduce crop productivity (Batish et al., 2008). Allelopathic affects were mainly reported for angiosperms and were shown to be responsible for bare soils and loss of species diversity in forests (Batish et al., 2008).

1.4 Effects on productivity

1.4.1 Productivity of the crops alleys

Kreutz (1952), Kort (1988), Cleugh (1998), Nuberg (1998) and Brandle et al. (2004) reported the positive effect of windbreaks on crop yield, especially for winter wheat, winter barley, rye and millet. Furthermore, Bender (1955) reported yield increases of 6.2 % for rye, 12.5 % for potatoes and 16.5 % for sugar beet thanks to windbreak hedges on a sandy soil in Northern Germany. According to Cleugh (1998), the greatest yield increase occurs between 3 and 10 h on the leeward side (where h is the height of trees)[2].

According to Grace (1988), McNaughton (1988), Cleugh (1998) and Brandle et al. (2004), due to the windbreak effect, for well-watered crops, photosynthetic activity tends to increase, and hence water-use efficiency, until 8 h behind the windbreak (where h is the height of trees). Thus, greater vegetative growth and greater leaf areas can be expected there, explaining enhanced yields, without a significant change in water use. However, for not well-watered crops growing behind the windbreak, a stomata closure could occur due to the temperature elevation, and thus stop the photosynthetic activity. In the sheltered area, due the earlier maturity of grain crops, the critical stages for yield formation (e.g., anthesis for cereals) are reached earlier in the vegetation period compared to non-sheltered areas, when water availability is still provided (Brandle et al., 2004). Cleugh (1998) reported other potential reasons to explain an increased crop yield, as a consequence of the modification of the microclimate and windbreak effect: less mechanical damage due to the wind, less stem lodging and modification of leaf stomatal resistance (increased exchange with the atmosphere). However, there are unlimited combinations of growth response to microclimate modification and the probability of one combination to reoccur in different years is relatively small (Brandle et al., 2004). The effects indeed depend on the climatic conditions which differ every year (Kreutz, 1973).

Shading also affects the plant growth directly, due to the reduced photosynthetic activity, mainly in temperate climates. Chirko et al. (1996) reported the negative effects of reduced light on the wheat yield in agroforestry systems in Northern China, whereas Brenner et al. (1995) reported its beneficial effects in semi-arid climates. According to Krueger (1981), the filtered light under deciduous trees can lead to greater leaf area index because more involved in cell elongation. Gillespie et al. (2000) concluded from his study in mid-western USA that shade

[2]Until now, only few studies have been conducted to investigate the effect SRC-strips on cereal yields in temperate regions. Studies on agroforestry systems focused mainly on systems with single or double tree rows for timber use, which have a different influence on crop yield than SRC-strips, as they are not cut regularly. However, many studies have been conducted to assess the effects of windbreaks on yield. As SRC-strips have a very similar structure, the literature available about windbreaks was mainly considered, as it has more similar interactions.

did not have a significant effect on the yield of maize inter-cropped with red oak and walnut tree rows. Indeed, when the below-ground competition was eliminated with polyethylene barriers, the yield was higher, in spite of shading, highlighting the great effect of the below-ground competition. Thus, depending on the region and the crop combination, different effects of shading can be expected. Generally, shade is considered to be a negative factor in temperate regions but can be managed with arrangement of trees (e.g. strip orientation) and maintenance (e.g. pruning, which is the cutting of branches situated over the adjacent crop field) (Jose et al., 2004). In alley-cropping systems (ACSs) with short rotation coppice (SRC)-strips, after each strip harvest (i.e. every 3 to 5 years) the shade, and as a consequence the negative effects on yield are reduced, due to the absence of branches and foliage.

Modifying the wind also changes the pathways for pollens and pathogens. Combined with higher air humidity, the risk of pathogen and pest infestation could increase in the leeward area (Cleugh, 1998; Brandle et al., 2004). This situation could occur in Northern Germany especially in years with high precipitation: delayed drying of grains before harvest leading to higher grain moisture contents and more chance of fungi infections (Röser, 1995). Furthermore, more insects (e.g. aphids) prefer the sheltered area, because they can fly easier and find more food and habitats (Pasek, 1988). Similarly to hedges, SRC-strips are suitable overwintering grounds for arthropod predators (e.g. carabids, spiders), but also appropriate habitats for birds and small mammals that feed on insect pests over winter and during the vegetation period (Dix et al., 1995). In China, the eradication of the Eurasian tree sparrow was followed by great insect outbreaks and crop damages (Dix et al., 1995). This suggests that the presence of the natural enemies' populations, favored by hedges, is indispensable for yield stability.

Negative allelopathic effects of eastern cottonwood (*Populus deltoides*) phenolics contained in leaves on germination, plant height and biomass were reported for wheat by Singh et al. (2001, 2012). However, not all wheat varieties are sensible to these phenolics (Nandal and Dhillon, 2007). Additionally, these allelopathic effects of fallen leaves, but also the shading, could be positive by reducing weed populations in agricultural fields (Batish et al., 2008), and thus be interesting in ACSs with SRC-strips, in which the regular harvesting could favor the weed development within the strip. Furthermore, high concentrations of salicylic acid were found in the root zone of willows SRC plantations in Northern Germany (Kahle et al., 2011). The effects of this compound was studied on tropical plants and showed positive effects on plant growth and yield (Muhal et al., 2014), notably on wheat (Sakhabutdinova et al., 2003). No information is available for the effects of this compound in ACS, but it is assumed that it affects positively the plants in the vicinity of the SRC-strips.

1.4.2 Productivity of the short rotation coppice-strips

Fast-growing trees used in short rotation coppice (SRC), such as poplars and willows, can reach dry matter yields between 8 and 10 t ha^{-1} year^{-1} on good sites, i.e. with good water and nutrient availability, warm soil and climate conditions (Petzold et al., 2010). These authors proposed the black locusts as an alternative for dry sites. Tsonkova et al. (2012) assumed that similar biomass yields to SRC plantations can be expected in SRC-strips, but only few studies are available on alley-cropping systems (ACSs) with SRC-strips. Grünewald et al. (2007) studied the productivity of different ACSs with poplar, black locust and willow SRC-strips in combination with alfalfa on marginal sites in Germany. They found out that the black locust was the most adapted tree species for post-mining sandy soils. Gamble et al. (2014) reported that poplars were slightly more productive than willows on loamy soils in an ACS with several herbaceous crops.

In an ACS with several SRC-strips, the number of outer rows is relatively high compared to a SRC plantation. The outer rows of the SRC-strip experience eventually some competition with adjacent crops, e.g. for nutrients and water, but less with other trees, e.g. for space, light, nutrients and water, and thus can show a better growth (Gamble et al., 2014). Fast-growing tree species have indeed especially high need of light (Petzold et al., 2010) and the shade intolerance of poplars is a common knowledge (Farmer, 1963). More light availability can result in better growth for the outer rows, but self-shading in the middle rows could lead to a slower growth there. Strip orientation also plays an important role. With north-south orientations, better results can be expected as greater apple tree growth and yield were reported by Christensen (1979) and greater growth of crops was reported by Mutsaers (1980). Plant spacing, which is greater for the outer rows due to the absence of neighbor on one side, also strongly influence tree growth: several authors already reported the positive effect of increasing plant spacing on poplar shoot diameter (Cannell, 1980; Auclair and Bouvarel, 1992b; DeBell et al., 1996; Benomar et al., 2012).

Due to the wind velocity reduction, microclimatic conditions are more favorable in the leeward zone with higher temperature and reduced evaporation (Brandle et al., 2004; Quinkenstein et al., 2009). Higher temperatures favor the leaf development of fast-growing trees (Petzold et al., 2010), and thus probably of the leeward rows, situated in the leeward zone. Conversely, the wind velocity is the highest on the windward side of a windbreak (Brandle et al., 2004), resulting in a greater potential leaf damage and evaporation (Grace, 1988), which could be less favorable for the windward rows of the SRC-strip. For poplars and willows in SRC, the most important growth factor is indeed water, because of their high evaporation rates (Petzold et al., 2010).

Petzold et al. (2010) recommended furthermore high nutrient concentrations for the good growth of fast-growing trees in SRCs. On arable sites where the ACSs are normally implanted, a sufficient nutrient stock should be given and the tree uptake occur very slowly. Thus, it can be expected that the growth of the trees in the SRC-strips will be not limited by nutrients, at least in the first growing years. However, a nutrient competition may occur after several rotation cycles, when the root system is well established, especially between outer and middle rows of the strip.

1.5 Scope of this thesis

As pointed out in this chapter, even though promising results are expected on the environment and on productivity with alley-cropping systems (ACSs) with energy wood production, their adoption is still limited in Northern Germany. Doyle and Waterhouse (2008) mentioned among others the lack of scientific knowledge as a restraint for the adoption of agroforestry systems in temperate regions, because the handling of these systems is more complex than conventional farming activities and includes the management of the component interactions. These interactions can influence crop and tree yields positively or negatively and thus influence the productivity of the whole system, in a positive or a negative manner. To sustain the productivity in an ACS, both components (i.e. crops and trees) should maximize resource utilization (e.g. exploitation of different soil layers, use resources at different period), while maintaining the complementary interactions (Thevathasan and Gordon, 2004). Furthermore, Cannell et al. (1996) stated that the productivity can only be increased if the trees utilize resources (e.g. water, light, nutrients) that the crop does not acquire. According to Ong and Huxley (1996), the understanding of the biophysical processes and mechanisms involved in the mutual utilization of resources, i.e. the interactions at the above- and below-ground level, is essential for the development of ecologically sound agroforestry systems. Among others, the following system parameters should be studied: optimal width between tree strips, as well as the optimum arrangement of crop and trees (Cardinael et al., 2012).

Considering all this, the main objective of this thesis is to study the modifications of the growing conditions, as a result of the above-ground interactions, and simultaneously, the yield effects on both, the tree and crop components, in the ACS established in 2008 at the Julius Kühn-Institute in Wendhausen (Lower Saxony, Northern Germany). The focus is laid on above-ground interactions because they probably play a more important role on the experimental site, due to the young age of the system in which trees have a less-developed root system. This ACS is made of nine poplar short rotation coppice (SRC)-strips and eight arable crop alleys. Negative effects on yield should occur especially at the tree/crop interface where the interactions are mainly concentrated, i.e the competition zone (Thevathasan and Gordon, 2004; Jose et al., 2004). The main above-ground interactions that are expected to occur in the competition zone of the studied ACS are the same as presented in fig. 1.1: shading (reduction of solar radiation), windbreak, microclimate modification and fall of leaves. Concerning the yield effects, the measurements are concentrated on plant development and spatial distribution of yield parameters for both components, tree and crop. The measurements focused on specific years: 2008/2009, the establishment year; 2013, the year before the harvest of all SRC-strips; and 2014, the year after the harvest of all SRC-strips. In doing so, the effects observed when trees were present can be compared to the effects observed when trees were barely established and, later on, when the above-ground tree biomass was removed, but the root system still remained.

This study aims furthermore at determining whether the productivity of the whole ACS is positively or negatively influenced by the interaction of trees with agricultural crops. For this reason, the ACS is compared to sole cropping systems (SCS), i.e. systems with only the crop/tree component, as suggested by Huxley (1985). Additionally, different arrangement designs of the ACS are assessed: two alley widths (narrow, 48 m; wide, 96 m), two rotation cycles of the SRC-strips (3- and 6-year) and two SRC-strip designs (SRC, sole energy wood; combined, combination of energy and timber wood). Thus, based on literature and the results of this study, design guidelines for optimizing the system productivity are proposed and discussed on strip design, orientation and length, but also on rotation cycle and alley width.

The following questions summarize the main issues addressed throughout this thesis:

- What are the modifications of the above-ground growing conditions, especially in the competition zone?
- What are the influences of these modifications on plant development and spatial distribution of the yield in the crop alleys?
- What are the influences of these modifications on plant development and spatial distribution of the yield in the SRC-strips?
- What is the potential total biomass and energy production of the alley-cropping system compared to the crop and tree sole-cropping systems?

2 Material and methods

2.1 Experimental layout and study site description

In the next section, a description of the experimental design will be provided, followed by a description of the soil and weather conditions at the study site.

2.1.1 Design of the experimental alley-cropping system

The experimental agroforestry field of the Julius Kühn-Institute is situated in Wendhausen (North 52° 19' 54", East 10° 37' 52"), near Braunschweig in Lower Saxony, Germany. The area lies at 85 m above sea level. The alley-cropping system (ACS) consists of eight crop alleys within nine poplar (*Populus* spp.) short rotation coppice (SRC)-strips. An open crop field without SRC-strips is situated south of the agroforestry field and is used as a control field for the crop alleys. The SRC-strips are harvested in two different rotation cycles: a 3-year rotation cycle (3y-RC) and a 6-year rotation cycle (6y-RC). A SRC plantation, situated west of the ACS, is considered as a control field for the SRC-strips (70 x 70 m, only 3y-RC). The whole experimental field covers approximately 30 ha. The open field and the SRC-control field are sole-cropping systems (SCSs), which are compared to the ACS. Crop alleys and SRC-strips cover 225 m in length and are north-south oriented to optimize the windbreak effect. SRC-strips are always 12 m wide, whereas five crop alleys have a width of 48 m (narrow alley) and three have a width of 96 m (wide alley). A space of 1.5 m between the edge tree row and the boundary of crop alley is included in the 12 m width of the SRC-strip, so that the actual widths from one tree row to the next one in the narrow and wide alleys are respectively 51 and 99 m. Fig. 2.1 gives a schematic overview of the ACS and SCSs and an aerial picture of the experimental site is available in fig. A.1 in appendix A.

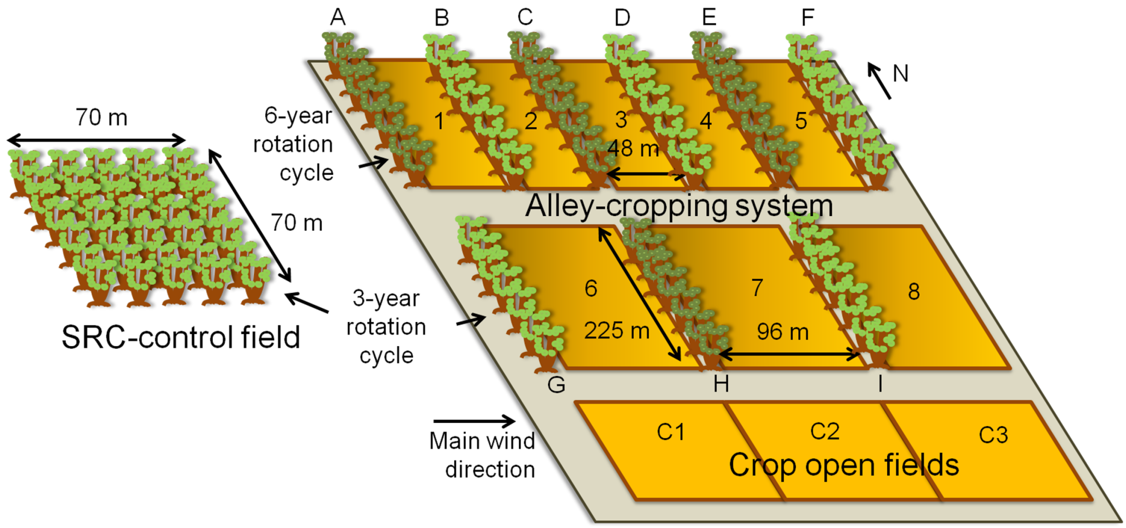


Figure 2.1. *Schematic overview of the alley-cropping system, the short rotation coppice (SRC)-control field and the crop open fields (C1-C3) at the experimental site in Wendhausen (Light green SRC-strips represent the 3-year rotation cycle and dark green SRC-strips represent the 6-year rotation cycle; crop alleys are designated with Arabic numerals (1-8) and SRC-strips with letters (A-I)).*

2.1.2 Crop rotation and management

Two crop rotations correspond to each alley width. For the wide alley, the crop rotation entails winter oilseed rape, winter wheat and winter barley and for the narrow alley, winter oilseed rape, winter wheat, fava bean, maize and summer barley.

During the seasons 2007/08-2010/11, the winter oilseed rape *Taurus* (Breeder Norddeutsche Pflanzenzucht Hans-Georg Lembke KG), the winter wheat *Mulan* (Breeder NORDSAAT Saatzuchtgesellschaft), the winter barley *Kathleen* (Breeder Ackermann Saatzucht), the fava bean *Scirocco* (Breeder Norddeutsche Pflanzenzucht Hans-Georg Lembke KG), the maize *DKC 2960* (Breeder Monsanto Technology LLC) and the summer barley cultivars *Adonis* (Breeder Limagrain UK Ltd) and *Simba* (Breeder NORDSAAT Saatzuchtgesellschaft) were cultivated.

For the seasons 2011/12-2013/14, the cultivars were changed because most of them were not available anymore. The new selected cultivars were: the winter oilseed rape *Visby* (Breeder Norddeutsche Pflanzenzucht Hans-Georg Lembke KG), the winter wheat *Arezzo* (Breeder Ragt), the winter barley *Meridian* (Breeder KWS), the fava bean *Fuego* (Breeder Norddeutsche Pflanzenzucht Hans-Georg Lembke KG), the maize *DKC 3094* (Breeder Monsanto Technology LLC) and the summer barley *Kathleen* (Breeder Limagrain).

Concerning the cultivars assessed in this study (winter wheat, winter barley and winter oilseed rape), *Mulan* was selected for its early ripeness, and for its suitability for early sowing and marginal sites. *Arezzo* is an awned wheat cultivar, which was chosen for its low attractiveness for wild animals, high number of grain per ear and early ripeness. The winter oilseed rape cultivars *Taurus* and *Visby* were chosen for their homogeneous ripening and high yield. The multiline winter barley cultivar *Meridian* has a particularly high number of grain per ear and a uniform maturation of grain and straw.

Table 2.1 presents the position of the different crops in the alley-cropping system (ACS) and the open field in each year. In order to be able to repeat the measurements on one crop each year, all crops of the rotation were grown in each year, that means that in one year each crop alley (1-8) and each crop open field (C1-C3) had a different crop. In 2008, only the summer barley was sown in the ACS, i.e., the rotation started there at the growing season 2008/09. In order to cultivate winter barley in both widths, summer barley was replaced by winter barley in the narrow crop alleys from the season 2012/13. For time management reasons, two crops had to be exchanged in season 2012/13: since it was not possible to sow directly winter barley after the maize harvest, it was decided to sow winter wheat instead and to sow winter barley after winter oilseed rape. Later on, the crop rotation was carried on as shown in table 2.1.

Table 2.1. *Position of the different crops (OSR = winter oilseed rape, WW = winter wheat, WB = winter barley, FB = fava bean, Ma = maize and SB = summer barley) in the narrow (1-5) and wide crop alleys (6-8) of the alley-cropping system and in the crop open fields (C1-C3) at the experimental site in Wendhausen from 2007/08 to 2013/14 (Crops followed by * were exchanged).*

Alley				**Season**			
no.	**2007/08**	**2008/09**	**2009/10**	**2010/11**	**2011/12**	**2012/13**	**2013/14**
1	SB	Ma	SB	OSR	WW	FB	Ma
2	SB	FB	Ma	SB	OSR	WB*	OSR
3	SB	WW	FB	Ma	SB	OSR	WW
4	SB	SB	OSR	WW	FB	Ma	WB
5	SB	OSR	WW	FB	Ma	WW*	FB
6	SB	WW	WB	OSR	WW	WB	OSR
7	SB	WB	OSR	WW	WB	OSR	WW
8	SB	OSR	WW	WB	OSR	WW	WB
C1	OSR	WW	WB	OSR	WW	WB	OSR
C2	WW	WB	OSR	WW	WB	OSR	WW
C3	WB	OSR	WW	WB	OSR	WW	WB

Crops were managed under conventional agriculture and equally in the open field and in the ACS. Most of the time, the fertilizers were applied for more precision with a pneumatic fertilizer spreader but with a centrifugal fertilizer spreader in fields where the weather stations were installed. In table 2.2, the amounts of nitrogen spread on the winter oilseed rape, the winter wheat and the winter barley are presented, when data were available.

Table 2.2. *Amounts of nitrogen (t ha^{-1}) applied on the winter oilseed rape and the winter wheat from the growing seasons 2008/09 until 2013/14 and on the winter barley for the growing seasons 2012/13 and 2013/14, in each field at the experimental site in Wendhausen (ND: No data).*

Season	Winter wheat	Winter oilseed rape	Winter barley
2008/09	ND	ND	ND
2009/10	179	239	ND
2010/11	ND	ND	ND
2011/12	202	184	ND
2012/13	188	155	148
2013/14	185	180	163

2.1.3 Short rotation coppice-strip design and management

All trees were planted in the spring 2008, at a density of 10,000 trees per hectare (2 m by 0.5 m within rows). Following designs were laid out (see fig. 2.2 (a)) and replicated once in each short rotation coppice (SRC)-strip: a SRC design (six poplar rows, 2 x 0.5 m), a combined design including aspen trees (*Populus tremula* L.) (two poplar rows 2 x 0.5 m, one aspen row 3 x 1 m, two poplar rows 2 x 0.5 m) and an ecological design (two rows with a mix of bushes and four poplar rows 2 x 0.5 m). The aspen trees are harvested in a 10-year rotation cycle. In each design, three poplar clones were planted on 25 m length each: "Max" (*P. nigra* L. x *P. Maximowiczii* Henry), "Hybrid 275" (*Populus maximowiczii* Henry x *P. trichocarpa* Hook) and "Koreana" (*P. koreana* J.Rehnder x *P. trichocarpa* Hook). These poplars clones were selected for their compatibility for SRC plantations (Petzold et al., 2010). Neither irrigation nor fertilization occurred in the SRC-strips. Weeds were controlled manually directly after planting. The coppicing and chipping of the SRC-strips is fully mechanized in one combined operation.

For the yield measurements of the SRC-strips, it was decided to focus on the "Max" clone in the combined and SRC designs. This clone was selected for its high yields, low disease susceptibility and high survival rate (Lamerre et al., 2015). The ecological design was not measured, notably because the bushes were not well established, and thus the effect would have not been homogenous and consistent between the strips. Only the SRC-strips C to F (dashed area in fig. 2.2) and the SRC-control field were assessed. At the time of the study in 2013, the SRC-strips which were in the 6-year rotation cycle (6y-RC) were not coppiced (because not harvested yet), whereas the SRC-strips in the 3-year rotation cycle (3y-RC) were already coppiced (one time harvested). For this reason, the comparison was done between non-coppiced SRC-strips in a 6y-RC and coppiced SRC-strips in a 3y-RC.

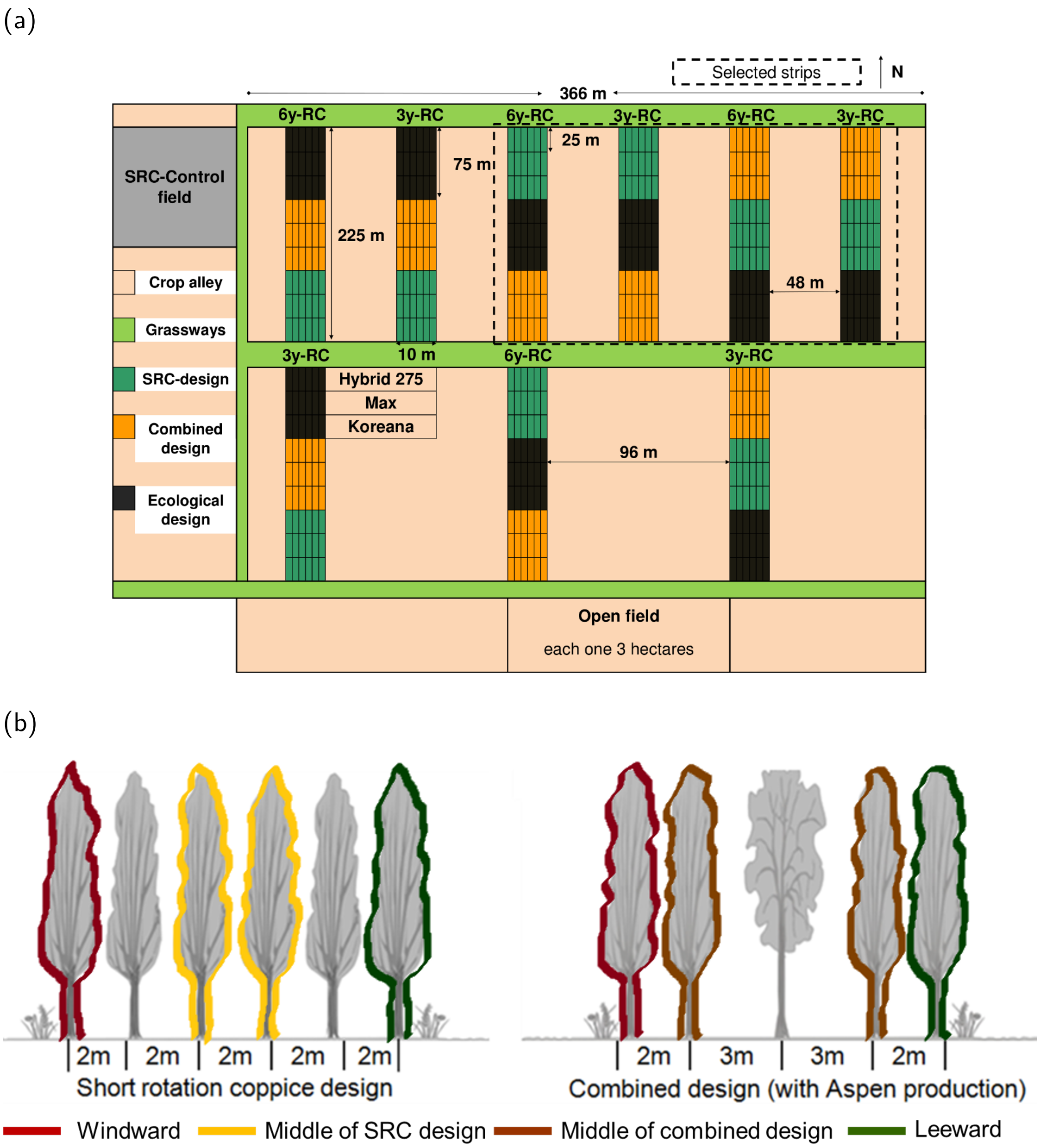


Figure 2.2. *Schematic overview of the experimental layout of the SRC-strips at the experimental site in Wendhausen: the position of the 3- and 6-year rotation cycles, the three designs (short rotation coppice (SRC), combined and ecological) and the three poplar clones (Hybrid 275, Max and Koreana) (the measured SRC-strips are in the dashed area) (a); sketch of the SRC and combined designs, as well as the measured rows (windward, middle of SRC design, middle of combined design, leeward) (b).*

2.1.4 Weather and soil conditions

The mean annual temperature at the experimental site is 9.2 °C and the annual precipitation sum is 628 mm (average of 54 years at Braunschweig, data from the Germany's National Meteorological Service). Monthly precipitation sums and temperature of the period 2008-2014 are presented in fig. 2.3. 2013 saw the highest precipitation sums, while 2011 and 2014 had the lowest. The summers of 2009, 2010, 2013 and 2014 showed higher temperatures than the mean of 54 years. The winter of 2009/10 and 2010/11 and spring 2013 were very cold compared to the long-term trend.

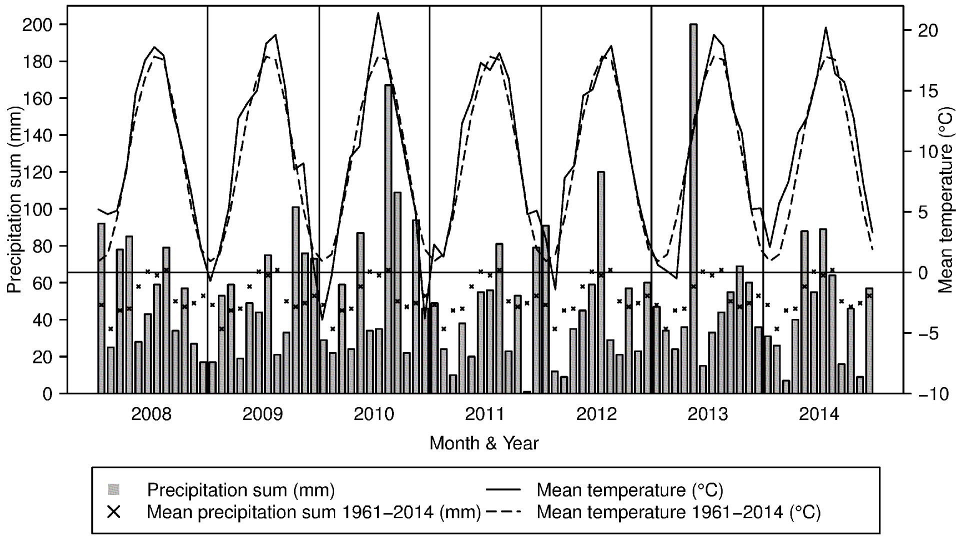


Figure 2.3. *Monthly mean temperature (°C) and precipitation sum (mm) from 2008 to 2014 and the average mean temperature and precipitation sum of the years 1961 to 2014 at the Bundesallee in Braunschweig (data from the Germany's National Meteorological Service).*

The site presents heterogeneous soil conditions and the yield potential is qualified there medium to low. In the alley-cropping system (ACS), the soil is mainly characterized by a silty clay texture (*Tu2*: 45-65 % clay, 15-30 % silt and 0-25 % sand, Ad-Hoc-AG Boden (2005)) and in the crop open field by a clayey loam texture (*Lt3*: 35-45 % clay, 30-50 % silt and 5-35 % sand, Ad-Hoc-AG Boden (2005)). According to Sauerbeck (2008), from east to west, three parallel main soil type zones can be distinguished: a Pelosol zone, a Pseudogley-Pelosol zone and a Pseudogley zone (see fig. 2.4). A small zone of Kolluvisol-Gley is present south-east of the crop alley no. 8, and the soil by short rotation coppice (SRC)-control field is a Pseudogley-Gley. The precise soil type in the crop open field was not analyzed.

According to Ad-Hoc-AG Boden (2005), Pelosols are characterized by a subsoil-horizon containing more than 45 % clay content and by the presence of desiccation cracks in dry conditions, whereas Pseudogley-Pelosols are Pelosols with soil layers influenced by stagnant water. Pseudogley and Pseudogley-Gleys soils gradually show more influenced layers under temporary stagnant water, notably of groundwater for Pseudogley-Gley, with some oxidation marks. Kolluvisol-Gleys are similar to Pseudogley-Gleys, except that the soil is mostly made of sedimented solum material rich in humus (Ad-Hoc-AG Boden, 2005).

The soil on the experimental site is thus strongly influenced by hydrological conditions (Sauerbeck, 2008), and this gradually more from east to west. During dry weather conditions, desiccation cracks of approximately 2 cm width and 30 cm depth appear, especially in the eastern part of the experimental field. During wet conditions, there is a higher risk of stagnant water on the western side of the site. In winter, due to the high clay content and the stagnant water at some places, there is a low traffic ability at the experimental site, unless the soil is frozen. In 2008, before the tree planting, the main soil zone of the ACS (Pelosol) had a water holding capacity of approximately 130 mm up to 1 m depth and a sufficient nutrient supply (Sauerbeck, 2008).

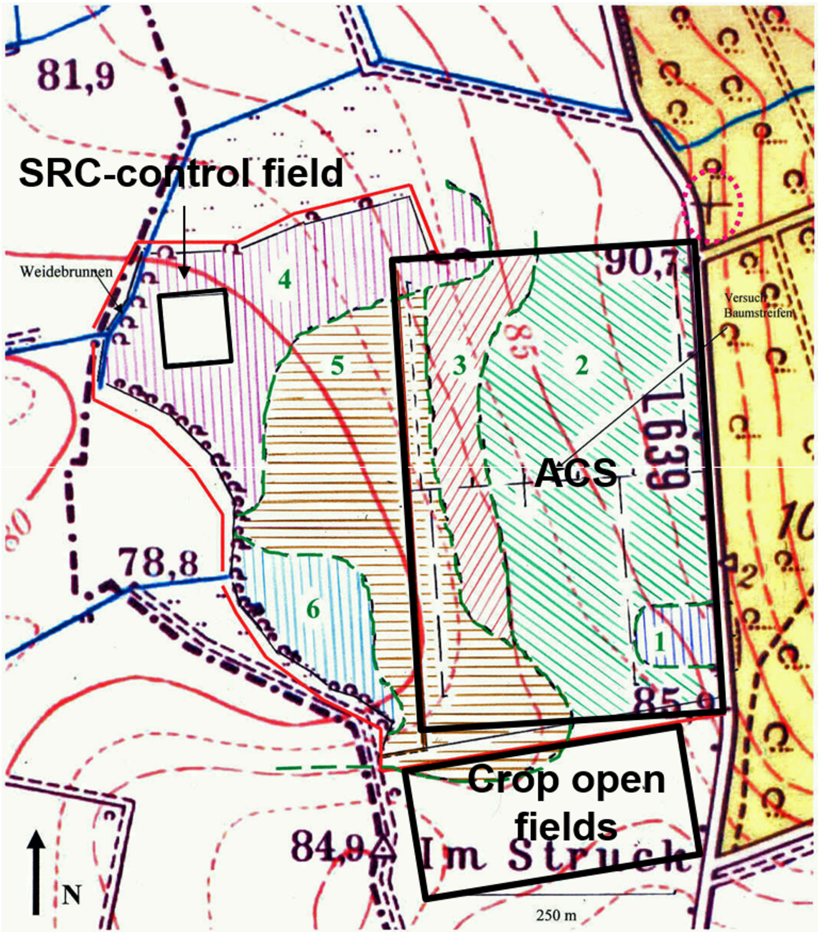


Figure 2.4. *Overview map of the different soil zones at the experimental site in Wendhausen (1: Kolluvisol-Gley; 2: Pelosol; 3: Pseudogley-Pelosol; 4: Pseudogley-Gley; 5: Pseudogley; 6 Anmoor-Gley); the alley-cropping system (ACS) lays within the black rectangle (Sauerbeck, 2008).*

In order to describe the modified growing conditions in the ACS, microclimate parameters, tree shading and leaf ground coverages were measured in 2013, just before the harvest of all trees, and in 2014, after the harvest of all SRC-strips. The methods will be described in the following section.

2.2 Measurement of modified growing conditions in the alley-cropping system

2.2.1 Microclimate parameters

To describe the modified microclimate behind the short rotation coppice (SRC)-strip, wind velocity, air temperature, air humidity and soil water tension were assessed.

Measurement sensors and layout

Wind sensors were used to measure wind speed and direction (wind velocity) in the crop alley, at several distances from the SRC-strip (see fig. 2.5). In total, 14 wind sensors were used: five mechanical anemographs (Woelfe 1482, LAMBRECHT meteo GmbH, Göttingen, Germany), eight wind monitors (Model 05103, Young, Traverse City, USA) and one wind anemometer (PESSL Instruments, Weiz, Austria). The wind velocity was measured simultaneously in the narrow and wide winter barley alleys of the alley-cropping system (ACS) in 2013 (crop alleys no. 2 and 6) from 06/01/13[1] to 07/10/13 and in the narrow and wide winter wheat alleys (crop alleys no. 3 and 7) from 11/25/13 to 12/28/13. In 2014, the wind velocity was measured only in the narrow winter wheat alley (crop alley no. 3) from 05/01/14 to 07/14/14. Wind monitors and mechanical anemographs were installed alternately (see fig. 2.5). In doing so, data collection at different distances from the SRC-strip was guaranteed, since wind monitors were connected in a chain that is disrupted if one monitor fails. An additional measurement was carried out in early autumn 2013 (from 08/28/13 to 09/18/13) using only the mechanical anemographs, which were placed in narrow alleys no. 1, 2, 3, 5 and in the open field in order to investigate the wind velocity reduction behind several SRC-strips (one, two, three and five).

Combined thermometers and hygrometers were implemented to measure air temperature and relative humidity (RH) in the leeward SRC-strip and at different distances from the leeward SRC-strip in the narrow alley (see fig. 2.5). Five combined air temperature and RH sensors (Hygroclip 2, Rotronic Messgeräte GmbH, Ettlingen) and one temperature sensor (SMT16030, PESSL Instruments, Weiz, Austria) were used. The temperature sensor had a measurement error of $0.3 + 0.005 * |t_{emp}|$, where t_{emp} is the measured temperature while the RH sensor had a measurement error of 0.8 %. Air temperature and RH parameters were measured in summer 2013 from 06/02/13 to 07/11/13 in the narrow winter barley alley (crop alley no. 2) and in summer 2014 from 05/22/14 to 07/08/14 in the narrow winter wheat alley (crop alley no. 3). Wind velocity, air temperature and RH measurements were carried out at 1.5 m above-ground level.

[1]This present work is written in American English, therefore dates are written with first the month, than the day and finally the year.

In order to compare the soil water status in the SRC-strip, in the middle of the crop alley and at 3 m distance from the SRC-strip, the soil water tension was measured at these three points. *Watermark* sensors, developed by Larson (1985) (PESSL Instruments, Weiz, Austria) were installed in the narrow crop alley (at 3 and 25.5 m) and in the adjacent leeward SRC-strip in 2013 in the narrow winter barley alley (crop alley no. 2) from 06/01/13 to 07/11/13 (see fig. 2.5). Four depths were selected to investigate the soil profile: 15, 30, 60 and 90 cm.

In order to compare the measurements carried out in the ACS with the conditions in the open field, the following parameters were also measured in the comparative winter barley open fields (C1) and winter wheat open fields (C2) over the same measurement periods than in the ACS: air temperature and RH (Hygroclip 2, Rotronic Messgeräte GmbH, Ettlingen), wind velocity (Wind anemometer, Firm PESSL Instruments, Weiz, Austria). As the soil texture is different in the open field, the soil water tension was not compared to the one in the ACS. Data were collected hourly by a data logger (iMeteos, PESSL Instruments, Weiz, Austria). In order to achieve data comparability, air temperature and RH sensors were calibrated in August 2013, and a correction formula was applied.

The following fig. 2.5 shows the positions of the different sensors installed in the narrow and the wide alley of the ACS.

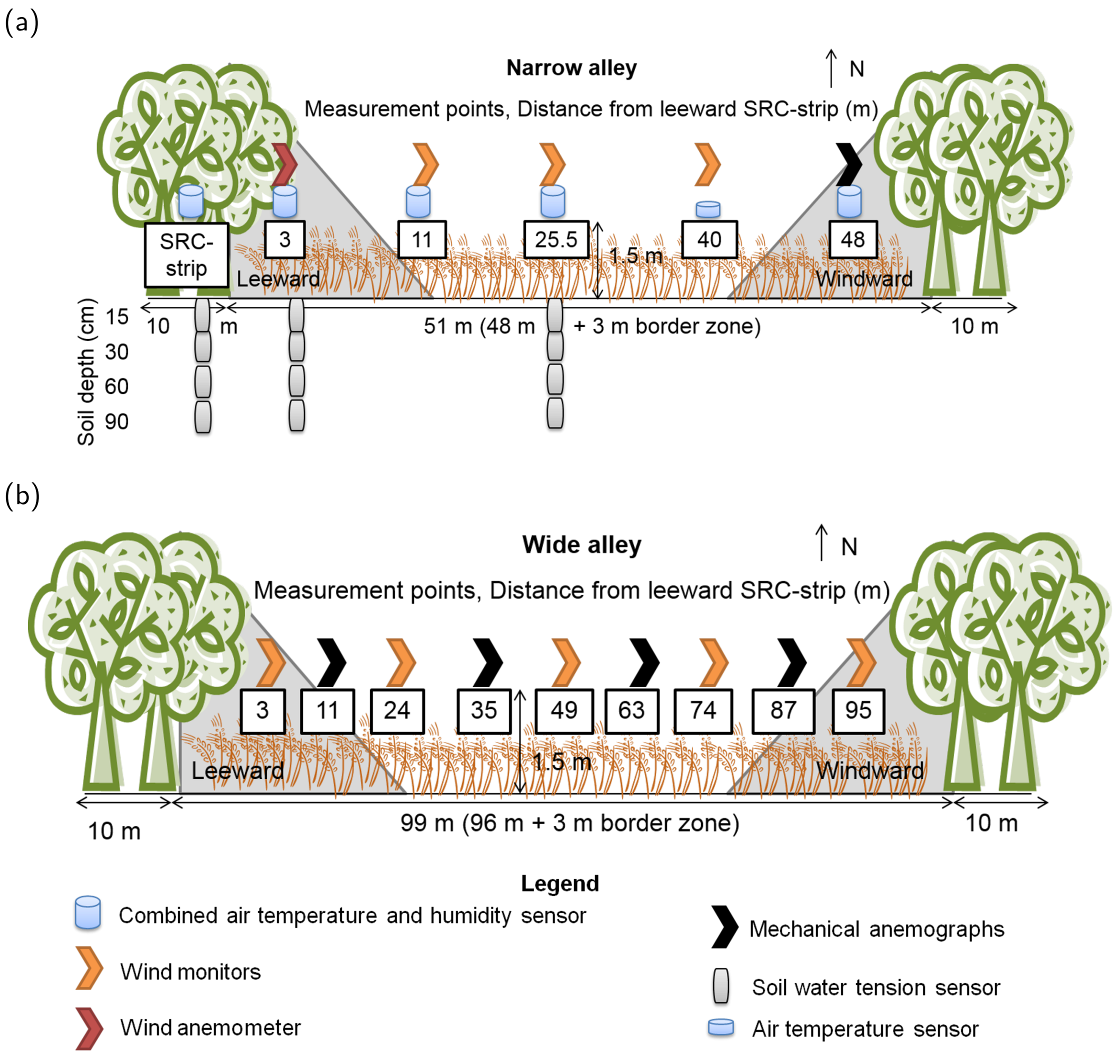


Figure 2.5. *Sketch of the different sensor positions for the measurement of microclimate parameters (wind velocity, air temperature and relative humidity, soil water tension), in the narrow (a) and wide alley (b) of the alley-cropping system in Wendhausen.*

Analysis of microclimate data

The wind velocities collected at the measurement points in the ACS were related to the wind velocity in the open field in percent (100 % is the open field wind velocitiy). Some days with pronounced west, north/south and east directions in the open field were selected over the measurement periods of 2013 and 2014 and analyzed separately from the whole data set.

Concerning air temperature and RH, the data were analyzed separately in three day periods in order to keep data comparability: morning, noon and afternoon. For each day period, the difference to the values in the open field was calculated. The upper and lower hour limits for these periods were selected according to the position of the sun and are presented in table 2.3, for each measurement period. The night hours were not included in the analysis. Additionally, a sunny and a cloudy day were analyzed separately from the whole period.

The air temperature and RH values were implemented in the calculation of the potential evapotranspiration (pET) developed by Haude (1955) and synthesized by Löpmeier (1994):

$$pET = a(e_s - e) \tag{2.1}$$

where a is an empirical monthly plant factor (here 0.38 for the winter wheat in June), e_s the saturated vapor pressure and e the vapor pressure, both calculated with air temperature and RH. The pET calculation requires the air temperature and RH value at 2:00 pm. However, the mean air temperature and RH value of each of the three day periods was used instead. Then, the pET was calculated at each measurement point for morning, noon and afternoon hours (see table 2.3), over the whole measurement period, and for one sunny and one cloudy day in summer 2013 and 2014. As no RH value was available for the open field and at 40 m in the crop alley in 2013, the pET could not be calculated for these points. Moreover, no factor was available for poplar cultivation, so the pET could not be determined for the SRC-strip either.

Table 2.3. *Upper and lower hour limits of the day periods used for the analysis of the air temperature, relative humidity and potential evapotranspiration.*

Measurement period	Morning	Noon	Afternoon
Summer 2013	5 - 11	12 - 14	15 - 21
Summer 2014 (until 06/01)	5 - 11	12 - 14	15 - 20
Summer 2014 (from 06/02)	5 - 11	12 - 14	15 - 21

2.2.2 Reduction of solar radiation

The reduction of the global solar radiation in the vicinity of the short rotation coppice (SRC)-strips was calculated using the *Area Solar Radiation* function of the *Spatial Analyst Tools* in Esri® ArcMap™ 10.2. Firstly, the shapes of the SRC-strips were traced on the digital elevation model of the Wendhausen site, as if being similar to walls with defined heights. The incoming solar radiation on the crop alley was calculated with and without the SRC-strips, using the same input parameters. Then, the reduction of incoming light as the percentage of solar radiation in the open field, i.e. without trees, was obtained for the crop alley over the whole growing season (from sowing to harvest). The tree heights and the sowing and harvest dates are presented in table 2.4. The calculation focused on the narrow and wide alleys of winter wheat and winter barley in the crop harvest years[2] of 2013 and 2014.

[2]"Year" refers to "Harvest Year", not only in this chapter, but also in the result section.

Table 2.4. *Input parameters for the solar radiation calculation: the short rotation coppice (SRC)-strips heights and the sowing and harvest dates of winter wheat (WW) and winter barley (WB) in both alley widths (48 and 96 m), for the growing seasons 2012/13 and 2013/14.*

Season	Crop	Width	Alley no.	Height of SRC-strip (m)		Date of	
				Leeward	Windward	Sowing	Harvest
2012/13	**WW**	**48 m**	5	9.4	6.8	09/21/12	08/05/13
		96 m	8	6.8	-	09/21/12	08/05/13
	WB	**48 m**	2	5.8	7.3	09/18/12	07/17/13
		96 m	6	5.8	7.9	09/18/12	07/17/13
2013/14	**WW**	**48 m**	3	1.2	1.4	09/30/13	07/21/14
		96 m	7	1.4	1.4	09/30/13	07/21/14
	WB	**48 m**	4	1.4	1.5	09/20/13	07/15/14
		96 m	8	1.4	-	09/16/13	07/15/14

2.2.3 Leaf ground coverage

After the leaf fall in autumn 2012 and 2013, the spatial distribution of leaves on the ground was recorded. Pictures of the ground were taken at several distances from the short rotation coppice (SRC)-strips (without repetition) on the leeward and windward sides of the narrow and wide alleys of the winter wheat and barley. Subsequently, each picture was analyzed using the program DatInf® Measure (Datinf GmbH, Tübingen), in order to determine the percentage of leaf coverage on the ground.

Moreover, in order to estimate the amount of the leaves which fell within the SRC-strip and on the crop alley, baskets of 40 x 40 cm surface were installed in autumn 2012, in and next to a SRC-strip in a 6-year rotation cycle (8 m height) and a SRC-strip in a 3-year rotation cycle (5 m height). The leaves were collected every week, during a period of five weeks, from 10/12/12 to 11/13/12. The content of each basket was dried at 60 °C until constant weight was reached, and subsequently weighed.

In the following section, the deployed measurements to assess the effects of the modified growing conditions on yield in the crop alleys will be described.

2.3 Yield and quality measurements in crop alleys

The present section is divided into two main parts: firstly, the assessment method of spatial distribution of yield and grain moisture content (MC) and secondly, the assessment methods of yield components, plant development, aphid infestation and hectoliter weight in the crop alley. As for the microclimate parameters, the measurements in the crop alley focus on year 2013, just before the harvest of all trees, and on the harvest year of 2014, after the harvest of all SRC-strips. As research time was limited, only cereal crops (winter wheat and winter barley) were evaluated, in both alley widths of the alley-cropping system (ACS), and compared to the open field. Thus, the crop alleys no. 2 and 6 (winter barley) and 5 and 8 (winter wheat) were studied in 2013 and the crop alleys no. 4 and 8 (winter barley) and 3 and 7 (winter wheat) in 2014. The spatial distribution of grain yield and MC of summer barley in the ACS in 2008 (just after tree planting) was also analyzed (all crops alleys).

2.3.1 Spatial distribution of yield and grain moisture content

Collecting yield and grain moisture content data

During the crop harvest, the combine harvester (Lexion 430, CLAAS, Germany), equipped with the volumetric flow sensor *Quantimeter* and a Global Positioning System (GPS) device, simultaneously measured the yield, the MC and the geographical coordinates every 5 seconds. The raw data collected by the combine harvester were subsequently screened in order to detect and delete error data due to a low speed or measurement errors, such as all yield, MC and speed values of 0 and speed values over 10 km h^{-1}. Then, the raw yield was recalculated to reach 14 % grain MC and allow for data comparison, using the following calculation:

$$Y14\% = \frac{(\frac{100-MC}{100}) * Y}{100 - 0.14} \tag{2.2}$$

where Y14 % is the yield corrected to 14 % MC (dt ha^{-1}), Y is the raw yield measured by the combine harvester (dt ha^{-1}), and MC is the moisture content measured by the combine harvester (%). At the end, outliers that fell three standard deviations above and below the mean were suppressed. The distance of each measured point to the adjacent leeward SRC-strip was at last calculated using the *Near* function in Esri® ArcMap™ 10.2.

Parallel to the harvest data, the soil apparent electrical conductivity (EC), measured in millisiemens per meter (mS m^{-1}), was recorded over all crop alleys and in the open field, after the crop harvest in 2013. The sensor EM38 (Agri Con GmbH, Ostrau, Germany) equipped with a GPS device was implemented. Thereafter, the EC was corrected to 25 °C (EC_{25}). Since the absolute EC_{25} values were not directly comparable, the data were normalized with the mean value of all fields cultivated with the same crop (nEC_{25}). Then, the tool *Geostatistical Analyst* in Esri® ArcMap™ 10.2 was used to compute a kriging interpolation map of the nEC_{25} data over the ACS and the open field in Wendhausen.

Statistical analysis of the yield and grain moisture content data

In order to assess the effect of the short rotation coppice (SRC)-strips on the spatial distribution of yield and grain moisture content (MC), and given the expected non-linear relationship between the yield/MC and the distance from the leeward SRC-strip, generalized and general additive mixed effects models were used, as they fit a smoothing curve through the data (Zuur et al., 2007). Additional explanatory variables were width (narrow and wide crop alleys) and crop (winter wheat and winter barley). In order to take the soil heterogeneity between and within fields into account, the additional numerical explanatory variable normalized soil apparent electrical conductivity corrected to 25°C (nEC_{25}) was included in the models. For each yield/MC measured point, the nearest nEC_{25} value was selected. To consider the spatial trend across the data, the coordinates of each point (X and Y) were also included in the models as numerical explanatory variables, as suggested by Dormann et al. (2007). Mixed effects models allow for non-independent errors that may occur due to the sampling within one field. Hence, the crop alley and open field no. (1 to 8 and C1 to C3, see fig. 2.1) was selected as random effect, to take differences in field cultivation history into account. As no width treatment was available for the open field, two subplots, with respectively 48 m and 96 m widths and 200 m length, were cut out in each of the open fields C1, C2 and C3 (see fig. 2.1). Then, the distance from the west subplot boundary was calculated. The position of these subplots are presented in appendix B. The base model used for each year (2008, 2013 and 2014) and each system (ACS and open field) was generated as in the following equation:

$$
\begin{aligned}
Y14\%_i/MC_i = \quad & \gamma + f_1(Distance_i) + f_2(Distance_i : Width_i) + f_3(Distance_i : Crop_i) \\
+ f_4(nEC_{25i}) + f_5(X_i, Y_i) + \varepsilon_i \quad & \text{with} \quad \varepsilon_i \sim N(0, \sigma^2)
\end{aligned}
\tag{2.3}
$$

where each $f()$ represents a smoothing curve for the response under each explanatory variable, for each predicted point i in the alley/subplot (Zuur et al., 2007); $Y14\%_i$ and MC_i are the response variables for, respectively, the yield at 14 % moisture content and the grain moisture content; $f_1(Distance_i)$ is the smoother term for the distance from the leeward SRC-strip or west subplot boundary, $f_2(Distance_i : Width_i)$ the smoother term for the interaction between the distance and the width, $f_3(Distance_i : Crop_i)$ the smoother term for the interaction between the distance and the crop, $f_4(nEC_{25i})$ the smoother term for the normalized soil apparent electrical conductivity corrected at 25 °C and $f_5(X_i, Y_i)$ the spatial smoother. γ is the intercept, ε represents the residuals and σ the standard deviation. The "mgcv" package (Wood, 2011) was used to compute the models in the statistical software R (R Core Team, 2014). For 2013 and 2014, one model for the ACS and one for the open field system were computed, whereas for 2008, only one model was computed for the ACS because no comparable crop was cultivated in the open field.

A set of models with all possible numbers and combinations of smoothers (with the two different crops and the two different widths) and linear effects ($Crop$,$Width$ and nEC_{25}), were computed. To reach the most parsimonious model, a selection was applied, using the

Akaike Information Criterion (AIC, Akaike (1978)), calculated with the following equation:

$$AIC = -2\log(L) + 2k \tag{2.4}$$

where L is the Likelihood value and k the number of parameters in the fitted model. For each computed model, the AIC value was calculated and the model with the lowest AIC value was selected. For model validation, normal distribution and homogeneity of model residuals were checked graphically. Subsequently, the yield/MC was predicted from $Distance_i = 1$ m (next to the leeward SRC-strip) for each meter up to the windward SRC-strip (48 m for the narrow alley and 96 m for the wide alley). As additional input parameters, the mean nEC_{25} and the mean X,Y coordinates of the crop alley/open field were used. Such a yield/MC transect was predicted for each crop and each width, for each year and each system.

2.3.2 Yield components, plant development, aphid infestation and hectoliter weight

In order to assess the effects of short rotation coppice (SRC)-strips on yield components, plant development, aphid infestation and hectoliter weight over the crop alley, several sampling points were installed at different distances from the SRC-strips. During the vegetation period 2013, these points were situated along a transect from one SRC-strip to another, including the leeward side (3 and 8 m), the middle zone (16, 25.5 and 35 m in the narrow alley and 32, 49.5 and 67 m in the wide alley) and the windward side (43 and 48 m in the narrow alley and 91 and 96 m in the wide alley) of the crop alley (see fig. 2.6). During the vegetation period 2014, in both, the narrow and the wide alleys, only the leeward side (3 and 8 m) and one point in the middle of the alleys were assessed.

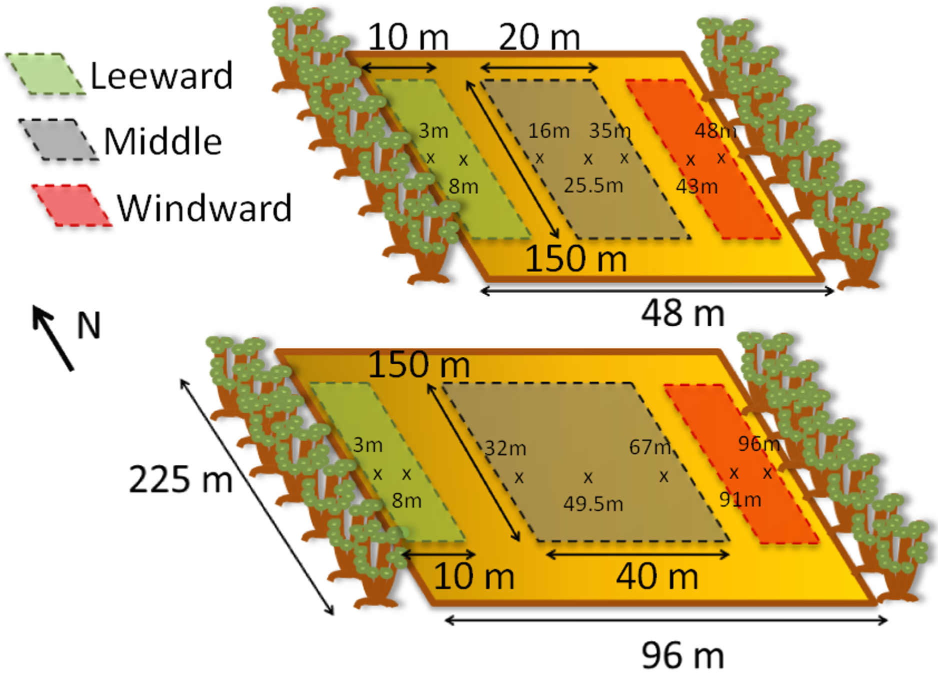


Figure 2.6. *Positions of the sampling points for the assessment of yield components, plant development, aphid infestation and hectoliter weight in the narrow and the wide alleys of the alley-cropping system in Wendhausen (distances are indicated from the leeward short rotation coppice-strip).*

These transects were replicated four times within an alley. In 2013, two repetitions were situated next to the SRC design and two next to the combined design of the SRC-strip, both next to the "Max" clone. It was considered that the effect of the poplar clone would be minimal after the strip harvest in January 2014. Thus, in 2014, the four transect repetitions were situated only next to the SRC design, in order to avoid the effect of the remaining aspens along the three clones. In both years, the same measurements were conducted in the open field for four randomly selected points in the middle of the fields.

Yield components

Shortly before the harvests 2013 and 2014, 0.5 m^2 parcels were sampled along the transects, as presented in the previous paragraph and in fig. 2.6. From each sampled parcel, the ears were counted to determine the ear number per m^2 (EN). Additionally, the weight of all grains (GW) was recorded. The thousand grain weight (TGW) was estimated with the average weight of three subsets of 100 kernels. The water content of each grain sample was assessed by drying it at 105 °C until constant weight was reached. The GW and the TGW were recalculated to reach 14 %grain MC with the water contents of each sample, using equation 2.2.

In order to statistically determine which of the EN or TGW was mainly responsible for the GW, linear regressions were applied. Linear mixed effects models and the package "nlme"

(Pinheiro et al., 2014) in the software R (R Core Team, 2014) were used to fit GW, with EN and TGW as explanatory variables, with and without interactions. The crop alley no. (1 to 8, see 2.1) was included as random effect. The Akaike Information Criterion (AIC) of each model was calculated, according to Akaike (1978) (see equation 2.4), and the most parsimonious model was chosen (lowest AIC value). Normal distribution and homogeneity of residuals were graphically checked. Analyses of variance were performed to test for the effect of both, EN and TGW, and eventually their interactions, on the GW. The significance level was set at 0.05. The same analysis was carried out for each cereal crop (winter wheat and winter barley) and each year (2013 and 2014), at first for the whole data set and then for leeward, windward and middle zones separately (see fig. 2.6). The points of the narrow and the wide alleys were pooled together.

Plant development, aphid infestation and hectoliter weight

During the vegetation periods in 2013 and 2014, the plant development of winter wheat and barley was recorded by assessing the phenological development stages at several dates, using the *Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie* (BBCH) scale edited by Meier (1997). Additionally, at one or two dates, depending on infestation, aphids, aphid mummies (parasitized aphids) and beneficial insects were counted on ten tillers (ear and flag leaf) per point. As a quality parameter, which is important for the price of cereals, the hectoliter weight was measured from samples taken directly out of the combine harvester at each track (three repetitions per track). To determine the hectoliter weight, a known volume was filled with the kernels and weighed (Egger, 1989).

The description of the methods used to assess growth and yield of the SRC-strips will be presented in the next section.

2.4 Growth and yield measurements in short rotation coppice-strips

The present section will be divided into two parts: the methods used to describe tree growth and the methods used to describe yield of trees.

2.4.1 Growth parameters

In order to record tree growth, several measurements were conducted on the leeward, middle and windward rows of the short rotation coppice (SRC) and combined designs of the SRC-strips C to F and in the "Max" clone, in winter 2009/10, 2013/14 and 2014/15 (see fig. 2.2). In these SRC-strips, diameters at breast height (DBH) were measured at 1.30 m above-ground level on shoots of 20 trees per row position (leeward, middle and windward), using a digital calliper (Alpha tools, Germany, 0.1 cm accuracy). Moreover, shoot heights of selected DBHs over the range of values were measured using a telescopic rule for each row position (mEssfix, Nedo, Switzerland, 1 cm accuracy) and the numbers of shoots of 20 trees per row position were counted. The same parameters were measured on 56 trees in the middle of the SRC-control field.

To assess the effect of the row position in both designs (SRC and combined) and in the control field (see fig. 2.2), linear mixed effects models were used to fit DBH with normal errors (package "nlme", Pinheiro et al. (2014)) and shoot number with Poisson errors and log link (package "glmmADMB", Skaug et al. (2012)), using the software R (R Core Team, 2014). Separate analyses were performed for the 3-year rotation cycle (3y-RC) and the 6-year rotation cycle (6y-RC) (control field only for 3y-RC). The tree no. (1-20 for the leeward and windward and middle rows of the SRC and combined design, 1-56 for the control field) nested within strips (C and E; D and F) were included as random factors. The model residuals were checked graphically for normal distribution and variance homogeneity, and shoot numbers were also checked for overdispersion. Since they were not normally distributed, the residuals of DBHs measured in winter 2014/15 in the 3y-RC and in the 6y-RC were log transformed, whereas data of the 3y-RC of winter 2013/14 had a double log transformation, followed by one inverse square transformation. Subsequently, *Post-hoc* comparisons of the 95 % confidence interval of mean difference ("Tukey" test) were performed using the function "glht", in the "multcomp" package (Hothorn et al., 2008) in R (R Core Team, 2014), with a probability level for rejection of the null hypothesis of 0.05.

Linear mixed effects models were used to fit shoot height with DBH and row position in each design and each rotation cycle (leeward, middle and windward rows of the SRC and the combined design; additionally for the 3y-RC, the SRC-control field) as explanatory variables were performed. The random factors tree number nested within strip were also selected and the analysis was carried out with the software R (R Core Team, 2014). Separate analyses were performed for each winter (2009/10, 2013/14 and 2014/15) and each rotation cycle (3-year and 6-year). In order to assess the correlation between height and DBH, a pseudo-correlation coefficient (R^2) was calculated as a R^2 of a regression between predicted and observed values. The R^2 was calculated at first using parameter coefficients for fixed effects only and subsequently the parameter coefficients for fixed and random effects.

2.4.2 Biomass estimation of outer and middle rows

A biomass estimation was carried out during winter 2013/14, in order to assess the biomass production specifically of the outer rows, leeward and windward, the middle rows in both designs (short rotation coppice (SRC) and combined) and the middle and leeward rows of the control field, in both rotation cycles. As similar effects were expected in the leeward rows of the SRC and the combined designs, the values of the leeward rows of both designs were pooled together. The same operation was carried out for the windward rows. However, the middle rows of the SRC and combined designs were assessed separately. Conversely to the previous measurements, in which only two middle rows were measured in the SRC design, the four rows were assessed for this estimation (Lamerre et al., 2015).

Firstly, the diameters at breast height (DBH) of 40 % of the trees were measured and subsequently, 25 from these DBHs were chosen. Then, 25 shoots with these diameters were manually cut (10 cm above the ground), chipped and weighed. In order to determine the water content, a sample was taken and dried for several days at 60 °C, until constant weight was reached. Allometric power equations were used to predict the shoot dry mass from the DBH (see 2.5):

$$DM = \alpha \cdot DBH^{\beta} \tag{2.5}$$

with *DM* is the shoot dry mass and α and β are the equations' coefficients. The models were linearized using logarithms and subsequently the equations' coefficients were calculated in R (R Core Team, 2014). Thereafter, the DM of each measured DBH was predicted. Using the mean stool method described by Hytönen et al. (1987), the yearly biomass production per hectare was estimated for each row, on the basis of the average DM and the number of shoots per hectare (Lamerre et al., 2015).

To assess the effect of row position (leeward, middle of the SRC design, middle of the combined design, windward and additionally for the 3y-RC, control field) on biomass production, the same statistical analyses were performed as for the DBH in the software R (R Core Team, 2014), for both rotation cycles.

An overall evaluation of the alley-cropping system (ACS) and sole-cropping systems (SCSs, crop open field and SRC-control field) was performed, in order to assess and compare their productivity. The methods employed will be presented in the following section.

2.5 Overall evaluation of the systems

In order to compare the total biomass production of the ACS and the SCSs, the crop and tree yield data were added over the harvest years. Within the ACS, the narrow and wide alleys were also compared. In the next section, the data collection of the crop and tree yield will be described, followed by the method used for the system evaluation.

2.5.1 Yield data collection of crop-alleys

In both, the ACS and SCS (i.e. crop open field), grain yield data collected by the combine harvester were available from 2008 to 2014. Data were prepared as presented in the first paragraph of section 2.3.1, but the dry matter yields were used and averaged in each field. As only the winter wheat and the winter oilseed rape were available in both alley widths and in both systems over this time period, the evaluation was performed only for these two crops. The yield data of 2008 could not be integrated in the evaluation because different crops were cultivated in the open field (see fig. 2.1). Furthermore, no data were available for the winter oilseed rape in 2013, because of technical problems regarding the combine harvester.

The yield means of each crop were tested within each year for significant differences between the narrow alley, the wide alley and the open field, using the "Tukey" test in the "nparcomp" package (Konietschke et al., 2015) in the software R (R Core Team, 2014).

2.5.2 Yield data collection of short rotation coppice-strips

The yield values of the short rotation coppice (SRC)-strips for the system evaluation were estimated in a non-destructive way, using the estimation model developed by Röhle and Skibbe (2012). This model is available as a program in internet (Röhle et al., 2014). It implements an allometric function as presented in equation 2.5, but the coefficients α and β are adjusted not only using the diameters at breast height (DBHs) but also the heights, which are entered for 25 different DBHs. Using the field size and the planting density, the sampling size for the measurement of DBH is calculated. Then, the required DBHs and heights are entered in the program. The outputs are the produced wood biomass in t ha^{-1} and the yearly biomass increment, which is the whole biomass divided by the age of the trees.

In the first place, the biomass productions of the leeward, middle and windward rows were estimated separately, for the SRC and combined designs (see fig. 2.2), as well as for the rotation cycles and the winter seasons of 2009/10, 2013/14 and 2014/15. It was carried out only for the clone "Max" in SRC-strips C to F (see fig 2.1), in order to keep the data collection feasible and to guarantee comparability between the years. The estimation was also conducted for the SRC-control field in the same winter seasons. The estimation conducted in winter 2009/10 represents the biomass production of two growing seasons (2008 and 2009). However, only the average value of both years was considered, in order to guarantee data comparability with the crop component, for which no data was available for the harvest year of 2008. The SRC-strips in the 3-year rotation cycle (3y-RC) were harvested in winter 2010/11. As a result, the measurement of 2013/14 includes the growing seasons 2011, 2012 and 2013 and thus, no data were available for the growing season 2010. The mean yearly growth estimated in the 3y-RC from 2009 to 2014 was used to replace this missing value of 2010. The SRC-strips in the 6-year rotation cycle (6y-RC) were first harvested in winter 2013/14. Thus, the estimation of winter 2013/14 comprises the biomass production from 2008 to 2013. The biomass production of 2008 was subtracted from the estimation of winter 2013/14, by using the yearly increment of 2009.

It was considered that each row was 2 m wide and 50 m long (0.01 ha), as two SRC-strips being in the same rotation cycle were combined (C and E; D and F). The same assumption was applied for the SRC-control field. The planting density was 2 x 0.5 m (10,000 trees per hectare). A homogeneous and very low mortality rate and an error of 10 % were assumed. Considering these input parameters, the sampling size amounted to 20 trees per row. Subsequently, data were collected and the biomass productions were calculated by using the program. Moreover, eight aspen trees were randomly selected, cut and weighed during winter 2013/14, in order to estimate the biomass production of the aspen trees. To determine the water content, one sample per tree was dried at 60 °C, until constant weight was reached, and the resulting dry weights were averaged.

To estimate the biomass production of a strip for each period, the following equations were used:

- Biomass production of the SRC design (B_{SRC}):

$$B_{SRC} = \frac{L_{SRC} + 4 * M_{SRC} + W_{SRC}}{6} \tag{2.6}$$

- Biomass production of the combined design (B_{Comb}):

$$B_{Comb} = \frac{L_{Comb} + 2 * M_{Comb} + B_{Asp} + W_{Comb}}{6} \tag{2.7}$$

where L_{SRC}, M_{SRC} and W_{SRC} respectively represent the biomass production (t ha^{-1}) of the leeward, middle and windward rows of the SRC design. L_{Comb}, M_{Comb} and W_{Comb} respectively represent the biomass production (t ha^{-1}) of the leeward, middle and windward rows of the combined design, whereas B_{Asp} represents the biomass production (t ha^{-1}) of the aspen trees.

2.5.3 System definition for evaluation

Four systems were defined for comparison: a sole-cropping system (SCS) with a crop open field, a SCS with short rotation coppice (SRC)-control field, an alley-cropping system (ACS) with two narrow crop alleys and three SRC-strips and an ACS with one wide crop alley and two SRC-strips. The mensuration of the fields was calculated at a surface of one hectare for each system, in order to make both systems comparable. The widths, the lengths and the proportion of SRC-strips and crop alleys in each system are presented in fig. 2.7.

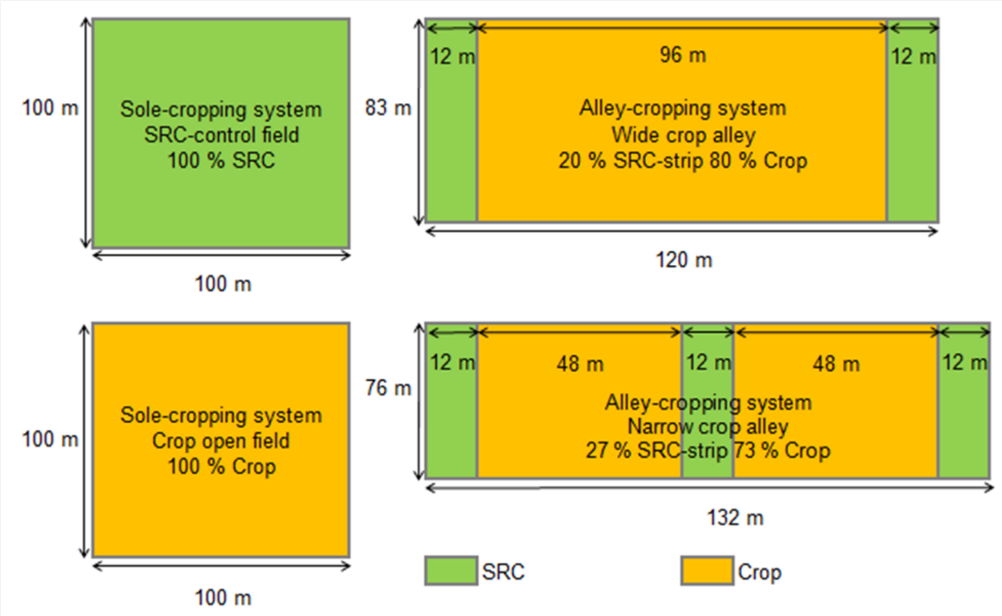


Figure 2.7. *Arrangements of the four evaluated systems (one sole-cropping system with crop open field, one sole-cropping system with short rotation coppice (SRC), one alley-cropping system with a wide alley and one alley-cropping system with narrow alleys) and their widths, lengths and proportions of SRC-strips and crop alleys.*

For each system, the proportions of SRC-strips and crop alleys were used to calculate the yields (in t ha^{-1}) of each component in each year, using the data as presented in section 2.5.1 and 2.5.2. Subsequently, the yearly crop and tree yields and were added to obtain aggregated yields. The calculation of each system was made considering the two rotation cycles (3y-RC and 6y-RC), the two SRC-strip designs (SRC and combined) and the two crops (winter oilseed rape and winter wheat). In total, 22 values were calculated. The grain yields of the winter oilseed rape in 2013 were not available, and thus only five years of aggregated yields were considered for this crop (one yearly yield was subtracted for the tree component), whereas six years were considered for the winter wheat systems.

The biomass values added over the years were subsequently converted into energy units, gigajoules per hectare (GJ ha^{-1}), using calorific values of dry weights for each component: 17.0 GJ t^{-1} for grains of winter wheat, 26.5 GJ t^{-1} for grains of oilseed rape and 18.5 GJ t^{-1} for poplar (Döhler, 2009). This way, the energy production of each system was compared.

3 Results

3.1 Modifications of growing conditions in the alley-cropping system

The results of microclimate measurements, solar radiation calculation and leaf ground coverage will be presented in the following paragraphs.

3.1.1 Microclimate parameters

In this section, the three assessed microclimate parameters will be presented: firstly, the wind profiles over the crop alleys, secondly the air temperature and relative humidity (RH) evolution within the short rotation coppice (SRC)-strips and in the narrow alley and thirdly the soil water tension. Microclimate parameters of the crop alleys will be directly compared to these of the open field, except for the soil water tension.

Wind profiles

The selected days with pronounced west, north/south and east wind directions in the different measurement periods are presented in table 3.1. As no wind velocity reduction occurred during summer 2014, it was decided not to analyze different wind directions. No day with pronounced east direction was identified in winter 2013/14 and no day with pronounced north/south direction was observed in autumn 2013.

Table 3.1. *Selected days with pronounced west, north/south and east wind directions for the analysis of the wind data of summer 2013, winter 2013/14 and summer 2014.*

Measurement period	West direction	North/south direction	East direction
Summer 2013	06/14, 06/30 07/04	06/01-03, 06/25-26 07/10	06/05, 06/17-19 07/07
Winter 2013/14	11/28, 12/06-07 12/09	12/24-25 12/27	-
Autumn 2013	09/01-03, 09/15	-	09/05-08

For each measurement period (summer 2013, winter 2013/14 and summer 2014), wind velocities in the alley-cropping system (ACS) relative to the open field velocity are presented in figs. 3.1, 3.2, 3.3.

Summer 2013

Over the whole measurement period, the winds blew mostly from the west and north-west (fig. 3.1 (a)). On selected days with west winds, wind velocities ranged mainly from 1 to 3 m s^{-1} (fig. 3.1 (b)). On selected days with north winds, wind velocities were quite high, mainly between 2 and 3 m s^{-1} (fig. 3.1 (d)), whereas winds were quite calm on selected days with east winds, mainly between 0 and 1 m s^{-1} (fig. 3.1 (e)).

Considering all wind directions, the relative wind velocity was in general lower in the narrow than in the wide crop alley (see fig. 3.1 (c)). The lowest wind velocities were observed directly on the leeward side of the SRC-strip and progressively increased with distance from the SRC-strip. 50 % of the open field wind velocity was reached between 11 and 25 m in the narrow alley and already between 3 and 11 m in the wide alley. In the narrow alley, the wind velocity of the open field was not reached at all (highest relative velocity of 85 %), whereas in the wide alley, the wind velocity of the open field was reached at 35 m, but stayed constant around 100 % up to the next SRC-strip.

When winds blew from the west, wind velocities in the ACS were lower than for winds coming from all directions, and this reduction was stronger in the narrow than in the wide alley (see fig. 3.1 (c)). 50 % of the open field wind velocity was reached roughly at 25 m in both alley widths. The highest relative wind velocity was observed at 63 m in the wide alley (93 %) and the lowest at 3 m in the narrow alley (1 %).

The effects of north winds in summer 2013 were similar to the effects of west winds (see fig. 3.1 (f)). 50 % was reached between 11 and 25 m in both alleys. However, 100 % of the open field wind velocity was already reached in the wide alley at 63 m, whereas the highest wind velocity in the narrow alley was 77 %.

Considering only east winds, a completely different wind profile was observed (fig. 3.1 (f)). The lowest wind velocity was measured on the windward side (44 % at 87 m in the wide alley and 23 % at 40 m in the narrow alley). Moreover, the highest wind velocities (more than 100 % in the wide alley) were measured on the leeward side and in the middle of the crop alley.

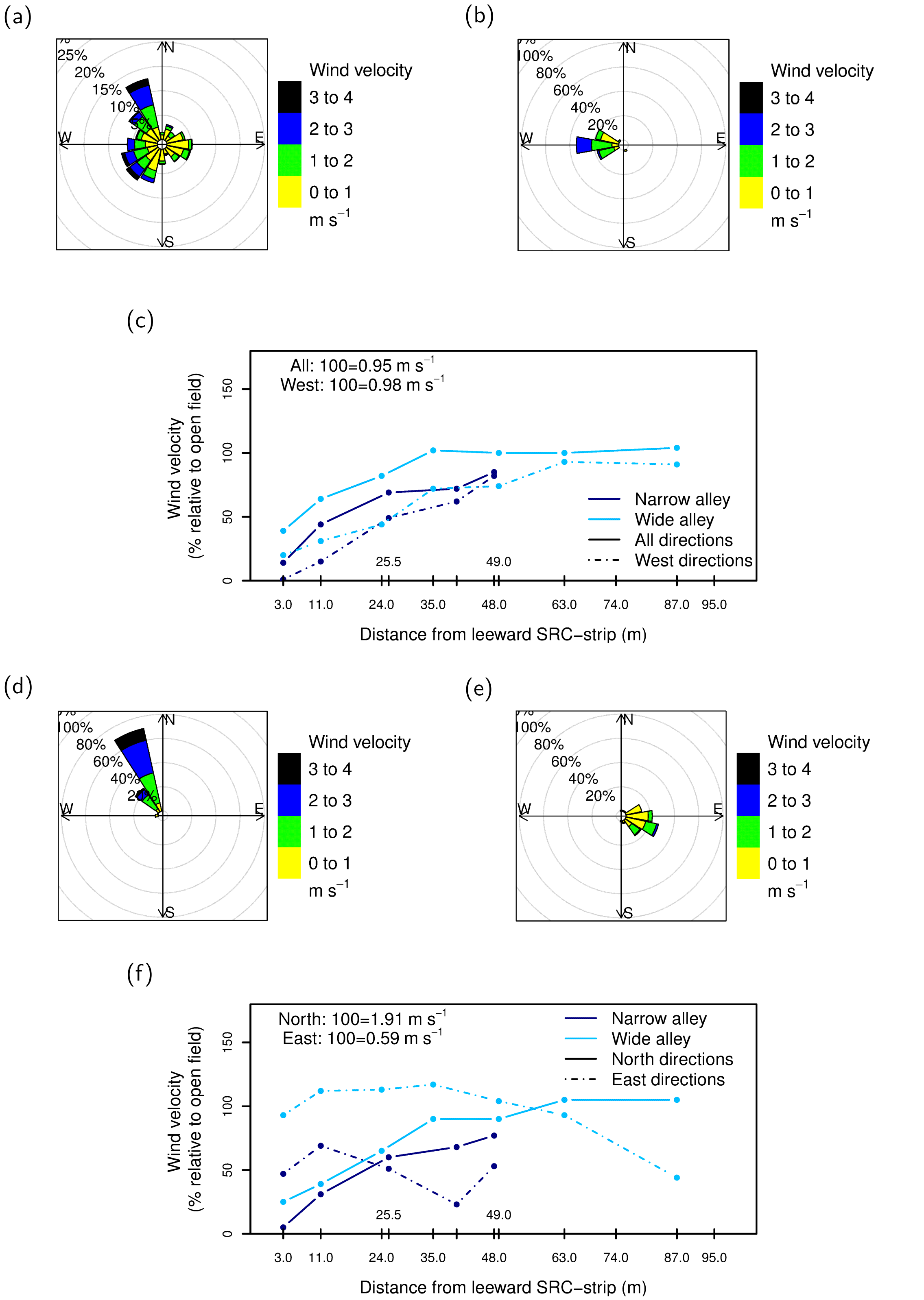


Figure 3.1. *Windroses showing the proportion of wind velocities (%) in each direction over the measurement period in summer 2013 (from 06/01 to 07/10) (a) and on the selected days with west (b), north (d) and east (e) directions; relative wind velocity (% to the open field) in the narrow and wide alley of the alley-cropping system, for all and west directions (c) and north and east directions (f). Measurements at 74 m and 95 m failed over the whole measurement period because of wrong sensor calibration.*

Winter 2013/14

In winter 2013/14, over the whole measurement period, winds came particularly from the west, south-west and south, with wind velocities reaching 8.90 m s^{-1} (see fig. 3.2 (a)). On selected days with south winds, the wind velocities mainly ranged from 4 to 7.12 m s^{-1} (see fig. 3.2 (c)) and on selected days with west winds, from 4 to 8.08 m s^{-1} (see fig. 3.2 (d)).

The relative wind velocities directly on the leeward side of the SRC-strip were in general higher than in summer 2013 (see fig. 3.2 (b)). Indeed, considering all directions, the lowest relative wind velocity was 40 %, at 3 m in the narrow alley and 58 %, at 3 m in the wide alley (see fig. 3.2 (b)). In general, velocities were lower in the narrow than in the wide alley. The highest relative velocity was measured at 74 m in the wide alley (126 %), whereas in the narrow alley values varied between 40 % and 66 % and in the wide alley between 58 % and 98 %.

When winds blew from the south, a reduction wind profile could be observed, with minimum relative wind velocity at 3 m of 35 % in the narrow alley and of 48 % in the wide alley (see fig. 3.2 (e)). Then, the wind velocity increased up to 90 % in the narrow alley and up to 122 % at 74 m in the wide alley. When approaching the windward side, the relative velocity in the wide alley decreased to 66 % at 87 m and increased again up to 100 % at 95 m.

When only west winds were considered, the relative wind velocity increased from 56 % to 82 % in the wide alley and from 44 % to 50 % in the narrow alley (see fig. 3.2 (e)).

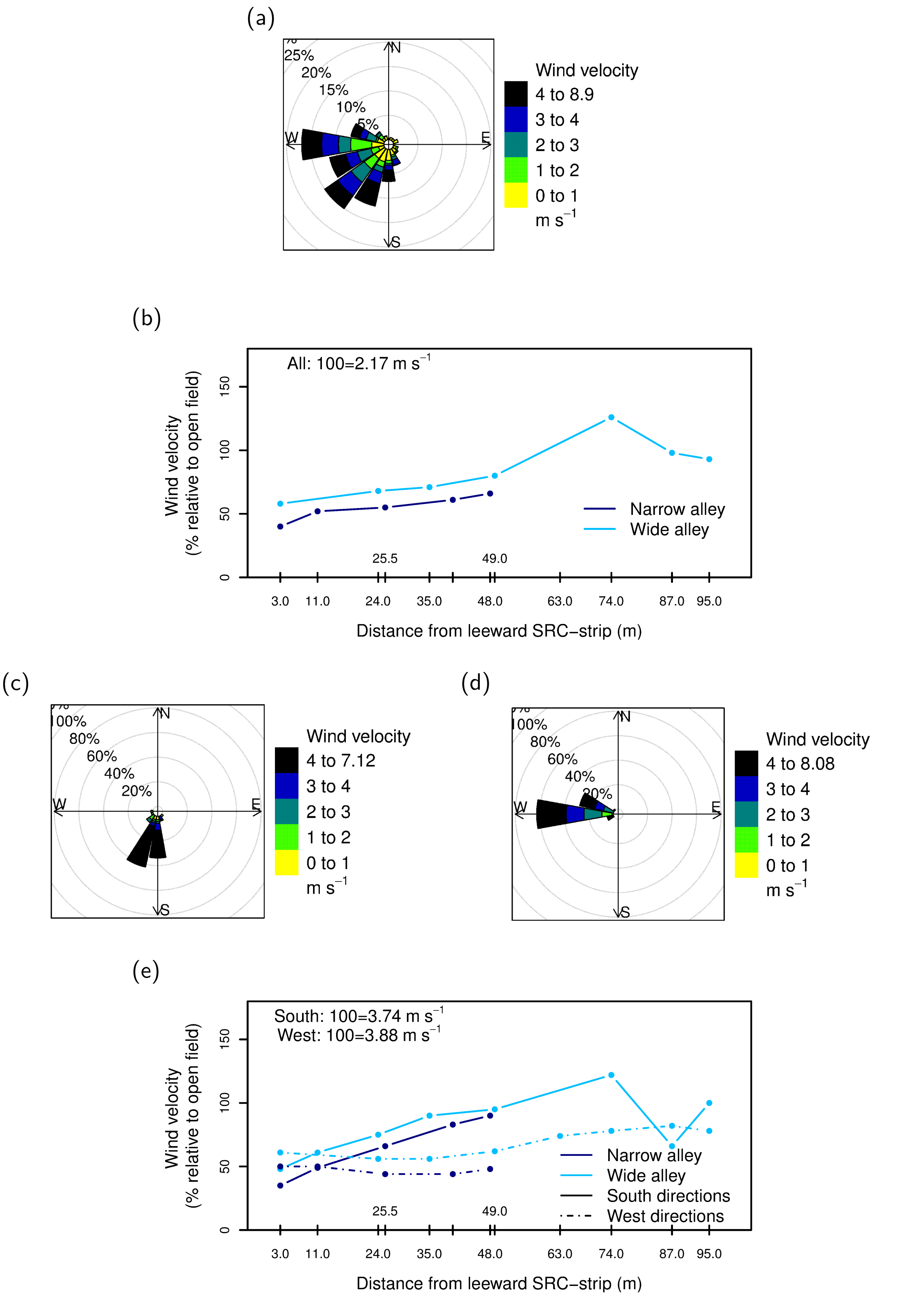
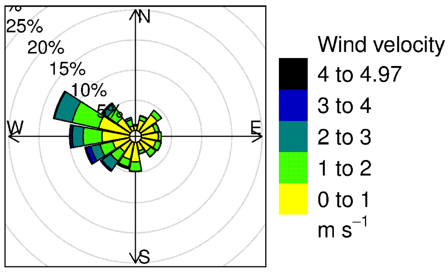


Figure 3.2. *Windroses showing the proportion of wind velocities (%) in each direction over the measurement period in winter 2013 (from 11/25 to 12/28) (a) and on the selected days with south (c) and west (d) directions; relative wind velocity (% to the open field) in the narrow and wide alley of the alley-cropping system, for all directions (b) and south and west directions (e). The measurement point at 11 m in the wide alley failed from 11/25 to 12/11 and was exchanged with the sensor at 63 m, resulting in missing values from 12/11 until 12/28 at 63 m.*

Summer 2014

During summer 2014, the winds came mostly from the west and velocities ranged mainly from 0 to 3 m s^{-1}, and increased up to 4.97 (see fig. 3.3 (a)). The relative wind velocity ranged from 103 % directly on the leeward side and up to 127 % on the windward side of the SRC-strips (see fig. 3.3 (b)).

(a)



(b)

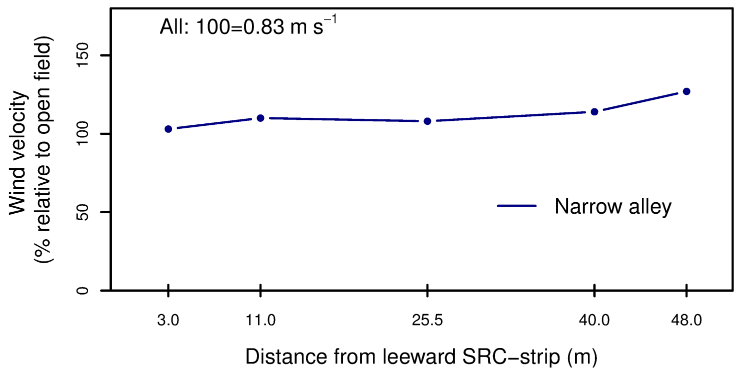


Figure 3.3. *Windrose showing the proportion of wind velocities (%) in each direction over the measurement period in summer 2014 (from 05/01 to 07/14) (a) and the relative wind velocity (% to the open field) in the narrow alley of the alley-cropping system, for all directions (b).*

Behind several strips

During the measurement behind several strips in autumn 2013, winds mainly came from the west (velocities ranged between 1 and 4 m s^{-1}) and the east (velocities ranged between 1 and 3 m s^{-1}) (see fig. 3.4 (a)). On selected days with west winds, velocities mainly lay between 2 and 5.25 m s^{-1} (see fig. 3.4 (c)), whereas on selected days with east winds, velocities were mostly between 1 and 3 m s^{-1} (see fig. 3.4 (d)).

When considering all wind directions, the relative velocity ranged from 42 % behind one strip to 38 % behind five strips and was the highest behind two strips (see fig. 3.4 (b)). When considering only days with west winds, it was observable that the wind velocity was the lowest behind five strips (25 %). However, when winds came from the east, the lowest relative wind velocity was reached behind two SRC-strips (43 %) (see fig. 3.4 (e)).

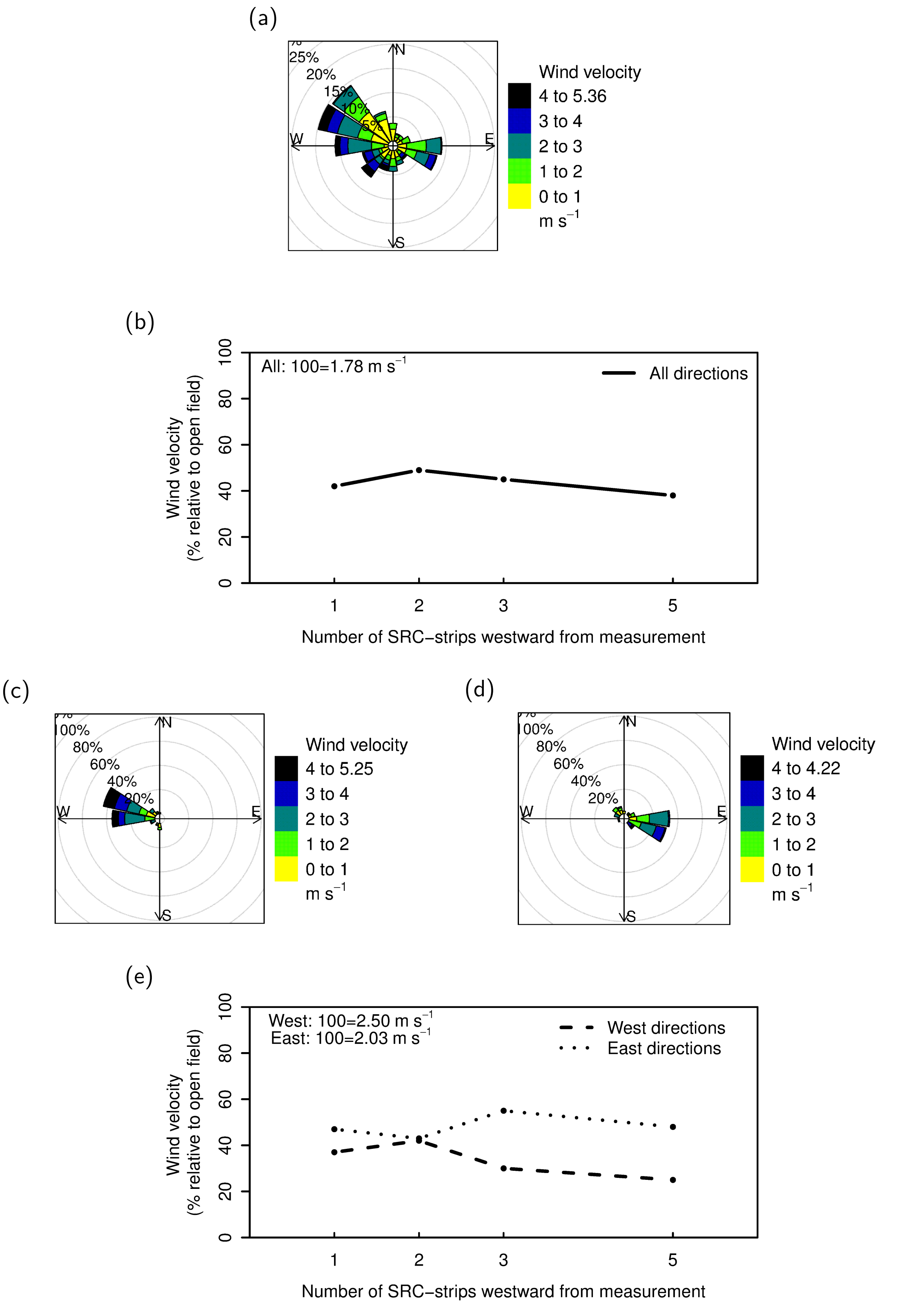


Figure 3.4. *Windroses showing the proportion of wind velocities (%) in each direction behind several strips over the measurement period in early autumn 2013 (from 08/28 to 18/09) (a) and on the selected days with west (c) and east (d) directions; relative wind velocity (% to the open field) behind several SRC-strips for all directions (b) and the west and east directions (e).*

Air temperature, relative humidity and potential evapotranspiration

Air temperature, relative humidity (RH) and potential evapotranspiration (pET) results were divided into three day periods: morning, noon and afternoon (see table 2.3). The average, minimum and maximum air temperature and relative air humidity values at the different measurement points over the two measurement periods are available in appendix C. Analysis focused on air temperature, RH (as differences to the open field mean) and pET variation from one short rotation coppice (SRC)-strip to another over the crop alley, over the whole measurement period and additionally on one sunny day and one cloudy day. The weather conditions on these days are presented in table 3.2.

Table 3.2. *Meteorological conditions on the selected sunny and cloudy days in summer 2013 and 2014 at the experimental site in Wendhausen (* Data of Braunschweig, from the Germany's National Meteorological Service, when no data was available for Wendhausen).*

Year	Day	Date	Mean air temperature (°C)	Sum of hourly solar radiation (W m^{-2})	Mean wind velocity (m s^{-1})
2013	all	06/02-07/11	16.6	4358*	0.93
	sunny	07/09	20.0	5545*	0.3
	cloudy	06/25	12.8	1497*	1.4
2014	all	05/22-07/08	15.6	4992	0.68
	sunny	07/05	21.0	5308	0.72
	cloudy	07/08	17.7	1476	0.36

In the next sections, the evolution of the air temperature, RH and pET values in the SRC-strip and the narrow alley will be presented for all days, one cloudy day and one sunny day of each measurement period (summer 2013: from 06/02 to 07/11; summer 2014: from 05/22 to 07/08) and for the three day periods separately (morning, noon and afternoon).

Summer 2013

Considering all days (together), in the morning hours, the temperature was in general lower in the crop alley than in the open field, as differences were negative. Over the crop alley, the greatest negative differences (to the open field) were measured at 48 m (-1.7 °C) and in the SRC-strip (-1.2 °C) (see fig. 3.5 (a)). On the cloudy day, temperatures were similar in the alley-cropping system (ACS) and in the open field, as well as over the crop alley (no differences to the mean). However, on the sunny day, greater temperature differences were observed. The biggest negative difference to the open field (lowest temperature) was measured at 48 m (-5.1 °C) and the smallest negative difference (highest temperature) at 3 m (-2.8 °C). At noon, differences to the open field mean were only observed in the SRC-strip, where these were negative (up to -1.8 °C on the sunny day). On the sunny day, a small negative difference was also measured at 48 m. In the afternoon, the temperature was in general higher in the crop alley than in the open field (positive differences). Considering all days together, the smallest difference (lowest temperature) was measured on the leeward side, at 3 m from SRC-strip (0.9 °C), and the greatest difference (highest temperature) at 40 m (2.2 °C). On the cloudy day, the temperatures were very similar over the crop alley and slightly higher than in the open field, with differences from 0.6 to 1.1 °C. On the sunny day, the temperature differences to the open field were positive and higher than on the other days, and differences between measurement points were greater (differences from 1.7 to 4.4 °C).

Concerning the RH, during the morning hours of all days, the differences to the ACS mean (crop alley + SRC-strip) were around 0 % in the SRC-strip, negative at 3 m (-1.9 %) and positively the highest at 48 m (2.7 %) (see fig. 3.5 (b)). On the cloudy day, the difference to the ACS mean was negative in the SRC-strip (-1.4 %), whereas the values stayed around 0 % over from 3 to 48 m. Conversely, on the sunny day, the difference was positive in the SRC-strip (2.4 %) and at 48 m (4.5 %), showing there higher RH compared to the ACS mean. The greatest negative differences on this day (lowest RH) were measured at 3 m (-3.6 %) and 11 m (-3.7 %). During the midday hours, the RH was in general higher in the SRC-strip than in the crop alley, as the greatest positive differences were measured mostly there. Considering all days, the greatest negative difference (lowest RH) was measured at 11 m (-1.1 %), followed by 3 m and the middle points. On the cloudy day, the greatest negative difference (lowest RH) was measured in the middle (-1.2 %) and the greatest positive difference (highest RH) was measured in the SRC-strip and at 48 m (0.9 %). When considering only the values of the sunny day, the greatest positive difference (highest RH) was observed in the SRC-strip (5.2 %). The difference at 48 m was around 0 %, whereas negative differences (low RH) were measured at 3 and 11 m (-1.7 %) and in the middle (-2.2 %). During the afternoon, considering all days, the greatest positive differences (highest RH) was measured at 3 m (1.1 %). On all days and the cloudy day, the other measurement points (11 m, middle, 48 m and 3 m for the cloudy day) showed differences around 0 %. On the sunny day, the differences in the SRC-strip (1.3 %) and at 3 m (2.7 %) were positive but decreased below the mean over the crop alley down to the greatest negative difference at 48 m (-2.1 %).

The pET was approximately the same over the crop alley in the morning hours (around 0.5 mm d^{-1} on the cloudy day and around 1 mm d^{-1} considering all days), except on the sunny day, where it was slightly higher at 3 m and 11 m (1.8 mm d^{-1}) (see fig. 3.5 (c)). In the noon and afternoon hours, the differences between all days and the sunny/cloudy conditions were quite remarkable but noticeable differences over the crop alley were observed only on the sunny day. In sunny conditions, the highest pET was measured at 3 m, 11 m and in the middle (7.3 mm d^{-1}), whereas the lowest was measured at 48 m (6.7 mm d^{-1}). The values of the cloudy day ranged from 1.6 to 1.8 mm d^{-1} over the crop alley, and considering all days, they ranged from 3.9 to 4.2 mm d^{-1}. In the afternoon, this trend was inverted: on the sunny day, the pET was the lowest at 3 m (5.7 mm d^{-1}) and increased over the field up to 48 m (6.9 mm d^{-1}). On the cloudy day, the pET stayed around 1.5 mm d^{-1} over the crop alley. Considering all days, the lowest values were calculated at 3 m (3.4 mm d^{-1}) and were around 3.7 mm d^{-1} at the other points.

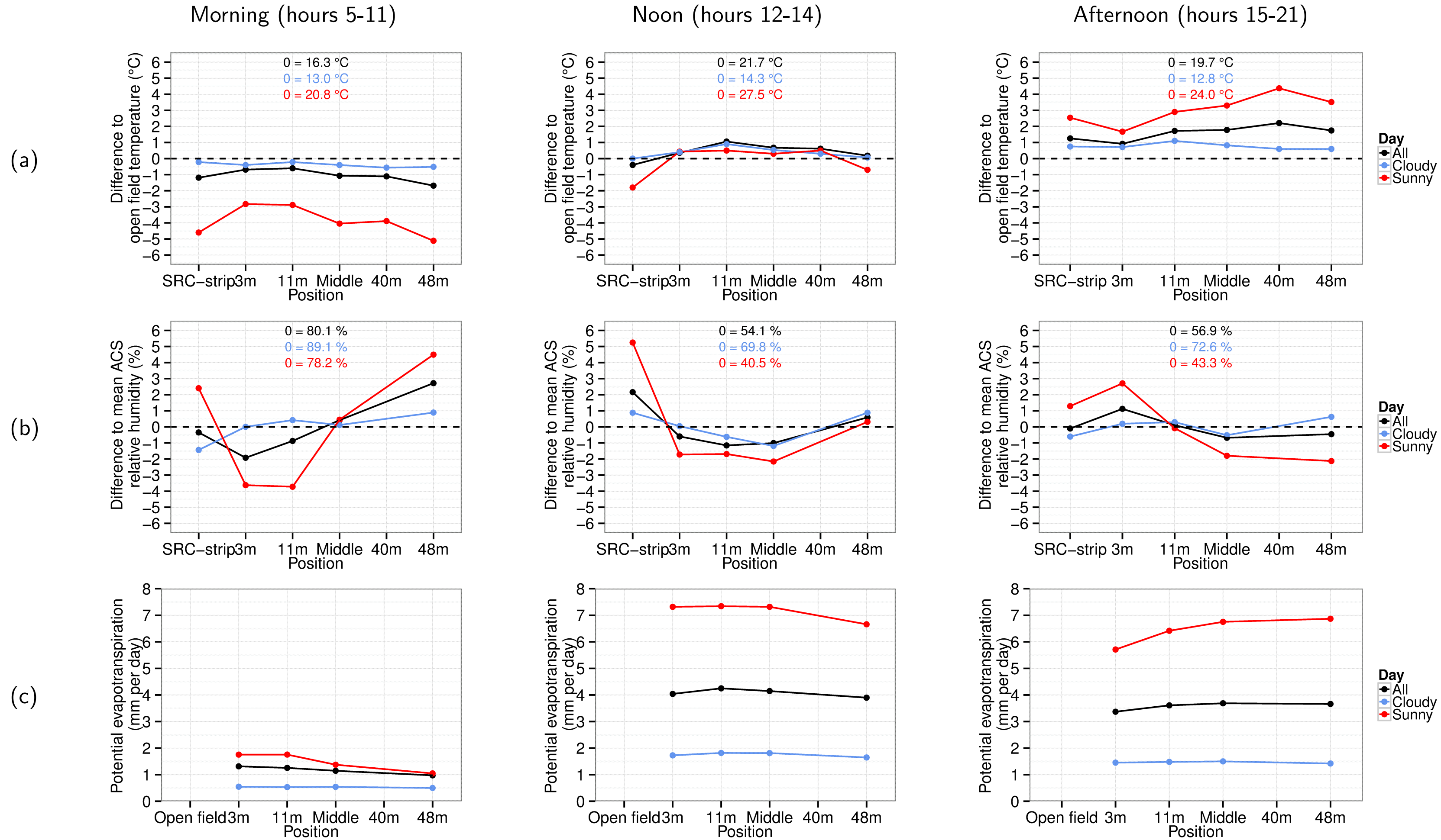


Figure 3.5. *Differences to the open field mean air temperature (°C, a), the alley-cropping system (ACS) mean relative humidity (%, b) and the potential evapotranspiration (mm d^{-1}, c), in the morning, at noon and in the afternoon, for all days, a sunny day and a cloudy day in 2013, at the different measurement positions (0 = open field/ACS mean). Sensors failed on 06/14 (hours 14-15) and from 06/26 (hour 9) to 07/06 (hour 1).*

Summer 2014

Concerning the air temperature parameter in the morning hours of all days and the sunny day, the differences to the open field mean were for both data sets around 0 °C at 48 m, whereas the greatest positive differences (highest temperatures) were measured for all days in the SRC-strip (0.4 °C) and at 11 m (0.5 °C) and on the sunny day in the middle of the crop alley (0.4 °C) (see fig 3.6 (a)). On the cloudy day, all differences were around 0 °C. In the midday hours, the differences to the open field mean followed approximately the same trend on all days, the sunny and cloudy day: they were around 0 °C at 3 m and positive at the other points. Between 11 m and 48 m, the temperature differences stayed around 0.3 - 0.4 °C when considering all days, whereas they ranged from 0.2 to 0.7 °C on the sunny day, and varied from 0.1 to 0.4 °C on the cloudy day. In the afternoon, all differences were also around 0 °C for all days, the sunny and cloudy day, except in the SRC-strip where the difference was slightly greater when considering all days (0.3 °C).

Concerning the RH, in all conditions and all days, the greatest positive differences (highest RH) were reached at 3 m, whereas the greatest negative differences (lowest RH) were reached in the SRC-strip (see fig. 3.6 (b)). In the morning hours, the three data sets showed the same trend, even though the greatest negative differences were measured in all days (-4.2 % in the SRC-strip, 1.4 % at 3 m and then varying between -0.9 and 0 % up to 48 m). On the cloudy day, the lowest difference value was -2.8 % in the SRC-strip, the highest 1.3 % at 3 m and decreased from 3 m to 48 m down to 0.2 %. On the sunny day, the lowest difference value was -1.8 % in the SRC-strip, the highest 3.4 % at 3 m, and it varied around 0 % for the rest of the field. At noon, the cloudy day showed a great positive difference at 3 m (6.3 %), a negative difference in the SRC-strip (-3.1 %) and differences around 0 % over the rest of the crop alley. All days and the sunny day showed similar differences to the open field value between 11 m and 48 m, varying from -1.1 to -0.6 %. In the SRC-strip, the greatest negative difference was observed when considering all days (-4.4 %), and the smallest on the sunny day (-1.5 %). At 3 m, the difference was around 0 %, when considering all days and the sunny day. In the afternoon, the same trend as in the morning was observed, as the differences of each data set were very similar. The greatest negative differences were -3.3, -1.8 and -2.0 % (in the SRC-strip), and the greatest positive differences were 1.3, 2.9 and 1.7 (at 3 m), respectively for all days, the cloudy and sunny day. The differences of the rest of the field stayed around 0 %.

The pET did not vary much between the measurement points but more between measurement conditions: except for the afternoon hours, the pET was always higher on the sunny day and all days than on the cloudy day (see fig. 3.6 (c)). A slightly lower pET was detected at 3 m for all data sets. In the morning hours, the pET was around 0 mm d^{-1} on the cloudy day, around 1.1 - 1.3 mm d^{-1} over all days and ranged from 2.2 mm d^{-1} (3 m) to 2.7 mm d^{-1} (middle) on the sunny day. At noon, the pET was the highest in sunny conditions, remaining around 7.0 mm d^{-1} by all points. No fluctuation between measurement points and to the open field were observed when considering all days (values around 3.0 mm d^{-1}). The lowest pET values were calculated on the cloudy day, ranging from 0.3 mm d^{-1} (3 m) to 0.8 mm d^{-1} (open field, 11 m, middle and 48 m). Considering all days, the pET was the highest in the afternoon hours (1.9 mm d^{-1}). On the cloudy day, the pET was the lowest, ranging from 0.2 mm d^{-1} at 3 m to 0.4 mm d^{-1} for the open field, 11 m, middle and 48 m points. On the sunny day, values ranged from 1.3 to 1.4 mm d^{-1}.

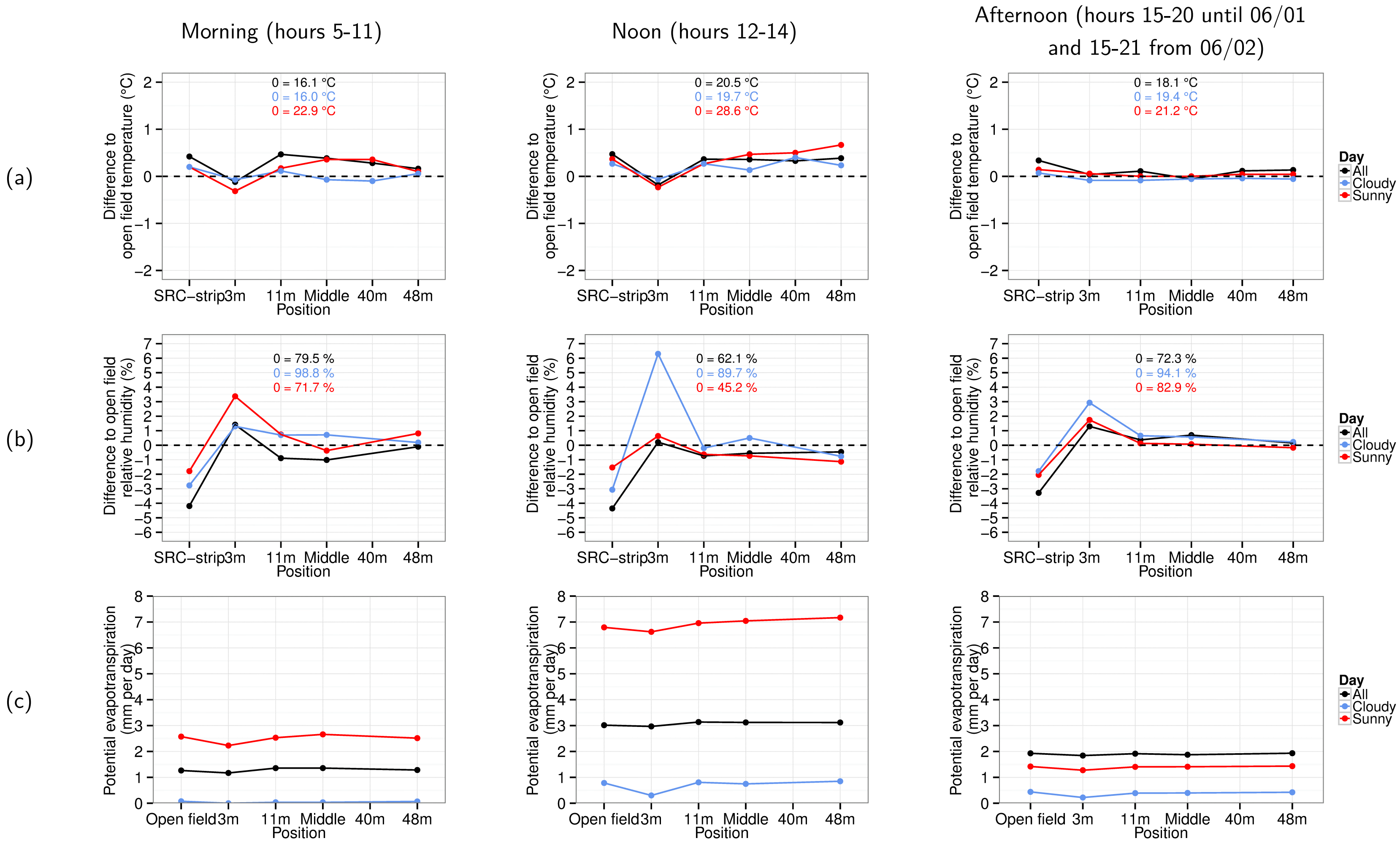


Figure 3.6. *Differences to the open field mean air temperature (°C, a), relative humidity (%, b) and the potential evapotranspiration (mm d^{-1}, c), in the morning, at noon and in the afternoon, for all days, a sunny day and a cloudy day in 2014, at the different measurement positions (0 = open field mean). Sensors failed on 06/05, 08 (hour 14-16), 12 (hour 22-23), 13, 15 (hour 8), 18 (hour 6), 20 (hour 10-12), 24 (hour 13), 25, 26 and 07/02, 06.*

Soil water tension

In fig. 3.7, the mean daily soil water tension over the soil profile (15, 30, 60 and 90 cm) is presented for the measurements in the short rotation coppice (SRC)-strip (a), at 3 m from the SRC-strip (b) and in the middle of the crop alley (c). In the SRC-strip, the soil water tension was increasing uniformly over the soil depth profile from the 06/01/13 to the 07/11/13 (on average, from 2 to 110 cBar). Three meters away from the SRC-strip, the tension increased at 30 cm and 60 cm depth (from 0 to 114 cBar at 30 cm and 72 cBar at 60 cm depth) and only slightly at 15 cm (from 0 to 23 cBar). The soil water tension stayed around 0 cBar at 90 cm depth. In the middle of the crop alley, at 25.5 meters away from the SRC-strip, the tension reached its maximum (200 cBar) at the end of the measurement period at 15 cm depth, and was still quite high at 30 cm depth (101 cBar). However, the maximum value reached at 60 and 90 cm depth was only 14 cBar. Under the SRC-strip and in the middle of the crop alley, periodic recessions of the soil water tension were observed.

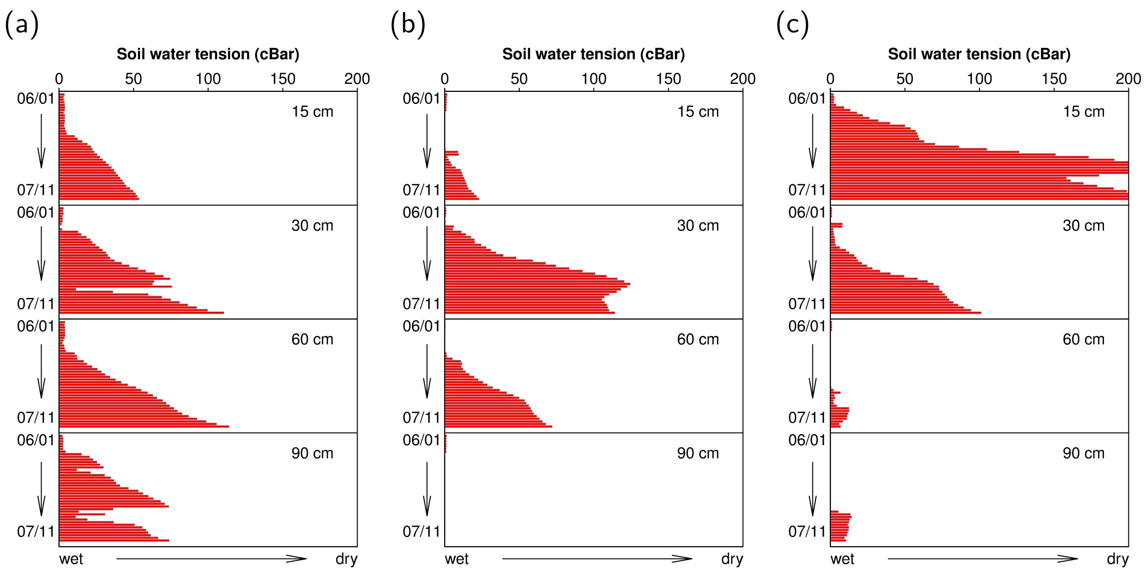


Figure 3.7. *Mean daily soil water tension (cBar) from 06/01/13 to 07/11/13, at 15, 30, 60 and 90 cm soil depth, in the SRC-strip (a), in the crop alley at 3 m from the leeward SRC-strip (b) and in the middle of the crop alley (c).*

3.1.2 Reduction of solar radiation

In the narrow alley of the winter wheat, in the growing season 2012/13, the relative solar radiation (to the open field solar radiation) was quite low (54 %) at 3 m from the western alley boundary, then increased to 91 % at 14 m and was the highest (98 %) in the middle of the crop alley (see fig. 3.8 (a)). Thus, it never reached 100 %. On the windward side, the solar radiation was 97 % at 32 m from western alley boundary and decreased to 80 % at 45 m. In the narrow alley of the winter barley, the incoming solar radiation was not as low as in the winter wheat (67 %) at 3 m from western alley boundary and was 75 % at 45 m but it also reached only 99 % in the middle of the crop alley. In the wide alley of the winter wheat, the relative solar radiation was around 60 % at 3 m and reached 100 % from 30 m from the western alley boundary to the next alley boundary, as no short rotation coppice (SRC)-strip was existent on the windward side (see fig. 3.8 (b)). In comparison, the relative solar radiation in the wide alley of the winter barley was 67 % at 3 m from the western alley boundary, 77 % at 93 m and by 100 % from 27 m to 63 m.

During the growing season 2013/14, the relative solar radiation in the narrow winter wheat alley was quite high at 3 m (95 and 99 %, respectively from the western and eastern alley boundary) and 100 % from 7 m to 43 m from the western alley boundary (see fig. 3.8 (c)). It was similar for the narrow alley of the winter barley, where the relative solar radiation reached 91 and 99 %, respectively at 3 m and 45 m from the western alley boundary and 100 % between 8 and 43 m. In the wide alley of the winter wheat, the relative solar radiation reached 98 % at 3 and 93 m from the western alley boundary and 100 % between 6 m and 90 m (see fig. 3.8 (d)). In the wide winter barley alley, only one SRC-strip was present on the leeward side. The relative solar radiation was 97 % at 3 m and reached 100 % from 7 m to the next alley boundary.

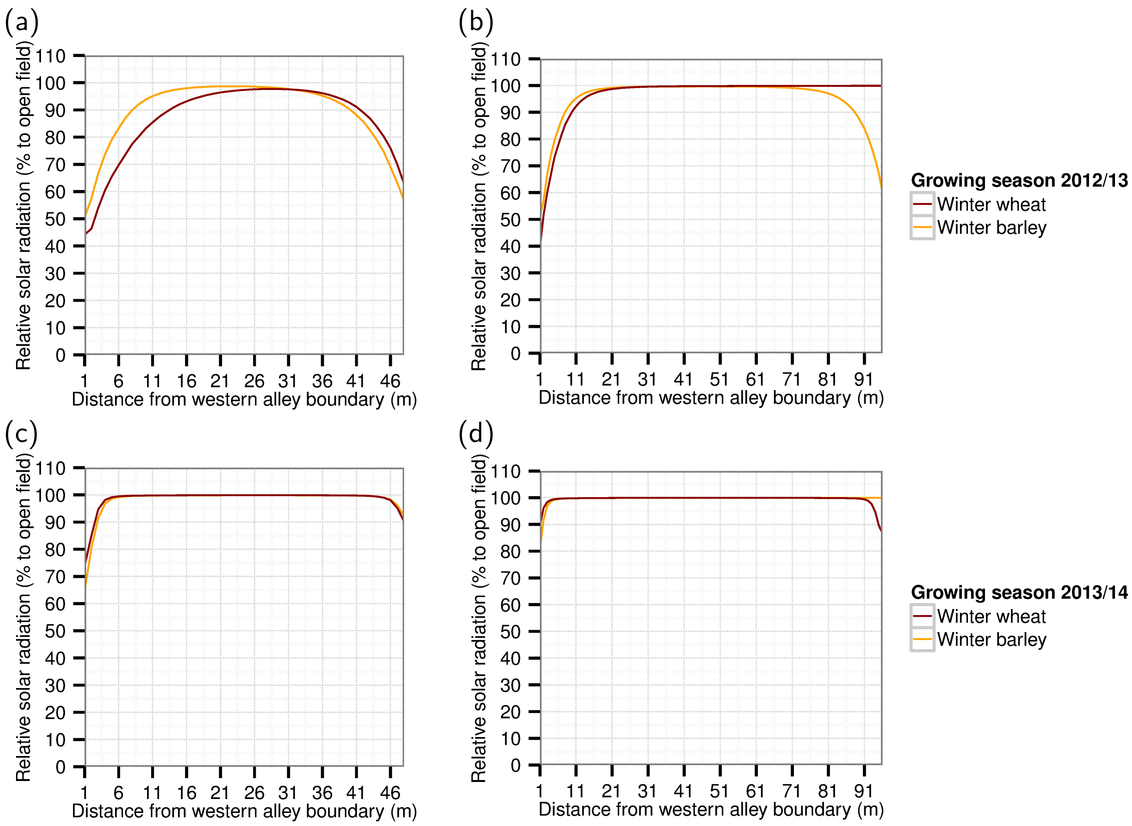


Figure 3.8. *Relative solar radiation (% of solar radiation incoming in the open field) from the western to the eastern alley boundary for the winter barley and winter wheat in the narrow (a) and wide (b) alleys in growing season 2012/13 and in the narrow (c) and wide (d) alleys in growing season 2013/14, calculated from the sowing to the harvest dates.*

3.1.3 Leaf ground coverage

Generally, in the narrow alley of the winter wheat, the highest leaf coverages were observed on the leeward side and decreased with increasing distance from the short rotation coppice (SRC)-strip (see fig. 3.9 (a)). The leaf coverages were 92 % (2012) and 98 % (2013) at 3 m from the leeward SRC-strip, but were higher in 2012 (63 %) than in 2013 (46 %) at 8 m. At 16 m from the leeward SRC-strip, the leaves covered the ground only during autumn 2013. At 43 and 48 m, no data were available in 2012 and no leaves were observed there in 2013. For the wide alley of the winter wheat similar results were observed but leaves were blown less far into this alley than in the narrow one (see fig. 3.9 (b)). They covered only 70 % of the ground at 3 m in 2012, 96 % at 3 m and 38 % at 8 m in 2013.

In the narrow alley of the winter barley, the leaves covered the soil on both sides of the SRC-strip, leeward and windward (see fig. 3.9 (c)). In autumn 2012, a higher coverage was observed on the windward than on the leeward side, 27 % at 3 m and 76 % at 48 m from the leeward SRC-strip. Conversely, in autumn 2013, 81 % leaf coverage at 3 m and 7 % at 8 m from the leeward SRC-strip were observed, whereas only 26 % was observed at 48 m. In the wide alley of the winter barley, only few leaves fell on the leeward and the windward sides in 2012 (36 and 13 %, respectively) (see fig. 3.9 (d)). Considerably more leaves covered the ground in 2013, however, only on the leeward side (76 % at 3 m and 14% at 8 m).

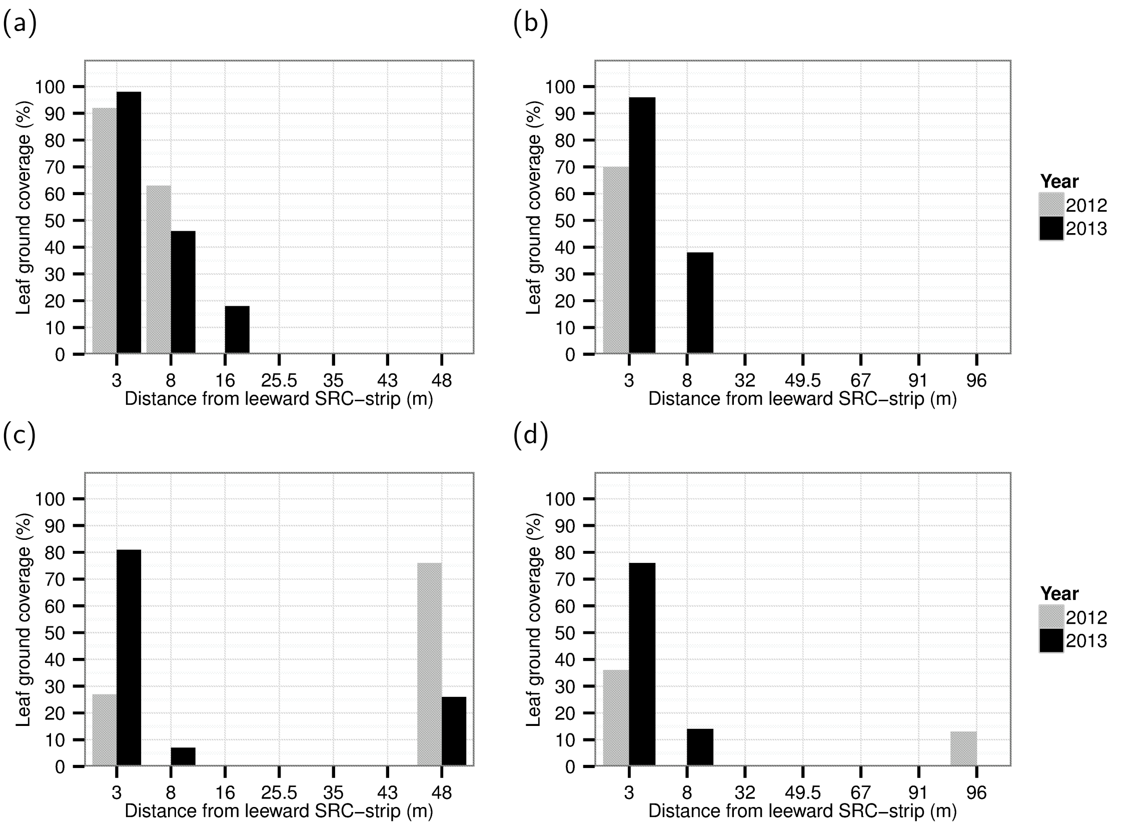


Figure 3.9. *Leaf ground coverage (%) at several distances from the leeward SRC-strip in the narrow (a) and wide (b) alleys of the winter wheat and in the narrow (c) and wide (d) alleys of the winter barley, assessed during autumn 2012 and 2013.*

In the following pictures (fig. 3.10), leaf coverages of 98 % and of 27 % are represented as an example.

(a)

(b)

Figure 3.10. *Pictures of the leaf ground coverage at 3 m: 98 % (a) on the narrow alley of winter wheat in 2013 and 27 % (b) on the narrow alley of winter barley in 2012.*

From the collected leaves out of the baskets next to the 8 m high SRC-strip, 7 g m^{-2} dry matter of leaves were weighed at 2 m from the strip on the windward side, 46 g m^{-2} inside the SRC-strip (between the fifth and sixth row from west to east) and 33 g m^{-2}, 12 and 3 g m^{-2} respectively at 2, 6 and 10 m from the SRC-strip on the leeward side. More leaves were weighed inside the 3-year rotation cycle SRC-strip: 56 g m^{-2}, between the fifth and sixth row from west to east. However, at 1 m on the windward side, only 1 g m^{-2} was collected. At 1, 3 and 5 m from the SRC-strip on the leeward side, respectively 16, 5 and 3 g m^{-2} dry matter of leaves were weighed.

3.1.4 Summary of the modifications of growing conditions in the alley-cropping system

The greatest wind velocity reduction was observed during summer 2013, in the narrow alley and with west winds, where 50 % reduction was observed up to the middle of the crop alley. Except for east winds, the lowest wind velocities were measured on the leeward side of the short rotation coppice (SRC)-strip and the highest on the windward side. Less wind velocity reduction was observed during winter 2013, and in this period, the greatest reduction was also given with west winds. Moreover, the wind velocity was more reduced behind several strips than behind one. However, no reduction was observed in 2014.

Concerning the air temperature and relative humidity (RH), greater differences to the open field mean between measurement points over the crop alley were observed in summer 2013 than in summer 2014, especially on sunny days. In 2013, in the morning hours, the temperature and the potential evapotranspiration (pET) were in general the highest on the leeward and the lowest on the windward side and in the SRC-strip, especially on the sunny day. The RH followed the opposite trend. Furthermore, the temperature was lower in the crop alley than in the open field, with differences from the mean temperature in the open field up to 5.1 °C. In the midday hours, the air temperature, RH and pET values were quite similar in the open field and over the crop alley, but very high pET values were calculated on the sunny day, compared to the other days. In the afternoon, the temperature was in general higher in the crop alley than in the open field, especially on the windward than on the leeward side. The RH followed again the opposite trend. The greatest pET was calculated on the sunny day on the windward side. In summer 2014, the main difference over the crop alley was between 3 m and the other measurement points, where lower temperature and pET as well as higher RH were measured than at the other points. The other temperature and RH values of the crop alley and of the open field were quite similar for the different conditions, but the pET values differed between the sunny and cloudy conditions. The values of both, the air temperature and RH, within the SRC-strip were similar to the windward points in the morning hours and to the leeward points in the afternoon hours in 2013. In 2014, the SRC-strip showed the lowest RH values, but similar temperatures than in the crop alley.

Under the SRC-strip, the soil water tension increased likewise over the measurement period at each investigated depth, except for some decreases observed at 30 and 90 cm. At three meters from the SRC-strip, the tension increased over the measurement period mostly at 30 and 60 cm depth, whereas in the middle of the crop alley, it increased mainly at 15 and 30 cm depth. Under the SRC-strip and in the middle of the crop alley, periodic recessions of the soil water tension were observed.

In both years and both crop alleys, the relative incoming solar radiation followed a bell-shaped curve: it was reduced next to the SRC-strip, and increased progressively up to the middle of the alley. The reduction of incoming solar radiation next to the SRC-strip was in general greater and extended further into the crop alley in season 2012/13 (approximately 20 m) than in season 2013/14 (approximately 5 m), especially on the leeward side of the winter wheat narrow alley. No shade was cast on the windward side of the winter wheat wide alley in 2012/13 and on the winter barley wide alley in 2013/14. Furthermore, considerably more leaves were observed on the ground next to the SRC-strips (mostly up to 8 m) than in the middle of the crop alley, especially on the leeward side and in the autumn 2013. However, the greatest amount of leaves was weighed within the SRC-strip.

3.2 Modifications of yield and quality parameters in crop alleys

The following section is divided into two parts: the results of the spatial analysis of yield and grain moisture content and the results of yield components, plant development, aphid infestation and hectoliter weight.

3.2.1 Grain yield and grain moisture content spatial distribution

In the following sections, the results of interpolation of the soil conductivity values will be firstly presented. Then, the measured and predicted yields/grain moisture contents (MCs) of summer barley in 2008 and of winter wheat and winter barley in 2013 and 2014 will be represented, depending on the distance from leeward SRC-strips. In each fig. (3.12-3.21), the yield/MC distribution of one year and of one crop will be presented, firstly in narrow (a) and wide (b) alleys of the alley-cropping system (ACS), and then in the narrow (c) and wide (d) subplots of the open field (only 2013 and 2014). The statistical model results are available in appendix D.1.

Soil conductivity

In table 3.3, the mean soil apparent electrical conductivity corrected to 25°C values (EC_{25}), used to calculate the normalized soil apparent electrical conductivity corrected to 25°C (nEC_{25}), are presented. The absolute EC_{25} values varied greatly depending on the crop which was cultivated on the field.

Table 3.3. *Mean soil apparent conductivity corrected to 25°C (EC_{25}, in mS m^{-1}) measured in the crop alleys and open fields cultivated with the same crops at the experimental site in Wendhausen.*

Crop	Crop alley and open field no. (see fig. 2.1)	EC_{25} (mS m^{-1})
Winter oilseed rape	3,7,C2	30.72
Winter wheat	5,8,C3	25.51
Winter barley	2,6,C1	63.27
Fava bean	1	30.97
Maize	4	71.88

In fig. 3.11, the map of the interpolated nEC_{25} data is presented and shows a great variability of the data (from 0.35 to 1.36), suggesting a high soil heterogeneity within one field. Moreover, the three main soil zones Pelosol, Pseudogley-Pelosol and Pseudogley-Gley of the experimental site (presented in fig. 2.4) were roughly identified, in the form of an east-west gradient. The Kolluvisol-Gley zone was also identified south-east of the crop alley no. 8.

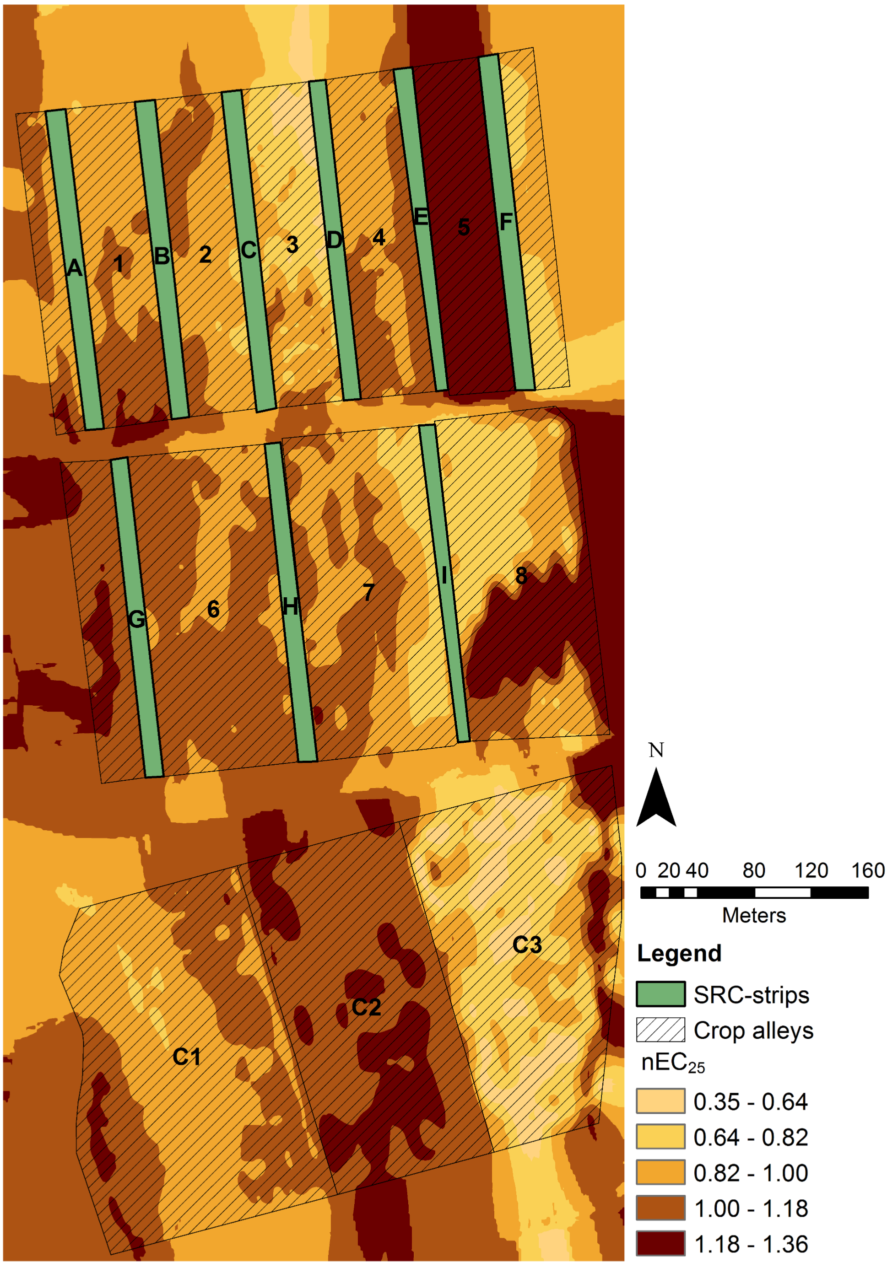


Figure 3.11. *Map of the interpolated normalized soil apparent electrical conductivity corrected to 25°C (nEC$_{25}$) values over the alley-cropping system (crop alley 1-8) and the crop open fields (fields C1-C3) at the experimental site in Wendhausen (different colors of nEC$_{25}$ correspond to the range of one standard deviation, i.e. 0.18).*

Grain yield in 2008

The yield model of 2008 for the summer barley had the significant terms of distance alone and distance in interaction with the wide alley. Moreover, both the smoothers $f_4(nEC_{25i})$ and $f_5(X_i, Y_i)$ were significant. However, the model showed a quite low correlation coefficient (0.30) (see appendix D.1).

The measured yield in the narrow alleys varied greatly around the mean (53.7 dt ha^{-1}), from 16.2 dt ha^{-1} to 91.5 dt ha^{-1} (see fig. 3.12 (a)) and the variability was quite similar over the alleys, even though some extremes were observable around 40 m. The predicted yield was almost a straight line up to the middle of the alleys but decreased slightly below the mean on the windward side (48.5 dt ha^{-1}). In the wide alleys, the mean yield was 54.8 dt ha^{-1} and the values also showed a great range, from 14.6 to 78.2 dt ha^{-1} (fig. 3.12 (b)). The predicted yield showed a slightly higher yield directly on the leeward side (60.0 dt ha^{-1}) and at 51 m (59.6 dt ha^{-1}) and the lowest values on the windward side (46.3 dt ha^{-1}).

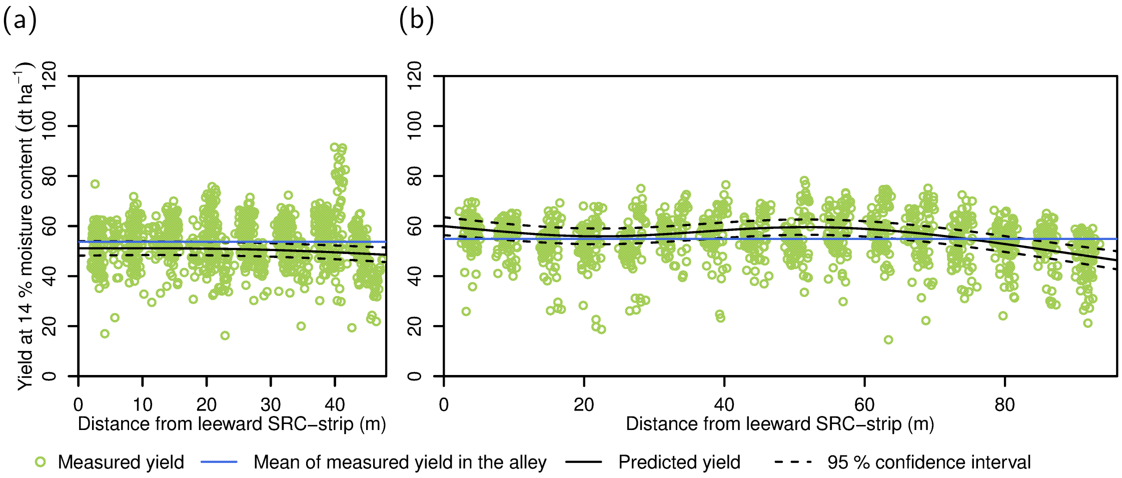


Figure 3.12. *Distribution of the measured and predicted grain yield at 14 % moisture content (dt ha^{-1}) of the summer barley in 2008, from the leeward to the windward short rotation coppice (SRC)-strip, in the narrow (a) and wide (b) alleys of the alley-cropping system.*

Grain yield in 2013

The model used to predict the yield of the winter wheat and barley in the alley-cropping system (ACS) in 2013 showed a significant effect of distance alone, in interaction with the narrow alley and in interaction with winter wheat. Moreover, the smoothers $f_4(nEC_{25i})$ and $f_5(X_i, Y_i)$ were significant. In the model used to predict the yield of the winter wheat and barley in the open fields, only the interaction of distance and the wide subplot and the spatial smoother $f_5(X_i, Y_i)$ were significant for yield spatial distribution. Both models showed a correlation coefficient of 0.67 (see appendix D.1).

In the narrow alley of the winter wheat in the ACS, the predicted and measured yields followed a bell-shaped curve (see fig. 3.13 (a)). The values were below the mean (84.1 dt ha^{-1}) in the first 10 meters close to the short rotation coppice (SRC)-strip, increased gradually above the mean up to reaching their maximum (92.0 dt ha^{-1} for predicted yield and 106.4 dt ha^{-1} for measured yield) in the middle of the alley, and decreased again down to the windward side where they reached a value around the mean. Concerning the wide alley of the ACS, the predicted yield was around the mean on the leeward side (85.8 dt ha^{-1}), the highest at 23 m (104.4 dt ha^{-1}) and the lowest on the windward side (60.7 dt ha^{-1}) (fig. 3.13 (b)).

The measured yield followed a slightly different evolution than the predicted yield: it was slightly below the predicted yield on the leeward side and mainly above on the windward side. Moreover, the measured data showed a greater range from the middle of the alley up to the windward side than on the leeward side. In the open field subplots, the measured and predicted yields were similar over the distance. In the narrow subplot, the mean measured yield was 96.7 dt ha^{-1}, whereas the mean predicted yield was 101.1 dt ha^{-1} (fig. 3.13 (c)). In the wide subplot, the mean measured yield (95.0 dt ha^{-1}) was slightly below the predicted yield (around 100 dt ha^{-1}) (fig. 3.13 (d)).

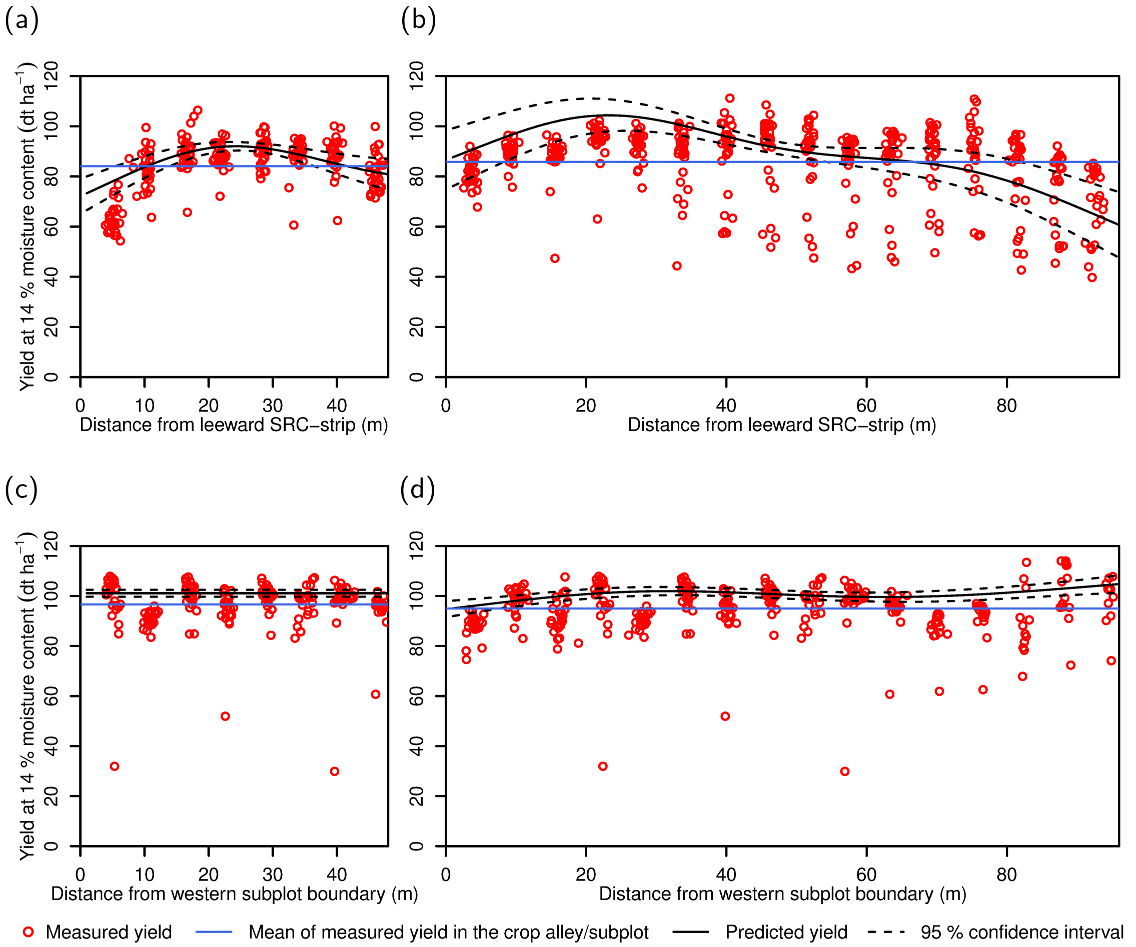


Figure 3.13. *Distribution of the measured and predicted grain yield at 14 % moisture content (dt ha^{-1}) of the winter wheat in 2013, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

In general, the yields measured in the winter barley were lower than the ones measured in the winter wheat (see fig. 3.14). In 2013, the winter barley showed a similar distribution of the predicted yield in the narrow alley than the winter wheat. The predicted yield of the barley ranged in this alley around the measured mean of 69.0 dt ha^{-1} (from 68-69 dt ha^{-1} next to SRC-strips up to 73.3 dt ha^{-1} in the middle of the alley) (see fig. 3.14 (a)). The measured yield was, however, in trend the lowest on the leeward (45.2 dt ha^{-1}) and the highest on the windward side (with the second highest point 93.7 dt ha^{-1} at 39 m). The predicted yield in the wide alley followed the same curve shape as the one in wide winter wheat alley (high on the leeward and low on the windward side), but with less differences between minimum (51.1 dt ha^{-1} at 96 m) and maximum (76.9 dt ha^{-1} at 20 m) (see fig. 3.14 (b)). As for the winter wheat wide alley, the measured yield of the winter barley slightly differed from the predicted yield, being lower next to SRC-strip and higher in the middle of the crop alley (bell-shaped curve), ranging around the mean of 66.1 dt ha^{-1}, from 35.1 dt ha^{-1} to 90.0 dt ha^{-1}. The results in the open field were the same as in the winter wheat, as almost no influence of distance was detected (straight line without slope) (see fig. 3.14 (c)(d)). The mean predicted yield was the same as the measured yield in both subplots (around 73 dt ha^{-1}).

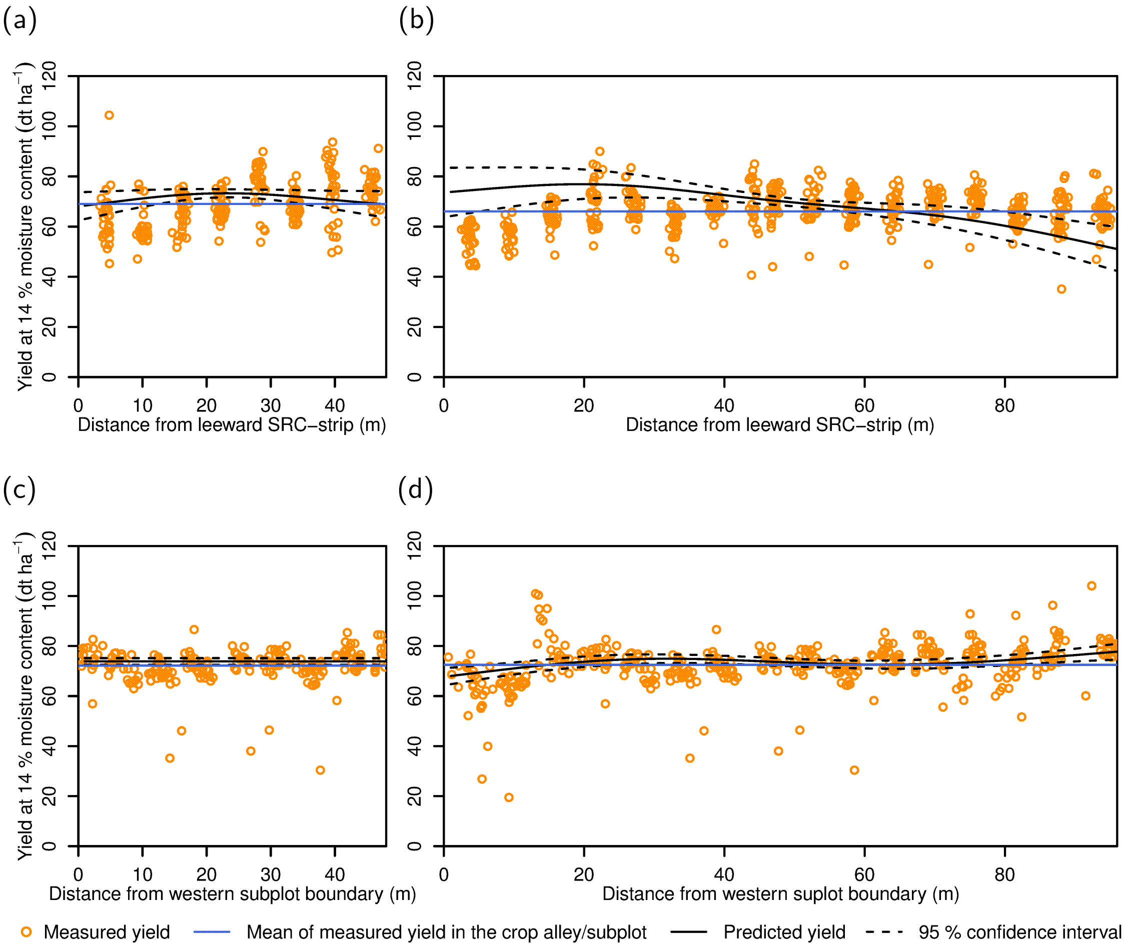


Figure 3.14. *Distribution of the measured and predicted grain yield at 14 % moisture content (dt ha^{-1}) of the winter barley in 2013, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

Grain yield in 2014

In 2014, for the model of the ACS, the smoothers distance alone, in interaction with winter barley and the terms $f_4(nEC_{25i})$ and $f_5(X_i, Y_i)$ were significant. A linear effect of width was detected, as slightly higher values were measured in the wide alleys of both crops in the ACS, however not significant. In the open field, only a significant effect of the spatial smoother $f_5(X_i, Y_i)$ on the yield spatial distribution was detected. The model of the ACS showed a correlation coefficient of 0.48 and the model of the open field, a coefficient of 0.18 (see appendix D.1).

For the winter wheat, the measured values ranged from 59.2 dt ha^{-1} to 102.2 dt ha^{-1} in the narrow alley (mean: 84.4 dt ha^{-1}) (see fig. 3.15 (a)) and from 40.5 dt ha^{-1} to 114.2 dt ha^{-1} in the wide alley (mean: 89.8 dt ha^{-1}) (see fig. 3.15 (b)). The predicted yield followed in general quite well the measured yield: in the narrow alley, it was the lowest on the leeward (83.7 dt ha^{-1}) and the highest on the windward side (89.3 dt ha^{-1}); in the wide alley, the highest predicted yield was 94.3 dt ha^{-1} at 61 m and the lowest around 87-88 dt ha^{-1} on both sides next to the trees. In the open field, the predicted values followed a straight line without slope (see figs. 3.15 (c)(d)). The mean measured yields in the open field were 93.9 and 93.2 dt ha^{-1}, whereas the mean predicted yields were 96.3 and 96.7 dt ha^{-1}, respectively in the narrow and wide subplots.

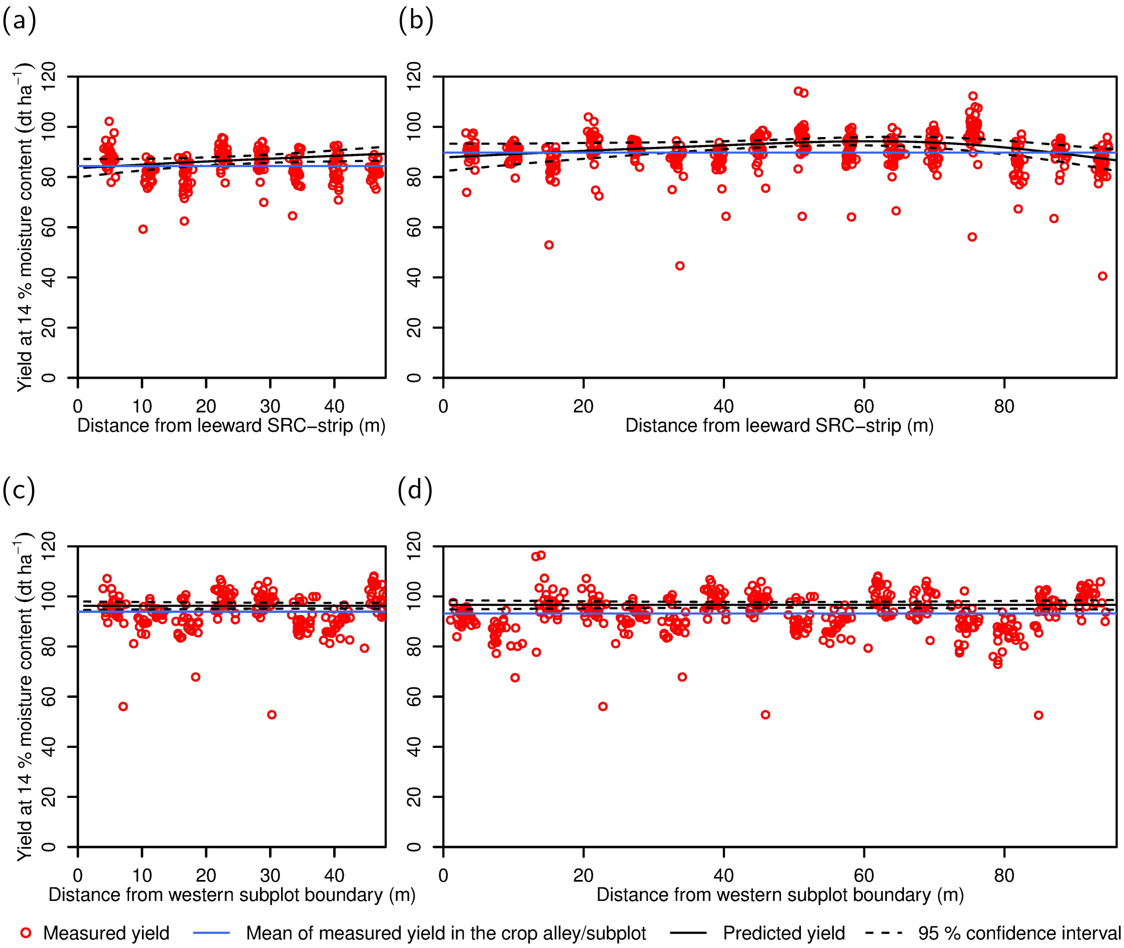


Figure 3.15. *Distribution of the measured and predicted grain yield at 14 % moisture content (dt ha^{-1}) of the winter wheat in 2014, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

In the narrow and wide alleys of the winter barley, the predicted and the measured values were lower next to the SRC-strips than in the middle of the crop alleys (see figs. 3.16(a)(b)). The measured yield ranged from 60.8 dt ha^{-1} to 98.9 dt ha^{-1} (mean: 76.0 dt ha^{-1}) in the narrow alley, and from 51.4 dt ha^{-1} to 121.5 dt ha^{-1} (mean: 90.6 dt ha^{-1}) in the wide alley. The predicted values were on average 66.2 dt ha^{-1} on the leeward side, 80.4 dt ha^{-1} in the middle and 73.6 dt ha^{-1} on the windward side of the narrow alley, and thus followed quite well the measured values. In the wide alley, the predicted yield was mainly above the measured mean, ranging from 85.9 dt ha^{-1} on the windward side up to 104.7 dt ha^{-1} at 25 m. There was no effect of distance in the open field, where the measured mean was 87.7 dt ha^{-1} and the predicted mean was 91.8 dt ha^{-1} in both subplots (see figs. 3.16(c)(d)).

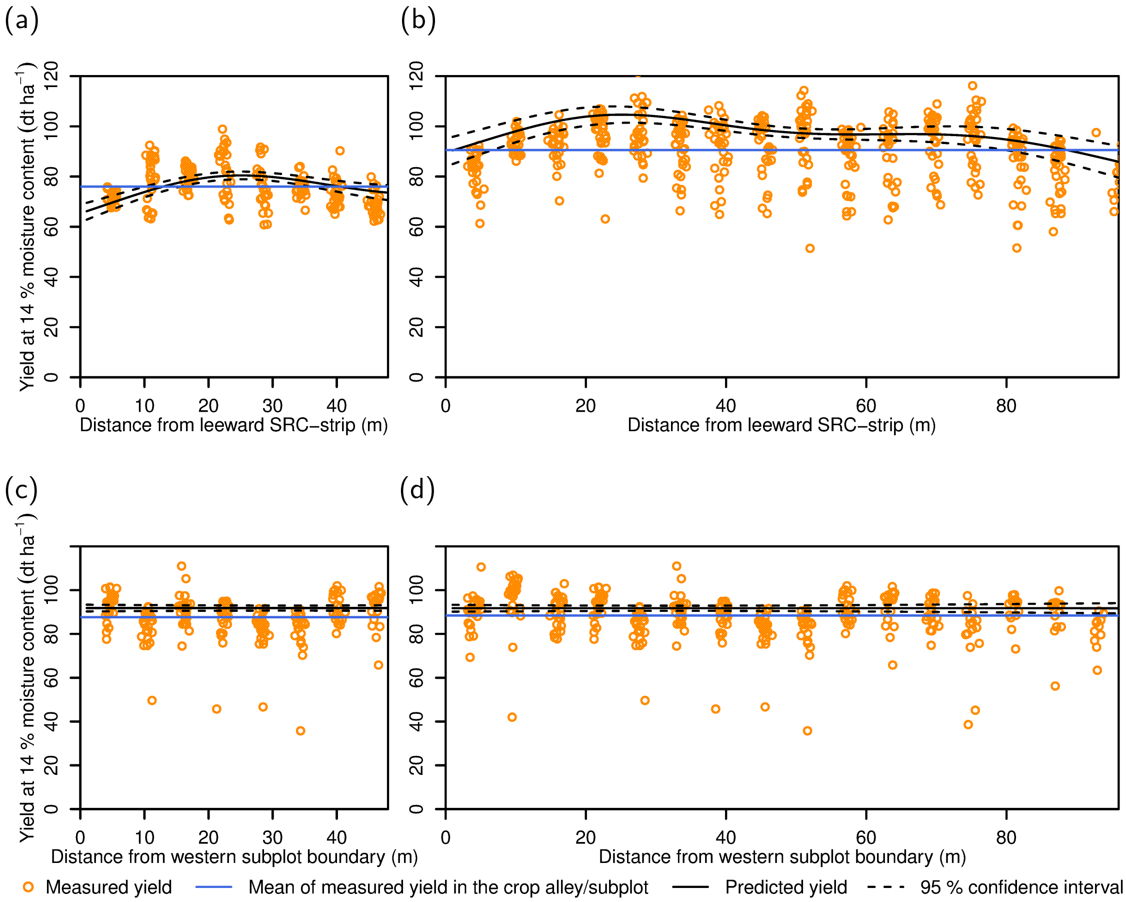


Figure 3.16. *Distribution of the measured and predicted grain yield at 14 % moisture content (dt ha^{-1}) of the winter barley in 2014, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

Grain moisture content in 2008

Similarly to the yield model of 2008, the model fitting the grain moisture content (MC) of the summer barley in 2008 had distance and distance in interaction with the narrow alley as significant smoothers. The smoother $f_5(X_i, Y_i)$ was also significantly involved, but nEC_{25} was only included as a linear factor. The model showed a correlation coefficient of 0.22 (see appendix D.1).

In general, the measured and predicted grain MC was slightly higher next to the SRC-strips than in the middle of the alleys (see fig. 3.17) and thus followed an inverted curve shape than the yield. In the narrow alleys, the mean measured MC was 16.8 % and the measured values ranged between 15.2 and 22.3 % (fig. 3.17 (a)). However, the predicted MC did not vary much: it followed the measured mean over the alley and was only slightly above it on the leeward (17.3 %) and on the windward side (17.1 %). In the wide alleys, the measured values varied less around the mean (16.3 %) than in the narrow alleys, even though extreme values were detected (minimum: 15.0 % and maximum: 23.6 %). The predicted values followed the measured mean over the alley, and were only slightly higher on the leeward and on the windward side (16.7 % for both sides) (fig. 3.17 (b)).

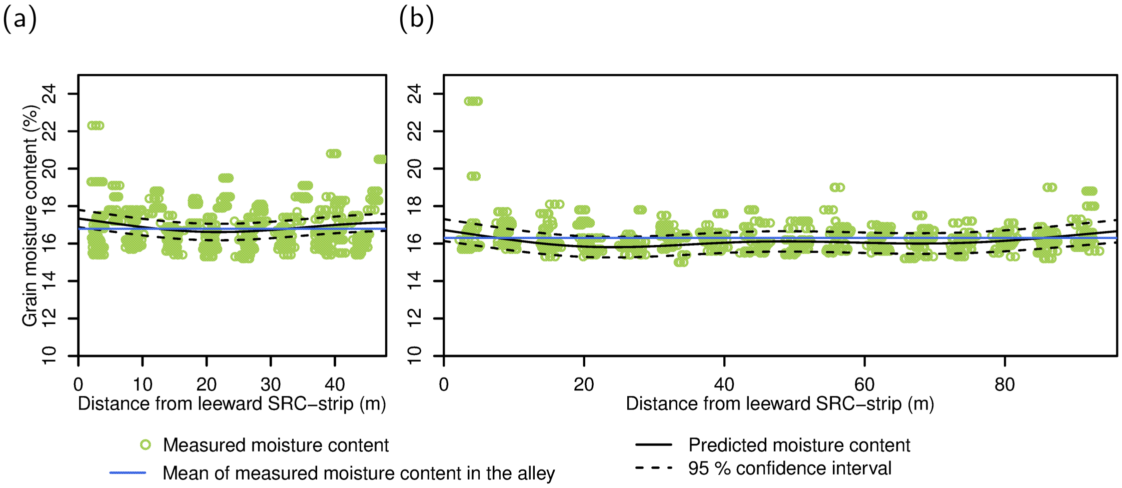


Figure 3.17. *Distribution of the measured and predicted grain moisture content (%) of the summer barley in 2008, from the leeward to the windward short rotation coppice (SRC)-strip, in the narrow (a) and wide (b) alleys of the alley-cropping system.*

Grain moisture content in 2013

In the model fitting the grain MC in the alley-cropping system (ACS) for 2013, the smoothers distance alone, in interaction with the narrow alley, in interaction with the crop winter barley and the normalized soil apparent electrical conductivity corrected to 25°C (nEC_{25}) as a linear factor were significant. The spatial smoother $f_5(X_i, Y_i)$ was not included in this model. The model used to predict the distribution of grain MC over the open field had two significant terms: the distance from SRC-strip in interaction with the crop winter barley and the spatial smoother $f_5(X_i, Y_i)$. Each of these models showed a high correlation coefficient: 0.95 for the ACS and 0.86 for the open field (see appendix D.1).

In this harvest year, in the winter wheat alleys of the ACS, the mean grain MC was in general higher in the narrow alley (19.4 %) than in the wide alley (17.7 %). Furthermore, the MC was higher next to the short rotation coppice (SRC)-strips than in the middle of the alleys, especially on the leeward side of the narrow alley (maximum measured MC 23 %) (see fig. 3.18 (a)), where the data spread was the greatest. The predicted MC in the narrow alley ranged from its maximum (20.5 %) on the leeward side up to its minimum (18.5 %) in the middle of the alley and was 19.8 % on the windward side, matching quite well the observed values. In the wide alley, the highest MC values were observed on the leeward side (measured MC 20 % and predicted MC 19.2 %) (see fig. 3.18 (b)). From approximately 20 m from the SRC-strip, the measured and predicted values stayed around the measured mean over the rest of the alley. In the open field, the predicted and measured MC of both subplots remained at the value of measured mean (16.1 %) over the distance from the western boundary (see figs. 3.18 (c)(d)).

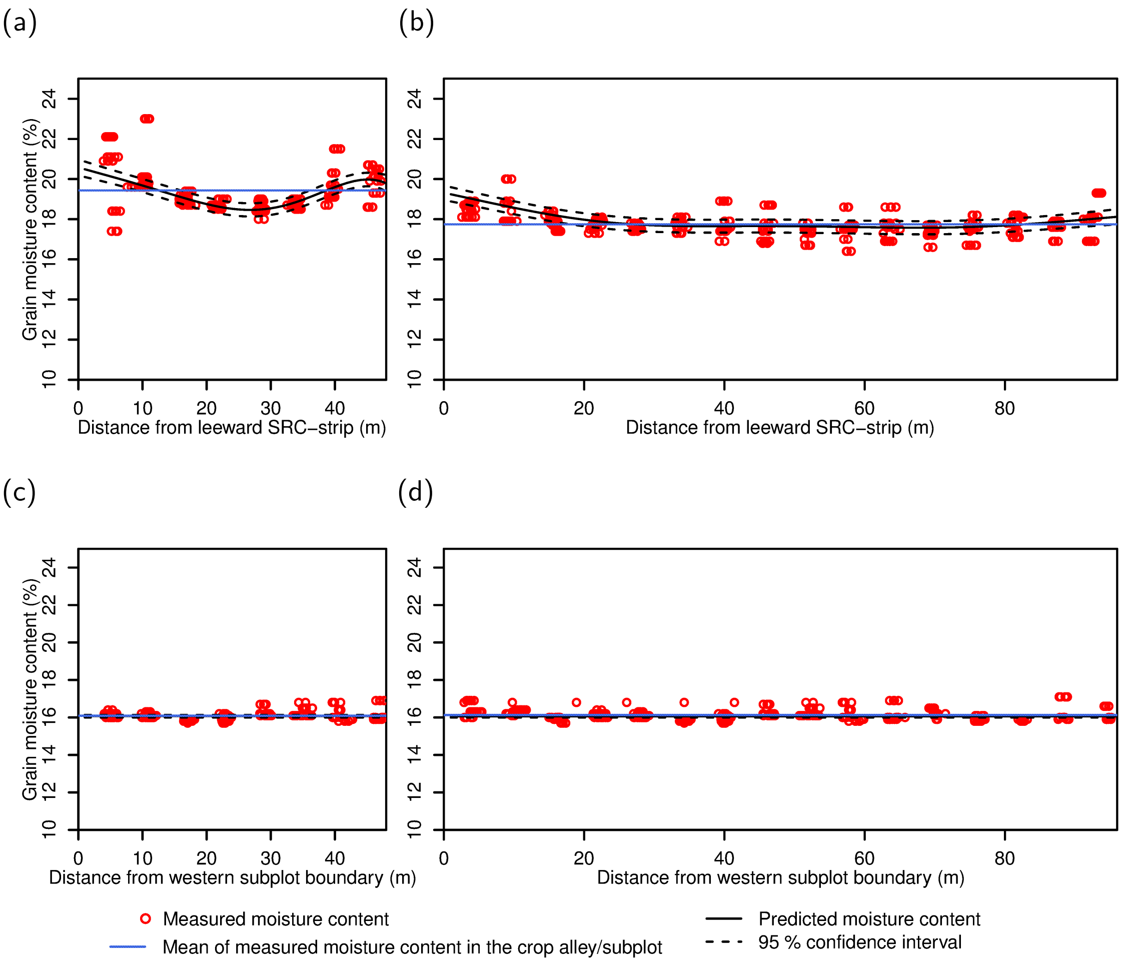


Figure 3.18. *Distribution of the measured and predicted grain moisture content (%) of the winter wheat in 2013, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

Concerning the MC in the winter barley in the ACS in 2013, the highest values were in general observed on the windward sides in both alleys (see fig. 3.19). In general, the mean measured MC was also higher in the narrow alley (14.1 %) than in the wide alley (13.2 %). In the narrow alley, the minimum measured value (13.2 %) was observed on the leeward side, whereas the minimum predicted value was calculated in the middle of the alley (13.5 % at 25 m) (see fig. 3.19 (a)). The highest measured value in this crop alley (16.0 %) was observed around 40 m and the highest predicted value (15.2 %) at 45 m. In the wide alley, the measured and predicted MC remained around the measured mean (around 13 %) up to 83 m, and then the predicted MC increased up to 14 % on the windward side, where the maximum MC value (15.3 %) was calculated (see fig. 3.19 (b)). As for the winter wheat, the MC of the winter barley in the open field was the same over the distance (straight line without slope), following the measured mean (13.8 % for both subplots) (see figs. 3.19 (c)(d)). However, in the last meters of the wide subplot, the predicted MC increased up to 14.7 % and the maximum measured MC up to 16.5 %.

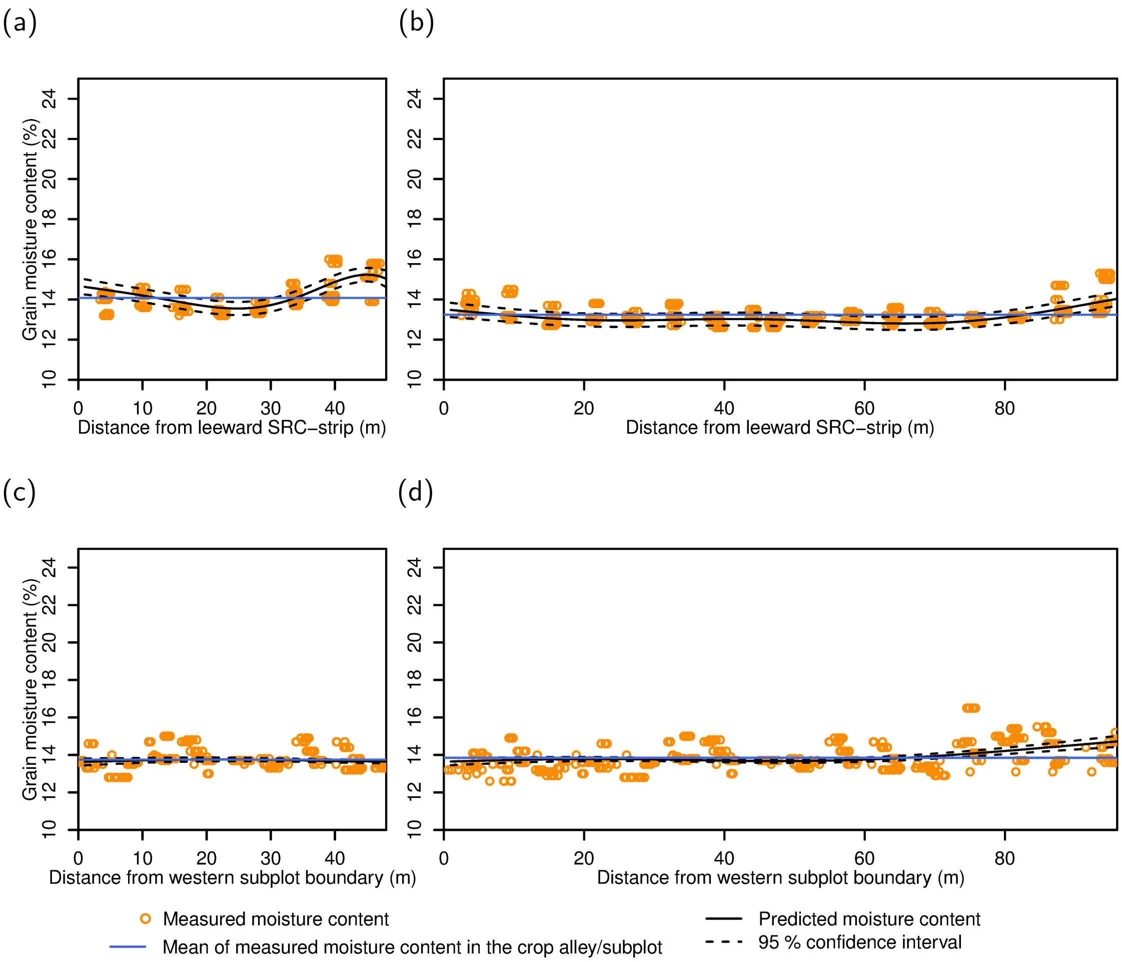


Figure 3.19. *Distribution of the measured and predicted grain moisture content (%) of winter barley in 2013, from leeward to windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

Grain moisture content in 2014

In 2014, the model used to fit the MC data of the ACS had the following significant terms: the smoother distance alone, in interaction with the narrow alley and with the winter barley. The smoother $f_5(X_i, Y_i)$ was also significant. nEC_{25} was integrated as a linear factor, but it was significant for the model. The model used to fit the data in the open field also showed the distance smoother, alone and in interaction with the winter wheat crop as significant. The terms nEC_{25} and $Width$ were significant as linear factors. The smoother $f_5(X_i, Y_i)$ was not integrated in this model. The correlation coefficients were high: 0.71 for the ACS and 0.84 for the open field (see appendix D.1).

The mean MC of the winter wheat in the ACS was similar in the narrow and the wide alley (respectively 15.9 % and 15.6 %). As shown in fig. 3.20, the distribution of the values over the alley was, however, quite different. In the narrow alley, the predicted MC was around the measured mean up to the middle of the crop alley, from where it decreased to 15.2 %, and then increased again up to 16.6 % around 41 m and finally decreased to 14.5 % very close to the SRC-strip (see fig. 3.20 (a)). The measured MC was a little more spread on the leeward side, with the lowest (14.6 %) and the highest (17.4 %) values, but then followed the mean up to the windward side. In the wide alley, the measured and predicted values were very close to the measured mean, except on the leeward side, where the highest predicted MC was calculated (16.2 %). The measured values ranged from 15.1 to 17.4 % (see fig. 3.20 (b)). In the open field, the predicted and measured MC were the highest on the western boundary and decreased progressively, reaching their minimum on the eastern boundary. In the narrow subplot, the predicted MC ranged from 15.6 % to 14.7 %, whereas the measured MC ranged from 14.3 % to 16.4 % (mean: 15.1 %) (see fig. 3.20 (c)). In the wide subplot, the predicted MC ranged from 15.7 % to 14.7 % and the measured MC from 14.0 % to 17.5 % (mean: 15.0 %) (see fig. 3.20 (d)).

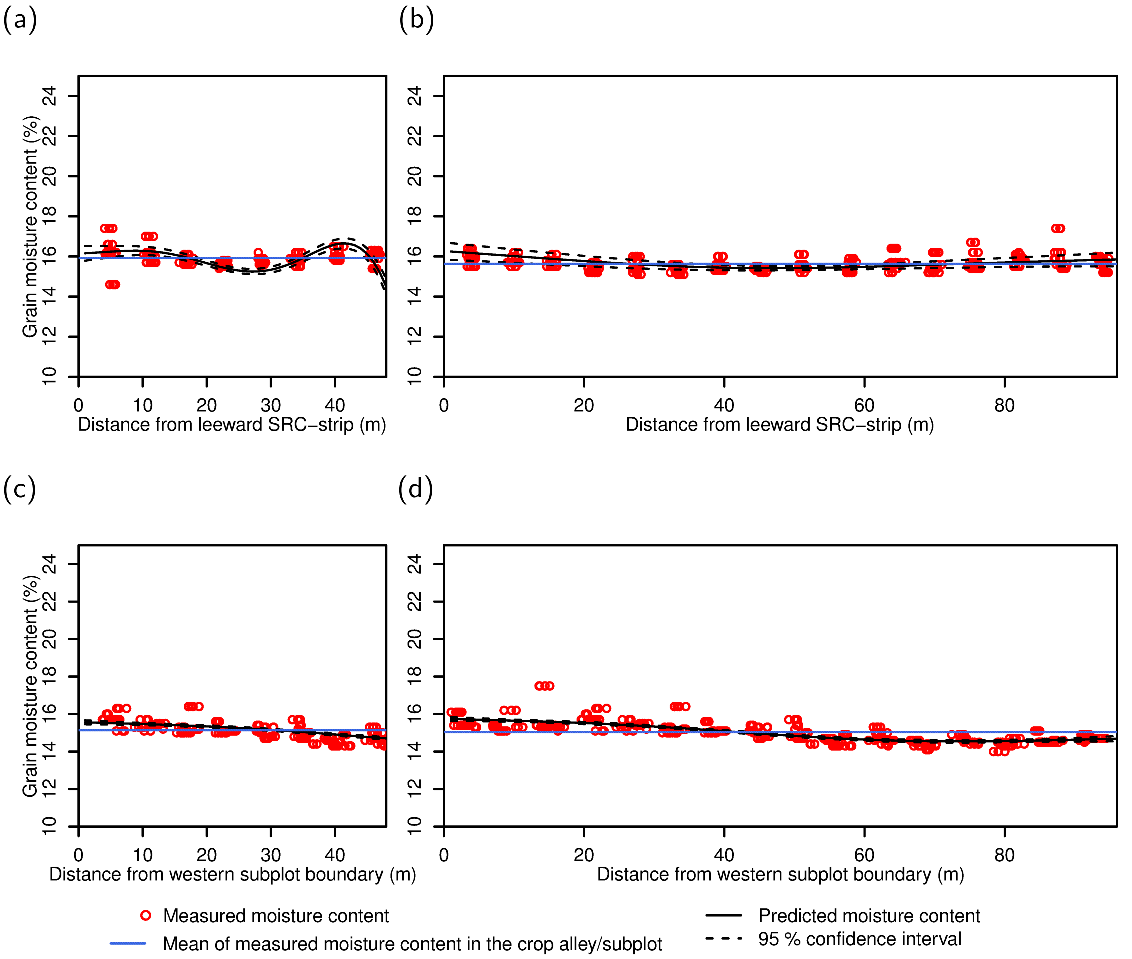


Figure 3.20. *Distribution of the measured and predicted grain moisture content (%) of the winter wheat in 2014, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

Concerning the winter barley, the measured MC showed a great spread in the narrow alley of the ACS (14.0 to 19.3 %), and a higher mean (15.0 %) than in the wide alley, where values ranged from 13.5 to 15.1 % around the mean of 14.0 % (see figs. 3.21 (a)(b)). In the narrow alley, the distribution of the predicted values was also quite different from the one in the wide alley: the values followed the measured mean up to the middle of the alley, decreased to 14.4 % in the middle, increased again to the maximum 16.1 % at 42 m, and decreased quite quickly to the minimum 14.0 % on the windward side. In contrast to the winter wheat, the MC in the wide alley of the winter barley was slightly lower on the leeward side (13.8 %) and increased progressively up to 14.3 % on the windward side. In the open field, the predicted MC followed a straight line without slope in both subplots, having the same value than the measured mean (13.4 % in both subplots) (fig. 3.21 (c)(d)). The measured values were slightly spread around this mean, ranging from 13.1 % to 14.2 % in the narrow subplot, and from 13.0 to 14.9 % in the wide subplot.

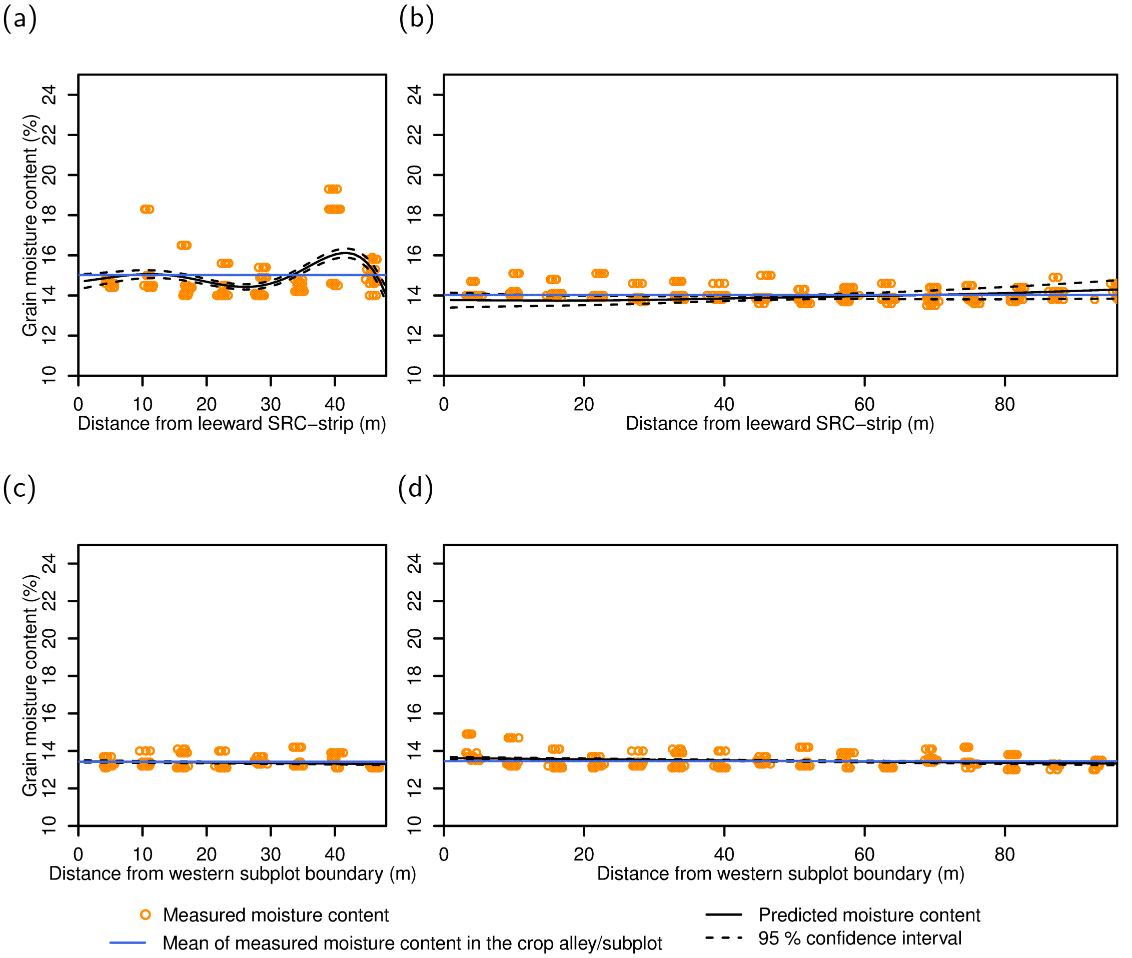


Figure 3.21. *Distribution of the measured and predicted grain moisture content (%) of the winter barley in 2014, from the leeward to the windward short rotation coppice (SRC)-strip of the narrow (a) and wide (b) alleys of the alley-cropping system and from the western to the eastern boundary of the narrow (c) and wide (d) subplots in the open field.*

3.2.2 Yield components

The results of the yield components will be organized per crop (firstly the winter wheat and then the winter barley). For each crop and each harvest year (2013 and 2014), the mean values and standard errors of the total grain weight (GW), the ear number per m^2 (EN) and the thousand grain weight (TGW) will be presented for each zone (leeward, middle, windward), and for all points of the alley-cropping system (ACS) and the open field. Then, the correlation graphs of the GW against the EN and the TGW will be presented, followed by the results of the variance analyses. The statistical results of these analyses are available in appendix D.2.

Winter wheat

As presented in table 3.4, in 2013, the GW, the EN and the TGW of the winter wheat were lower on the leeward (3 and 8 m in both alley widths) and the windward sides (43 and 48 m in the narrow crop alley, 91 and 96 m in the wide crop alley from the leeward short rotation coppice (SRC)-strip) than in the middle of the crop alleys (16, 25.5 and 35 m in the narrow crop alley, 32, 49.5 and 67 m in the wide crop alley from the leeward SRC-strip, see fig. 2.6). Furthermore, the highest values were reached in the open field for all parameters. In 2014, almost no differences in the GW were observed between the different systems and zones. However, the EN was lower on the leeward side than in the middle of the alley, whereas the highest EN was observed in the open field. The TGW was higher in the ACS than in the open field, whereas the highest TGW was reached on the leeward side.

Table 3.4. *Mean ± standard error of the total grain weight (GW), the ear number per m^2 (EN), the thousand grain weight (TGW) and number of observations (n) in the leeward (L), the windward (W) and the middle zones (M) (see fig 2.6), for all points of the alley (ACS) and in the open field (OF) of the winter wheat in 2013 and 2014 (GW and TGW are presented at 14 % moisture content) (ND: No data).*

Position	**L**	**W**	**M**	**ACS**	**OF**
Parameter			**2013**		
n	15	7	24	46	4
GW (kg m^{-2})	0.66 ± 0.07	0.79 ± 0.08	1.02 ± 0.02	0.87 ± 0.04	1.13 ± 0.03
EN (per m^2)	534 ± 39	568 ± 51	661 ± 11	606 ± 18	709 ± 17
TGW (g)	44.7 ± 0.9	44.4 ± 0.5	47.0 ± 0.5	45.9 ± 0.4	49.9 ± 0.6
Parameter			**2014**		
n	15	ND	8	23	4
GW (kg m^{-2})	0.96 ± 0.04	ND	1.03 ± 0.03	0.98 ± 0.03	1.06 ± 0.04
EN (per m^2)	570 ± 25	ND	613 ± 13	585 ± 17	632 ± 22
TGW (g)	50.5 ± 0.7	ND	49.3 ± 0.9	50.1 ± 0.6	46.7 ± 0.7

In fig. 3.22, the correlations between the GW and the EN ((a) and (b)) and between the GW and the TGW ((c) and (d)) are graphically shown for the leeward and windward points together, and for the middle points, for 2013 and 2014. Generally, in both years, the values in the leeward and the windward zones had a greater range than the values in the middle zone. The measurement points at 3 m from the SRC-strip showed in general lower values of GW and EN than at 8 m, in both years. Moreover, there was a clearer relationship between the GW and the EN than between the GW and the TGW, especially for the windward and leeward zone, in both years.

(a) (b)

(c) (d)

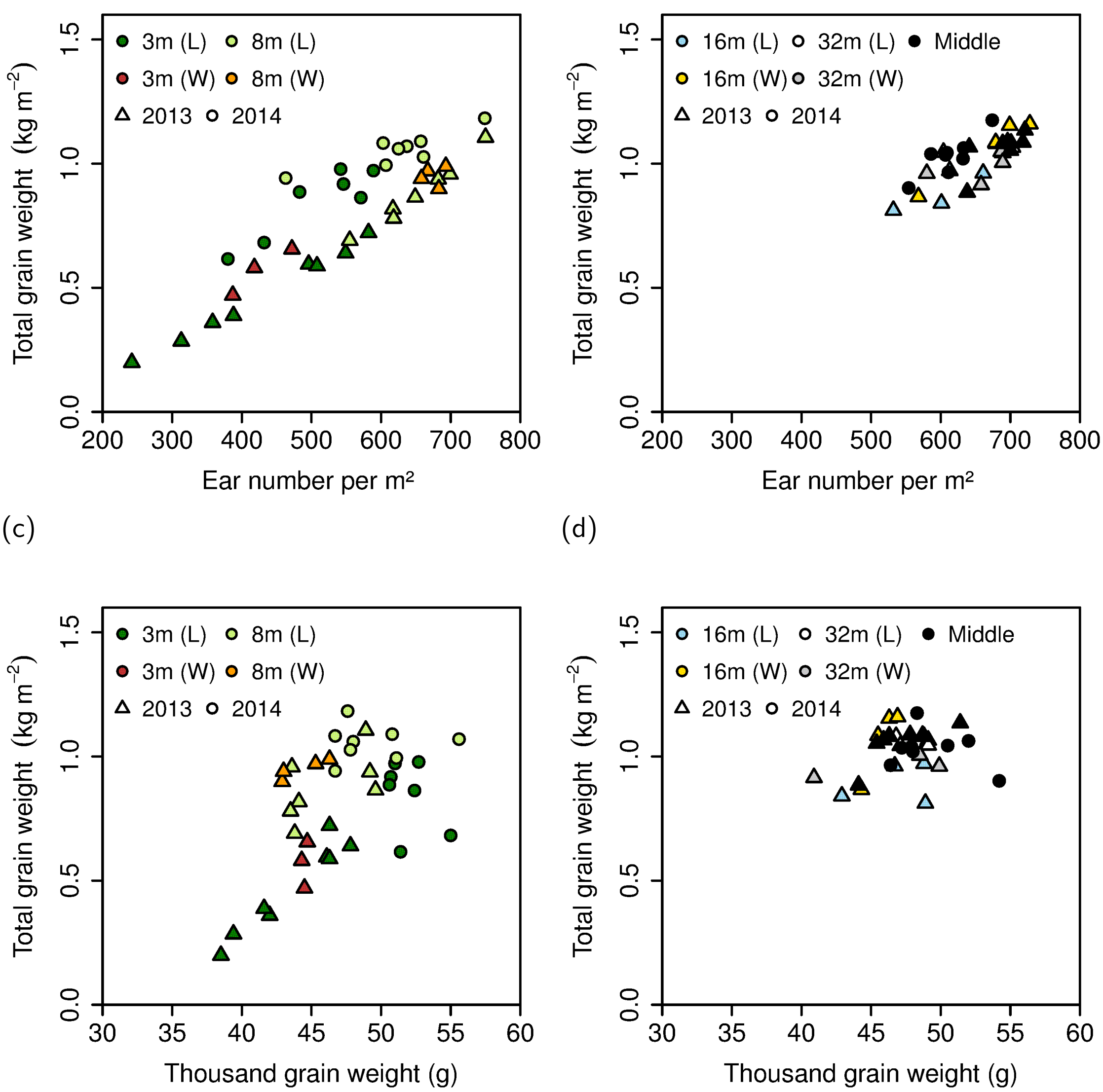


Figure 3.22. *Correlation between the total grain weight (kg m^{-2}) and the ear number per m^2 in the leeward and windward (a) and the middle (b) zones, and between the total grain weight and the thousand grain weight (g) in the leeward and windward (c) and the middle (d) zones of the winter wheat alleys of the alley-cropping system in 2013 and 2014 (Distances are indicated respectively from the leeward (L) and windward (W) short rotation coppice (SRC)-strips).*

Considering all data of 2013 (including the open field), both components, the EN and the TGW, significantly explained the GW and there was no significant interaction (see appendix D.2). When only the leeward points were considered, the TGW and the interaction of the TGW and the EN were significant, whereas when only the windward points were considered, only the EN was significant. By analyzing only the middle points (16m (L), 32m (L), Middle, 32m (W) and 16m (W)), no parameter was significant. For 2014, in the model including all data, the EN and the TGW and their interactions, had a significant effect on GW. When including only the leeward points in the model, only the EN had a significant effect on GW. Concerning the middle points, again no parameter was significant. Each model fitted well the data, as the correlation coefficients were all > 0.69 (see appendix D.2).

Winter barley

In the winter barley, the trends of 2013 were quite similar to the ones observed in the winter wheat (see table 3.5). The total grain weight (GW) was the lowest on the leeward side (3 and 8 m from leeward short rotation coppice (SRC)-strip, in both alley widths), slightly higher on the windward side (43 and 48 m in the narrow crop alley, 91 and 96 m in the wide crop alley from leeward SRC-strip) and in the middle of the crop alleys (16, 25.5 and 35 m in the narrow crop alley, 32, 49.5 and 67 m in the wide crop alley from leeward SRC-strip) and the highest in the open field. The ear number per m^2 (EN) was the lowest on the leeward side, followed by the windward side, whereas the highest EN was observed in the middle of the crop alleys, being slightly higher than the one in the open field. Within the alley-cropping system (ACS), the thousand grain weight (TGW) was the highest on the windward side, but considering all systems, it was the highest in the open field. In 2014, the GW and the EN were also the lowest on the leeward side and the highest in the open field. In contrast to the winter wheat, the differences between the measured values were similar to the ones observed in 2013. However, in 2014, the TGW was the highest in the ACS.

Table 3.5. *Mean ± standard error of the total grain weight (GW), the ear number per m*^{2} *(EN), the thousand grain weight (TGW) and the number observations (n) in the leeward (L), the windward (W) and the middle zones (M) (see fig 2.6), for all points of the alley (ACS) and in the open field (OF) of the winter barley in 2013 and 2014. GW and TGW are presented with 14 % moisture content (ND: No data).*

Position	**L**	**W**	**M**	**ACS**	**OF**
Parameter			**2013**		
n	14	16	23	53	4
GW (kg m^{-2})	0.67 ± 0.02	0.73 ± 0.05	0.79 ± 0.02	0.74 ± 0.02	0.80 ± 0.04
EN (per m^2)	356 ± 17	383 ± 14	410 ± 12	387 ± 8	406 ± 33
TGW (g)	49.2 ± 0.9	49.8 ± 0.9	48.9 ± 0.8	49.2 ± 0.5	54.2 ± 0.3
Parameter			**2014**		
n	15	ND	8	23	4
GW (kg m^{-2})	0.60 ± 0.05	ND	0.70 ± 0.05	0.63 ± 0.04	0.76 ± 0.02
EN (per m^2)	290 ± 22	ND	325 ± 22	302 ± 17	385 ± 17
TGW (g)	52.1 ± 0.6	ND	52.3 ± 1.0	52.2 ± 0.5	47.4 ± 0.2

In fig. 3.23, the correlations between the GW and the EN ((a) and (b)) and between the GW and the TGW ((c) and (d)) are graphically presented in the three zones. The correlation between the GW and the EN was stronger than the correlation between the GW and the TGW, however, the spread of data was not so great as for the winter wheat.

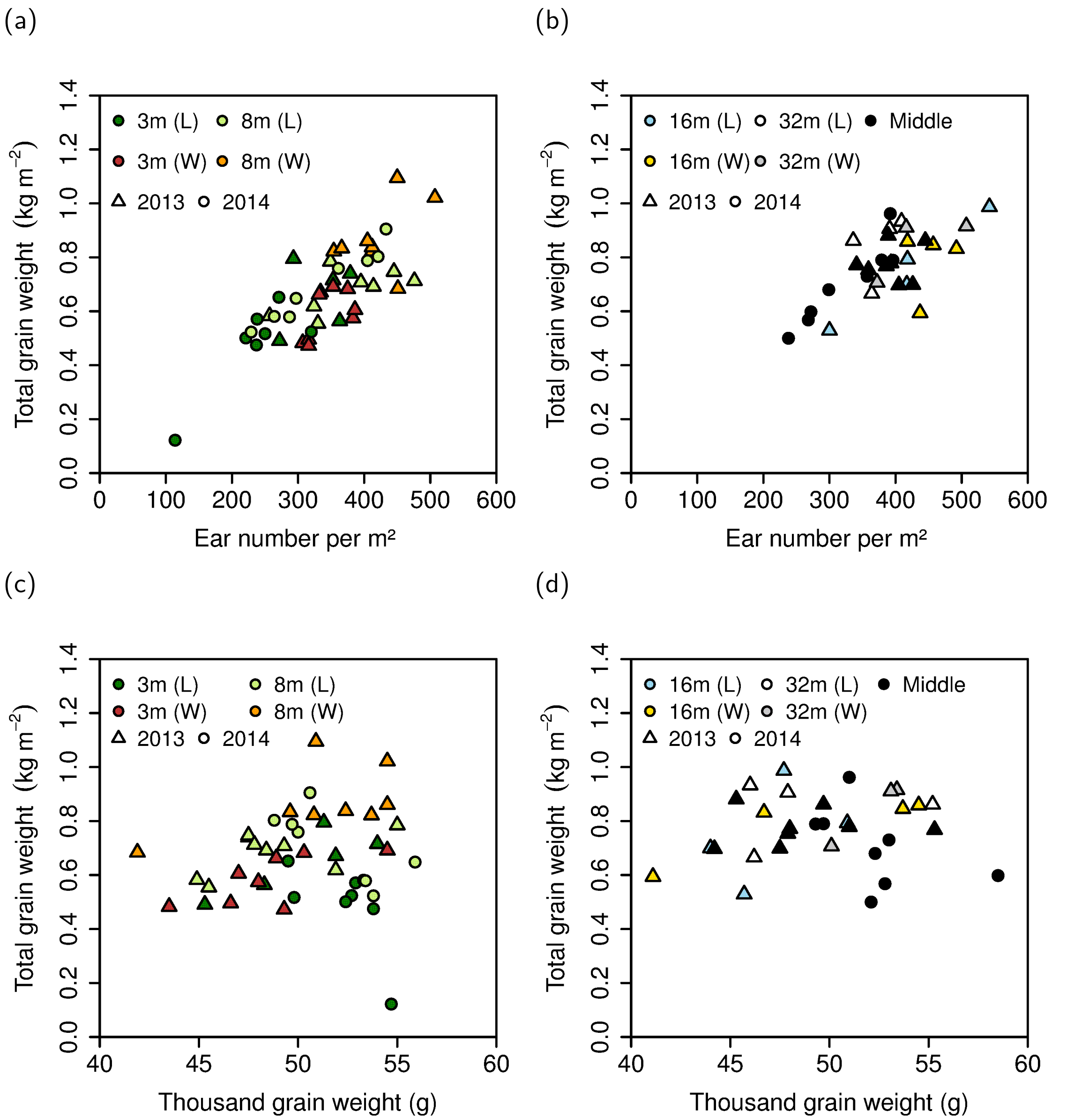


Figure 3.23. *Correlation between the total grain weight (kg m^{-2}) and the ear number per m^2 in the leeward and windward (a) and the middle (b) zones, and between the total grain weight and the thousand grain weight (g) in the leeward and windward (c) and the middle (d) zones of the winter barley alleys of the alley-cropping system in 2013 and 2014 (Distances are indicated respectively from the leeward (L) and windward (W) short rotation coppice (SRC)-strips).*

After performing variance analyses with the whole data set (including the open field) and separately for the leeward, the windward and the middle points, it appeared that in 2013 both, the TGW and EN parameters, always significantly explained the GW (see appendix D.2). In 2014, including all data in the model, both parameters and their interactions were significant. For the leeward and the middle points (without the open field), only the EN was significant. The correlation coefficients were for almost all models higher when including the random effects. They ranged from 0.64 to 0.91, showing a good fit to the data (see appendix D.2).

3.2.3 Plant development, aphid infestation and hectoliter weight

Plant development

In table 3.6, the phenological stages assessed on different dates are presented for the narrow and wide alleys of the winter wheat and the winter barley. Only the stages at 3 m from the leeward and windward short rotation coppice (SRC)-strips and in the middle of the crop alley and in the open field are presented. At the other measurement points of the transect, the plants had rather the same development as at the middle points (data not shown).

In both years, the winter wheat and winter barley plants on the leeward and windward measurement points reached in general later the phenological stages than the plants in the middle of the alley and in the open field. However, the differences between the measurement points were still quite small, in both years. The greatest differences were measured in 2014 in the narrow winter wheat alley (05/20/14) and in the narrow winter barley alley (05/20/14; 06/12/14).

Table 3.6. *Phenological stages according to the BBCH scale (Meier, 1997), assessed at several dates, at 3 m on the leeward (L) and on the windward (W) sides and in the middle of the narrow and wide alleys of the winter wheat and winter barley, in the alley-cropping system and the open field (OF) (ND: No data).*

Crop	2013					2014			
	Date	3 m (L)	Middle	3 m (W)	OF	Date	3 m (L)	Middle	OF
Winter	04/24	22	24	22	25	04/16	30	32	32
wheat	05/21	37	38	37	38	05/20	54	59	58
narrow	06/26	65	65	66	67	06/12	75	75	75
alley	07/04	74	75	75	75	07/01	85	85	85
Winter	04/24	23	23	ND	25	04/16	30	31	32
wheat	05/21	38	38	ND	38	05/20	53	59	58
wide	06/26	67	68	ND	67	06/12	74	75	75
alley	07/04	75	75	ND	75	07/01	85	85	85
Winter	04/18	24	25	24	25	04/16	30	31	32
barley	05/21	50	51	50	51	05/20	60	69	70
narrow	06/20	75	76	75	75	06/12	78	83	86
alley	07/04	85	87	85	85	-	-	-	-
Winter	04/18	23	24	24	25	04/16	31	33	32
barley	05/21	49	51	50	51	05/20	70	71	70
wide	06/20	76	76	75	75	06/12	85	85	86
alley	07/04	85	87	85	85	-	-	-	-

Aphid infestation, aphid mummies and beneficial insects

In 2013, in the winter wheat, a lot of aphids were observed in the crop alley during the first counting on the 06/18 (from 61.5 aphids on 10 tillers at 45 m up to 174.3 aphids on 10 tillers at 3 m in the narrow alley, data not shown). However, after one application of insecticide (Pirimor®, Syngenta), the whole population died and almost no aphids were observed on the second date of counting (07/02/13). Some aphid mummies and beneficial insects (mainly ladybug and its larva, green lacewing and its larva and syrphid flies) were observed all over the crop alley on both dates, however, only maximum 3 at one point (mean of 4 counts on 10 tillers).

In the winter barley alleys, on the first counting date (06/18/13, see fig. 3.24 (a)), some aphids were also counted in both alleys (from 1.3 to 13.0 aphids observed on 10 tillers). No insecticide was applied and the population grew especially at 3 m next to the short rotation coppice (SRC)-strips, on both, the leeward and the windward sides, and in both, the narrow and the wide alleys, reaching populations of 88.3 aphids on the second counting date (07/02/13, see fig. 3.24 (b)). On both counting dates, few aphid mummies and beneficial insects were also observed next to the SRC-strips, but not at all at the other measurement points in the crop alley and in the open field.

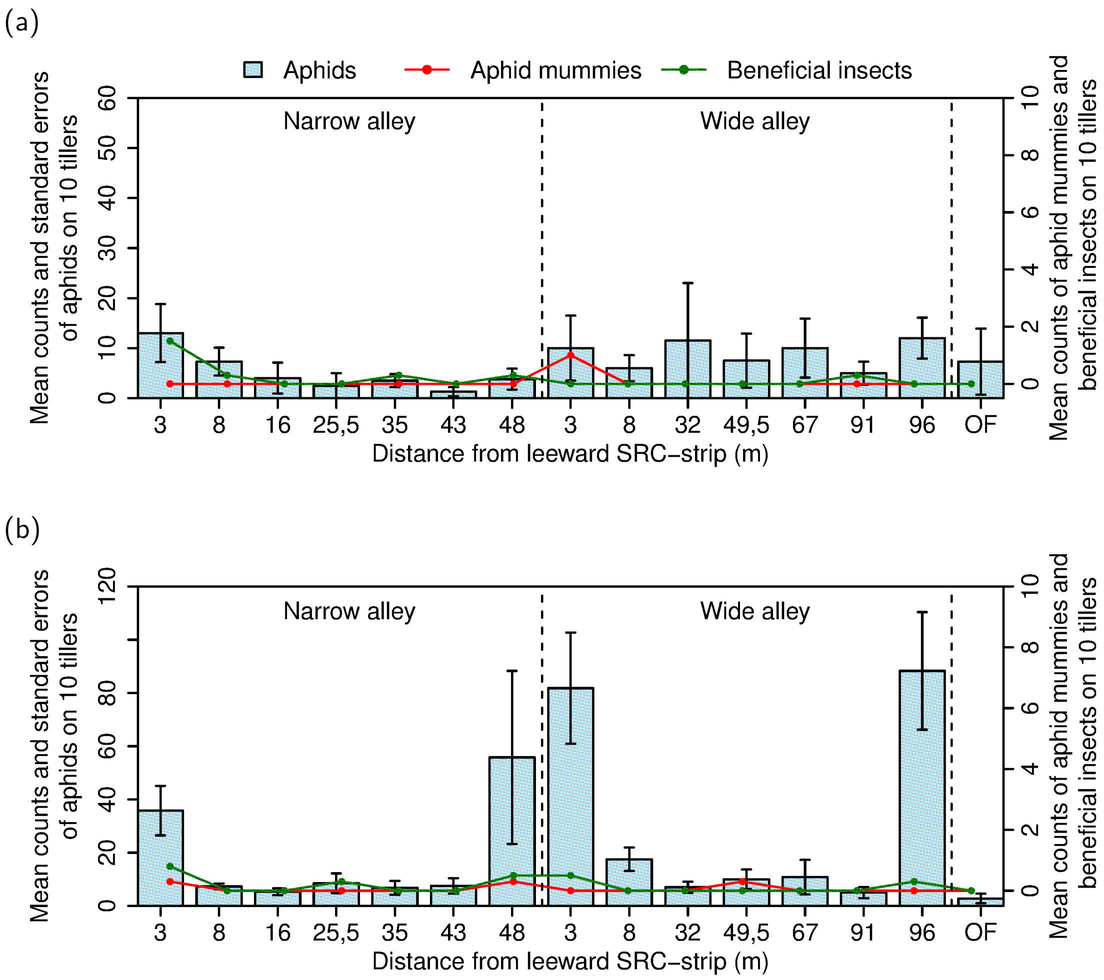


Figure 3.24. *Mean counts of aphids (± standard error), aphid mummies and beneficial insects on 10 tillers at different distances from the leeward short rotation coppice (SRC)-strip, in the winter barley narrow and wide alleys of the alley-cropping system and in the open field (OF) on the 06/18/13 (a) and on the 07/02/13 (b).*

In 2014, aphid populations stayed very small in both, the narrow and the wide alleys, of the winter wheat and the winter barley, next to the SRC-strip and in the middle of the alley (data not shown). The number of aphids on 10 tillers ranged from 0.5 to 3.3 in the winter barley and from 0.5 to 2.3 in the winter wheat.

Hectoliter weight

In fig. 3.25, the distribution of the hectoliter weight over the alley is presented for both crops and both widths of the alley-cropping system (ACS) and for the open field, in 2013 and 2014. The winter wheat showed higher values than the winter barley (respectively around 80 and 60 kg hL^{-1}). Moreover, for each crop, the values were lower in 2013 than in 2014 (for the winter wheat, around 81 kg hL^{-1} in 2013 and 86 kg hL^{-1} in 2014 and for the winter barley around 61 kg hL^{-1} in 2013 and 65 kg hL^{-1} in 2014). Generally, the distribution of the hectoliter weight over the alley, from the leeward side next to the SRC-strip to the windward side, was different in 2013 than in 2014, for both crops and both widths. In 2014, similar values were observed over the alley whereas in 2013, lower hectoliter weights were measured next to the SRC-strips. For the winter wheat in 2013, the minimum value (77.1 kg hL^{-1}) was measured in the first track of the narrow alley, on the leeward side, whereas the maximum value of the ACS (82.6 kg hL^{-1}) was measured in the middle track of the wide alley. The values of the open field were slightly above the maximal value of the ACS (82.8 kg hL^{-1}). Concerning the winter barley in 2013, the lowest value was also measured in the first track of the wide alley (57.9 kg hL^{-1}), whereas the highest value was measured in the middle of the narrow alley (63.8 kg hL^{-1}). In the open field, the hectoliter weight was slightly below the highest value of the ACS (63.4 kg hL^{-1}). In 2014, no value was available in the last track of the winter barley wide alley.

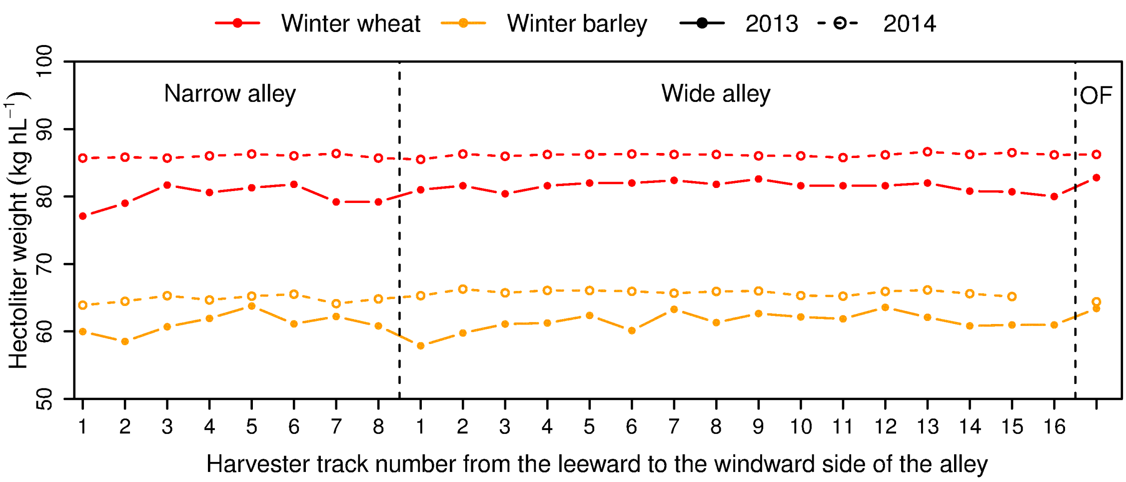


Figure 3.25. *Hectoliter weights (kg hL^{-1}) of the winter wheat and the winter barley at each track of the combine harvester from the leeward to the windward side of the narrow and wide alleys of the alley-cropping system and in the open field (OF), in 2013 and 2014.*

3.2.4 Summary of the modifications of yield and quality parameters in crop alleys

Concerning the alley-cropping system (ACS), in 2008, the measured and predicted yield and grain moisture content (MC) values were almost following a straight line over the alleys, with, however, a slight reduction of yield on the windward side of the wide alleys. In 2013, for both crops (winter wheat and winter barley) in the ACS, the yield was following a bell-shaped curve with lower values next to the short rotation coppice (SRC)-strip, on both sides, than in the middle of the crop alleys. This effect was amplified for the predicted values on the windward side of the wide alleys, even though the measured values followed a different evolution. In general, the winter wheat showed higher yield values and a greater data range than the winter barley. The grain MC also showed in the ACS a bell-shaped curve, but inverted: higher values were observed next to the SRC-strip than in the middle of the crop alley. This effect was for the MC more amplified for the narrow alleys, where the grain MC was in general higher. The reduced values (below the mean) of the yield and the MC were mainly extending up to 10 m into the alleys. A significant effect of distance, alone, in interaction with the alley width and the crop was detected for both yield and MC models of the ACS. Furthermore, the smoothers $f_4(nEC_{25i})$ and $f_5(X_i, Y_i)$ were significant for the yield, whereas only the normalized soil apparent electrical conductivity corrected to 25°C (nEC_{25}) as a linear factor was significant for the MC. In 2014, the bell-shaped curve of predicted yield in the ACS was observed only for the winter barley yield, where the distribution of values over the crop alleys was similar to the one in 2013. Moreover, in the narrow alley of the winter barley, quite high MC values were measured and predicted at 40 m.

Conversely, the measured and predicted yield and MC values in the open field were mostly following a straight line without slope over the distance, in both years and for both crops. However, the yield in the wide subplot of both crops showed a light curved line, and slightly higher MC were predicted at the eastern boundary of the winter barley wide subplot. In 2013, a significant effect of distance in interaction with the subplot width was indeed detected for the yield model and a significant effect of distance in interaction with crop was detected for the MC model. A distance effect in interaction with the crop was detected for the MC model in both years, and an additional sole distance effect was detected in 2014. Furthermore, the measured and predicted means were in general quite similar. For the yield model, the spatial smoother $f_5(X_i, Y_i)$ was significant in both years and only in 2013 for the MC model.

In 2013, the total grain weight (GW), the ear number per m^2 (EN) and the thousand grain weight (TGW) of the winter wheat and the winter barley were lower and showed a greater range on the leeward and the windward sides than in the middle of the crop alley and in the open field. In general, for both crops, a stronger correlation between the GW and the EN than between the GW and the TGW was observed graphically. However, for all and the middle points of the winter wheat, both, the EN and the TGW, explained significantly the GW. The EN had more effect on the GW than the TGW on the windward side, whereas the TGW affected more the GW on the leeward side. Concerning the winter barley, all parameters and their interactions had significant effects on the GW at all points, and separately in the three zones: leeward, windward and middle.

In 2014, the GW differences between the measurement points were not as big as in 2013 for the winter wheat. For both crops, the EN was slightly low on the leeward side, but the TGW was in general higher in the ACS than in the open field. Similarly to 2013, when considering all points together, both, the EN and the TGW, significantly explained the GW of the winter wheat and the winter barley. However, when considering only the leeward points, only the EN had a significant effect on the GW in both crops, and additionally on the GW of the middle points for the winter barley.

In both years, both crops showed in general smaller phenological stages next to the SRC-strip than in the middle of the crop alley and in the open field on the same date. Moreover, when no insecticide was applied, greater populations of aphids, and slightly more beneficial insects, were recorded next to the SRC-strip than in the middle of the crop alley and in the open field. Furthermore, the winter wheat showed higher values of hectoliter weight than the winter barley. For both crops, the values were in general higher and more similar over the crop alley in 2014 than in 2013, where lower values were recorded next to the SRC-strips than over the rest of the alleys.

3.3 Modifications of growth and yield in short rotation coppice-strips

In the following section, the results of the growth measurements will be presented, i.e. the diameters at breast height (DBHs), the shoots heights and the number of shoots per tree. Subsequently, the results of the biomass estimation conducted in winter 2013/14 will be reported as in Lamerre et al. (2015).

3.3.1 Diameters at breast height

In winter 2009/10, the data were not differentiated regarding the rotation cycle as no harvest was carried out yet. The significantly largest DBHs were observed in the leeward rows of the short rotation coppice (SRC) design (3.1 cm), whereas the smallest were measured in the SRC-control field (1.8 cm) (see fig. 3.26 (a)). Generally, the DBH range was greater and the values lower in the combined than in the SRC design.

Concerning winter 2013/14, two different ranges[1] of DBHs were observed depending on the rotation cycle; however, no significant differences could be detected (see fig. 3.26 (b)). In the 3-year rotation cycle (3y-RC), the values mostly ranged from 1 to 3 cm. In this rotation cycle, the DBHs were the largest in the outer rows of the SRC design (leeward and windward, respectively 2.6 and 2.5 cm). The DBHs measured in the SRC-control field were similar to the ones in the middle rows of the SRC and combined design (around 2.2-2.3 cm). In the combined design, the largest DBHs were observed in the windward rows (2.5 cm). In the 6-year rotation cycle (6y-RC), most of the values ranged from 4 to 8 cm. The DBHs in the combined design were in general larger than in the SRC design. Within the combined design, the largest DBHs were situated in the leeward rows (6.6 cm), whereas in the SRC design, the largest DBHs were observed in the windward rows (6.4 cm). The smallest DBHs were measured in the middle rows of the SRC design (5.0 cm).

[1]In the box and whiskers plots, the gray bold line in each box represents the median, the crosses represent the mean, the bottom of the box represents the first quartile and the top of the box the third quartile. The ends of the whiskers represent ± 1.5 x interquartile range.

In winter 2014/15, the DBHs were around 1 cm in both rotation cycles (see fig. 3.26 (c)). In the 3y-RC, within each design, the DBHs of the windward rows (1.1 cm) were significantly larger than the ones of the middle rows (for both designs 0.9 cm). In the 6y-RC, the values measured in the middle rows of the SRC design (mean of 0.9 cm) were the smallest, and significantly different from the ones measured in the windward (mean of 1.2 cm) and the leeward rows of the combined design (mean of 1.1 cm). The statistical results of the variance analysis for the DBHs measured in winter 2009/10, 2013/14 and 2014/15 in both rotation cycles are available in appendix D.3.

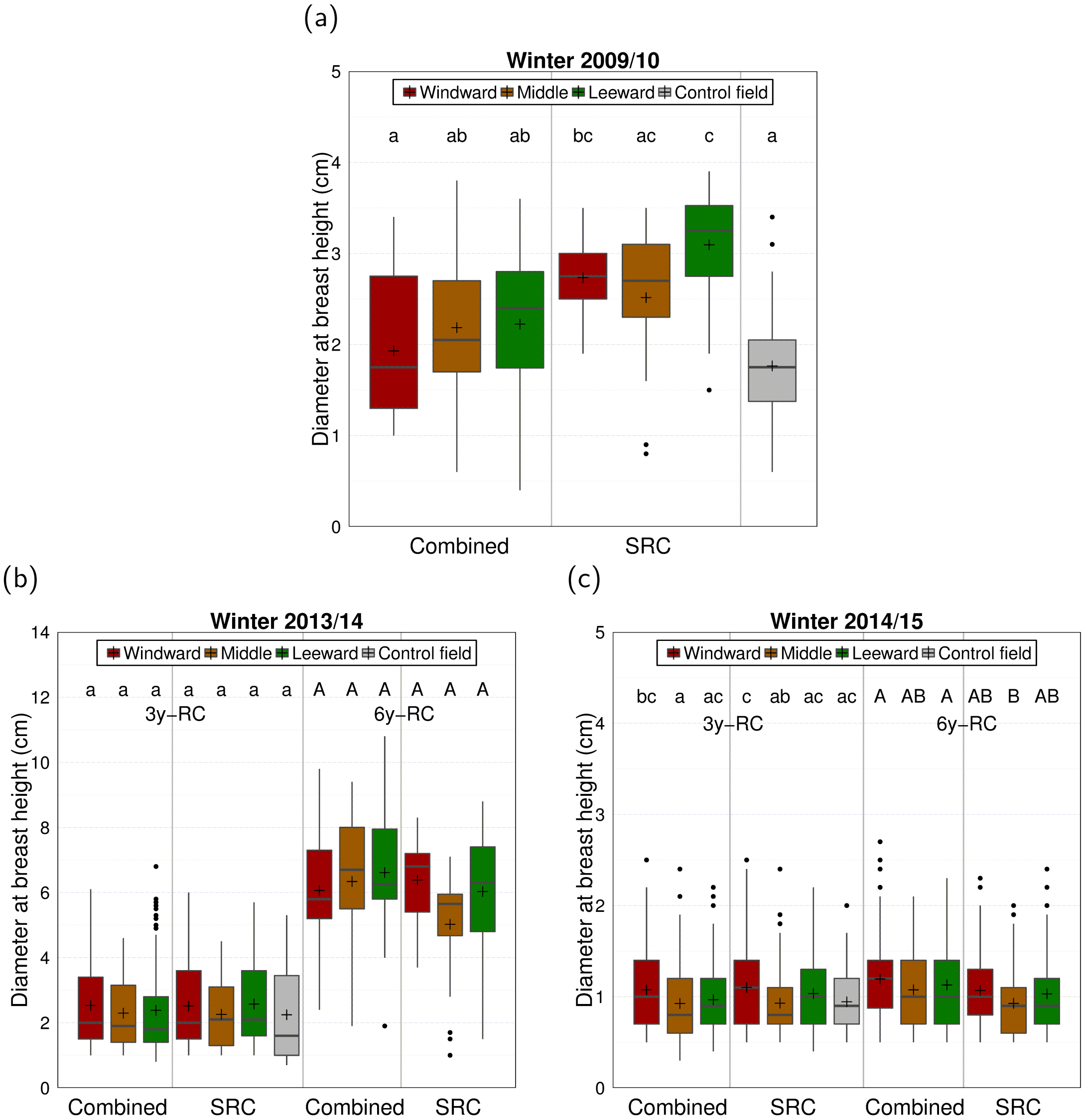


Figure 3.26. *Box and whiskers plots of the diameters at breast height measured in the leeward, windward and middle rows of the combined and short rotation coppice (SRC) designs, in winter 2009/10 (a), 2013/14 (b) and 2014/15 (c) in the 3-year rotation cycle (3y-RC) and the 6-year rotation cycle (6y-RC) SRC-strips and in the SRC-control field (Control field). Different letters at the top of each box and whiskers indicate a statistical difference at the 0.05 level of probability.*

3.3.2 Shoot heights

In fig. 3.27, the predicted shoot heights for several diameters at breast height (DBHs) are presented for the different designs and rotation cycles (for each rotation cycle and each design: leeward, middle and windward rows; additionally for the 3-year rotation cycle (3y-RC), the short rotation coppice (SRC)-control field). For almost each model, the correlation coefficient (R^2) was higher with than without random effects. Moreover, the R^2 values were > 0.80, showing a good fit to the data.

In winter 2013/14, the shoots in the 3y-RC with similar DBH and > 2 cm were the tallest in the middle rows of the SRC design and in the SRC-control field, whereas they were the smallest in the leeward and middle rows of the combined design (see fig. 3.27 (a)). In contrast, shoots with a DBH < 2 cm were taller in the leeward and middle rows of the combined design than in the SRC-control field and the windward rows of the SRC design. For trees in the 6-year rotation cycle (6y-RC), the shoots with a similar DBH had the smallest heights in the windward rows of both designs, for the whole DBH range (see fig. 3.27 (b)). For DBH < 4 cm, the tallest shoots were found in the leeward rows of the SRC design and the middle rows of the combined design. For DBHs > 4 cm, the tallest shoots were located in the middle rows of the SRC design.

In winter 2014/15, a similar trend as in 2013/14 was observed; however, less distinctively when DBH showed smaller values. In the 3y-RC, for DBHs < 1 cm, shoots were the tallest in the windward rows of the SRC design and the smallest in the control field, whereas for DBHs > 1 cm, the opposite was observed: the tallest shoots were situated in the SRC-control field, in the leeward rows of the SRC-strips in both designs and the middle rows of the combined design (see fig. 3.27 (c)). The smallest heights of this rotation cycle were observed for DBHs > 1 cm in the windward rows of both designs and the middle rows of the SRC design. In the 6y-RC, slopes and intercepts for the different rows and designs were very similar to each other, as prediction lines were very close and parallel (see fig. 3.27 (d)). Only the middle rows of the combined design showed slightly taller shoots than the other rows for DBHs < 1 cm, and slightly smaller ones for DBHs > 1 cm.

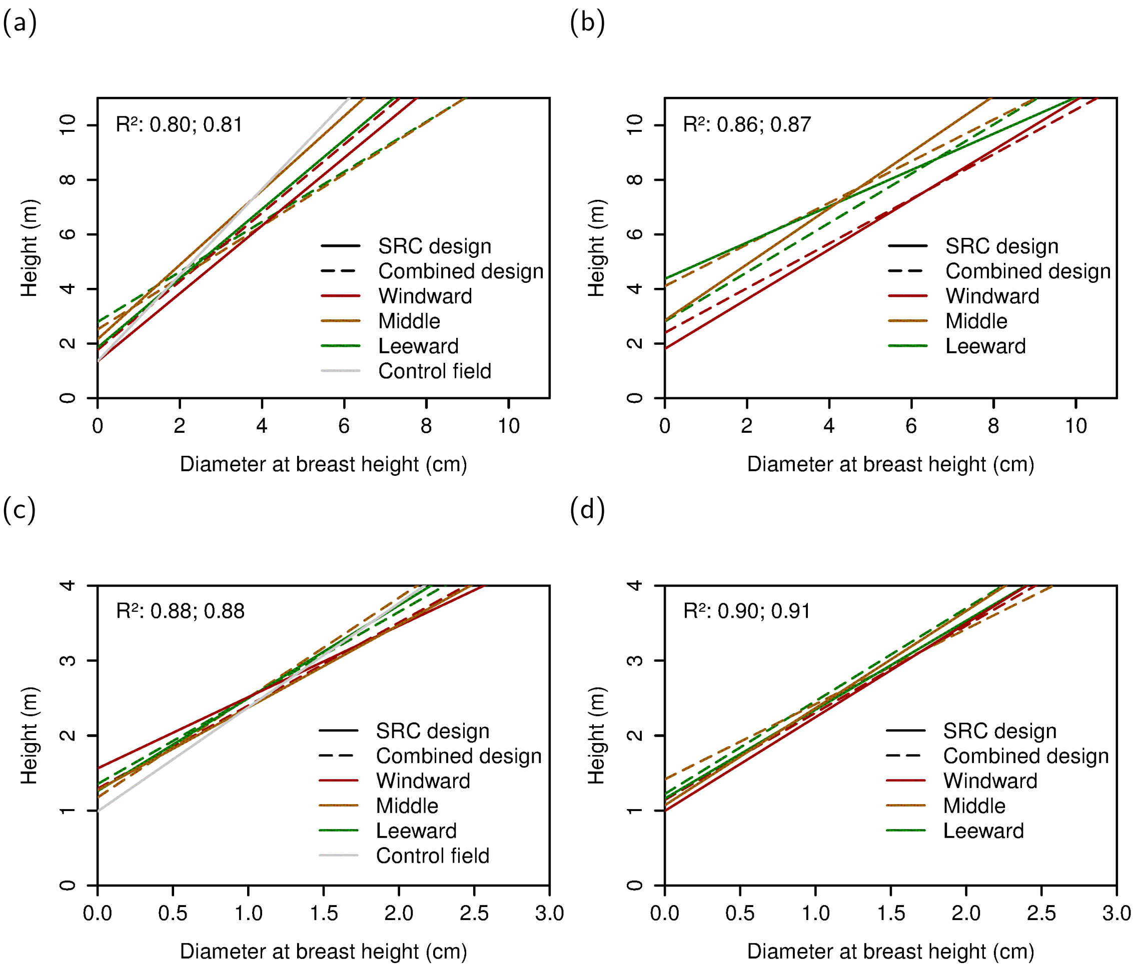


Figure 3.27. *Predicted shoot heights (m) for several diameters at breast height (cm) from measured values in winter 2013/14, in the 3-year rotation cycle (a) and the 6-year rotation cycle (b), and in winter 2014/15 in the 3-year rotation cycle (c) and the 6-year rotation cycle (d), for the leeward, windward and middle rows of the short rotation coppice (SRC) and combined designs, as well as for the SRC-control field (Control field) for the 3-year rotation cycle (R^2: correlation coefficient. First R^2, of fixed effects; second R^2, of fixed and random effects).*

3.3.3 Number of shoots per tree

In winter 2013/14, the trees in the 6-year rotation cycle (6y-RC) had considerably less shoots than the trees in the 3-year rotation cycle (3y-RC), which were already harvested once (around 1.1 shoot per tree in the 6y-RC and 4.2 in the 3y-RC) (see table 3.7). Almost no differences were observed in the shoot number between the row positions and the desings for the 6y-RC. However, in the 3y-RC, the trees situated in the windward and leeward rows had more shoots (up to 5.5) than the trees in the middle rows, especially in the short rotation coppice (SRC) design (2.9). The SRC-control field showed on average 3.6 shoots per tree. Here, no significant differences could be detected.

In winter 2014/15, one growing season after the harvest of all SRC-strips, the trees in the 3y-RC showed on average 7.1 shoots, whereas trees in the 6y-RC had on average 5.9 shoots.

Similar tendencies as in winter 2013/14 were observed, such as higher shoot numbers in the windward and leeward rows (up to 8.3) than in the middle rows (5.0 to 6.5), in both rotation cycles and both designs. However, no significant differences between rows was detected. The trees in the SRC-control field showed on average 7.4 shoots and thus had more shoots than the middle rows but less than the outer rows.

Table 3.7. *Shoot numbers per tree in the windward, middle and leeward rows of the combined and short rotation coppice (SRC) designs, for both rotation cycles (3-year: 3y-RC; 6-year: 6y-RC), in winter 2013/14 and 2014/15 (Mean ± standard error) (ND: No data).*

Design	**Row**	**2013**		**2014**	
		3y-RC	6y-RC	3y-RC	6y-RC
Combined	Windward	4.6 ± 0.4	1.1 ± 0.1	8.3 ± 0.8	5.2 ± 0.5
	Middle	4.0 ± 0.3	1.1 ± 0.1	6.5 ± 0.5	5.0 ± 0.5
	Leeward	4.5 ± 0.4	1.1 ± 0.1	7.5 ± 0.5	6.5 ± 0.9
SRC	Windward	5.5 ± 0.5	1.1 ± 0.1	6.9 ± 0.5	6.5 ± 0.5
	Middle	2.9 ± 0.2	1.1 ± 0.1	5.2 ± 0.4	5.7 ± 0.4
	Leeward	4.8 ± 0.5	1.3 ± 0.1	8.2 ± 0.8	6.9 ± 0.7
SRC-control field		3.6 ± 0.2	ND	7.4 ± 0.7	ND

3.3.4 Biomass estimation of outer and middle rows

The estimated yearly biomass productions of winter 2013/14 for each row position and in both rotation cycles (leeward, middle of the short rotation coppice (SRC) design, middle of the combined design, windward and additionally for the 3-year rotation cycle (3y-RC), control field) are presented in fig. 3.28. In general, the significantly highest biomass productions were reached in the leeward rows of the SRC-strips in both rotation cycles (3y-RC: 16.0 t ha^{-1} year^{-1} and 6-year rotation cycle (6y-RC): 16.1 t ha^{-1} year^{-1}), but the leeward row of the control field showed also a high value (13.6 t ha^{-1} year^{-1}). The windward rows presented a high biomass production only in the 3y-RC (15.7 t ha^{-1} year^{-1}) (Lamerre et al., 2015).

In the 6y-RC, the values predicted for the windward rows were significantly lower than the ones of the leeward rows, but still similar to the ones of the middle rows of the combined design (respectively 12.8 and 13.8 t ha^{-1} year^{-1}). In this rotation cycle, the predicted biomass production in the middle rows of the SRC design was significantly the lowest (8.6 t ha^{-1} year^{-1}). In the 3y-RC, the predicted biomass productions of the middle rows of the SRC and of the combined design were both significantly the lowest (respectively 8.0 and 9.6 t ha^{-1} year^{-1}) (Lamerre et al., 2015).

Moreover, each allometric equation showed a high adjusted correlation coefficient (> 0.92), showing that equations fitted well the observed data. The correlation and the equations' coefficients are presented in appendix D.4.

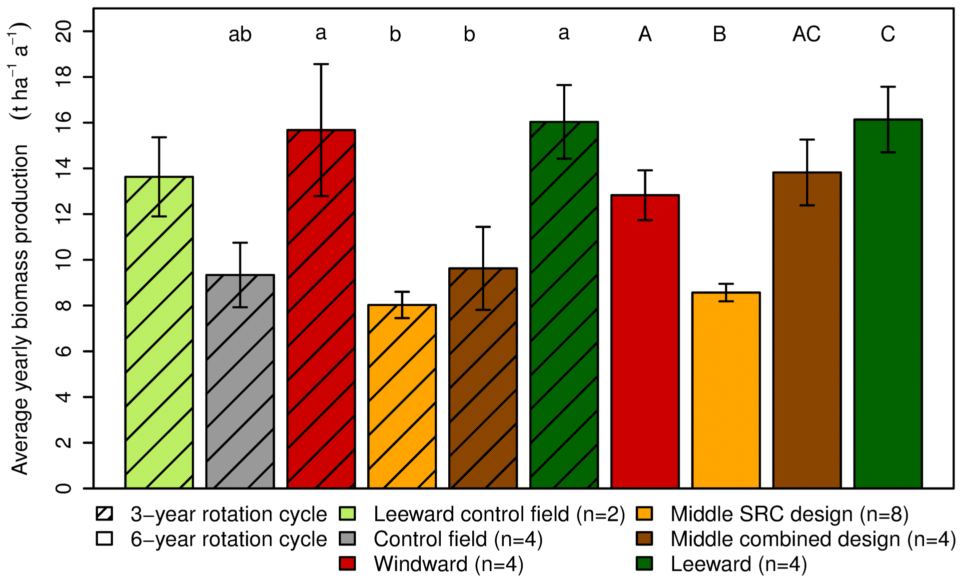


Figure 3.28. *Mean yearly biomass production of poplars (t ha^{-1} year^{-1}) in the different short rotation coppice (SRC)-strip row positions and designs of the alley-cropping system and in the SRC-control field (Control field) (Mean of all rows ± standard error, bars with different letters are statistically different ($p < 0.05$)) (Lamerre et al., 2015).*

3.3.5 Summary of the modifications of growth and yield in short rotation coppice-strips

In winter 2009/10, the diameters at breast height (DBHs) were the largest in the leeward rows of the short rotation coppice (SRC) design, whereas the smallest were observed in the SRC-control field. In winter 2013/14, higher values were observed in the 6-year rotation cycle (6y-RC), especially in the leeward rows and in the combined design, whereas the lowest were recorded in the middle rows of the SRC design. Conversely, in the 3-year rotation cycle (3y-RC), slightly larger DBHs were measured in the windward rows of both designs than in the others rows, even though the leeward row of the SRC design showed almost similar DBHs. In winter 2014/15, all DBHs were quite small, but higher values, sometimes even significant, were detected in outer rows than in middle rows.

From the measurement in winter 2013/14, greater shoot heights were detected in the middle rows of the SRC design and in the SRC-control field than in the other rows, for DBHs > 2 cm in the 3y-RC, and for DBHs > 4 cm in the 6y-RC. In winter 2014/15, the shoot heights were quite similar in all row positions, even though similar trends as in 2013/14 were detectable.

Concerning the number of shoots per tree, similar trends were detected for both designs, in the 3y-RC in winter 2013/14, and in both rotation cycles in winter 2014/15: the trees in the edge rows (leeward and windward) had more shoots than in the middle rows. However, the trees in the middle rows of the combined design showed in general a higher shoot number than in the middle rows of the SRC design. The trees in the 6y-RC in winter 2013/14 (not harvested yet) had in all rows only one or more rarely two shoots per tree.

The leeward rows of the SRC-strips in both rotation cycles and of the SRC-control field and the windward rows in the 3y-RC showed a great yearly biomass production. However, the middle rows of the SRC design showed in both rotation cycles the significantly lowest yearly biomass production, similarly to the other SRC-control field rows. The middle rows of the combined design showed a high yearly biomass production in the 6y-RC and a quite low in the 3y-RC.

3.4 Overall evaluation of the systems

In this last section, the results of the overall system evaluation will be presented. The grain and wood yields of the different years used in the calculation will be described in the first place, followed by the biomass and energy yields of the systems aggregated over the years. The compared systems are two alley-cropping systems (ACSs), one with narrow and one with wide alleys, and two sole-cropping systems (SCSa), the crop open field and the SRC-control field.

3.4.1 Grain and wood yields at the experimental site

Concerning the winter wheat, the yield in the open field was in 2012 significantly the lowest compared to the narrow and wide alleys, but it was significantly the highest in the other years (see table 3.8). The yields in the narrow and wide alleys were each year significantly different, except in 2009. In 2009, 2011, 2012 and 2014, the yield was higher in the wide than in the narrow alley, whereas in 2010 and 2013, the yield was higher in the narrow than in the wide alley of the ACS. When considering the sum of all years, the highest cumulative yield was measured in the wide alleys of the ACS, followed by the values of the open field and of the narrow alley.

Table 3.8. *Crop yields (t dry matter ha^{-1}, mean ± standard error (number of observations)) in the narrow and wide alleys of the alley-cropping system (ACS) and in the crop open field of the sole-cropping system (SCS) for the winter wheat, from 2009 to 2014 (different letters within one year indicate a statistical difference at the 0.05 level of probability between the means).*

System	ACS		SCS
Design	Narrow alley	Wide alley	Open field
Year			
2009	7.54 ± 0.06 (232) a	7.67 ± 0.03 (452) a	7.94 ± 0.04 (901) b
2010	7.67 ± 0.08 (225) a	6.99 ± 0.07 (494) b	7.74 ± 0.07 (445) a
2011	5.69 ± 0.07 (231) a	7.16 ± 0.03 (461) b	7.37 ± 0.03 (659) c
2012	7.49 ± 0.05 (275) a	7.75 ± 0.03 (515) b	5.10 ± 0.07 (974) c
2013	7.22 ± 0.06 (235) a	7.18 ± 0.07 (472) b	7.52 ± 0.06 (620) c
2014	7.25 ± 0.03 (235) a	7.59 ± 0.04 (500) b	7.83 ± 0.05 (654) c
Sum	42.8	44.5	43.4

For the winter oilseed rape, in 2010 and 2011, the significant highest yield was measured in the wide alley of the ACS (see table 3.9). In 2009 and 2010, the yield was slightly higher in the narrow alley than in the open field, even significantly in 2010. Conversely, in 2011 and 2014, the yields in the open field were significantly higher than the yields in the narrow alley. In 2012, no significant difference was observed between the fields. In 2014, the yield in the wide alley was significantly higher than the yield in the narrow alley but both were significantly lower than the yield in the open field. However, over the years, the highest accumulated yield was calculated in the wide alley, followed by the open field and the narrow alley values.

Table 3.9. *Crop yields (t dry matter ha^{-1}, mean ± standard error (number of observations)) in the narrow and wide alleys of the alley-cropping system (ACS) and in the crop open field of the sole-cropping system (SCS) for the winter oilseed rape, from 2009 to 2014 (ND: No data) (different letters with one year indicate a statistical difference at the 0.05 level of probability between the means).*

System	ACS		SCS
Design	Narrow alley	Wide alley	Open field
Year			
2009	3.31 ± 0.04 (263) a	3.02 ± 0.03 (511) b	3.14 ± 0.03 (677) a
2010	3.50 ± 0.03 (216) a	4.15 ± 0.03 (435) b	3.35 ± 0.07 (470) c
2011	1.94 ± 0.05 (284) a	2.67 ± 0.04 (523) b	2.16 ± 0.03 (864) c
2012	3.00 ± 0.02 (265) a	3.03 ± 0.03 (515) a	3.01 ± 0.02 (670) a
2013	ND	ND	ND
2014	2.48 ± 0.03 (239) a	3.27 ± 0.02 (489) b	3.43 ± 0.03 (779) c
Sum	14.2	16.2	15.1

The dry wood biomasses produced in the different designs and in both rotation cycles are reported for the short rotation coppice (SRC)-strips of the ACS and the SRC-control field as a SCS in table 3.10. From winter 2009/10 to winter 2013/14 (except winter 2010/11 for the 3y-RC because no data was available), the highest amount of wood biomass was recorded in the ACS in both rotation cycles, and especially in the SRC design. In winter 2014/15, a lower wood biomass production was estimated in the ACS than in the SRC-control field. Between the rotation cycles, slightly more biomass was produced yearly in the 6-year rotation cycle (6y-RC), especially in the SRC design. The average biomass production of the aspen trees in the combined design was 4.5 t ha^{-1} $year^{-1}$ (Lamerre et al., 2015).

Table 3.10. *Dry wood biomasses (t ha^{-1}) produced in the different designs and in both rotation cycles (3-year: 3y-RC; 6-year: 6y-RC) in the alley-cropping system (ACS) and in the short rotation coppice (SRC)-control field in the sole-cropping system (SCS) (ND: No data; Cont.: SRC-control field).*

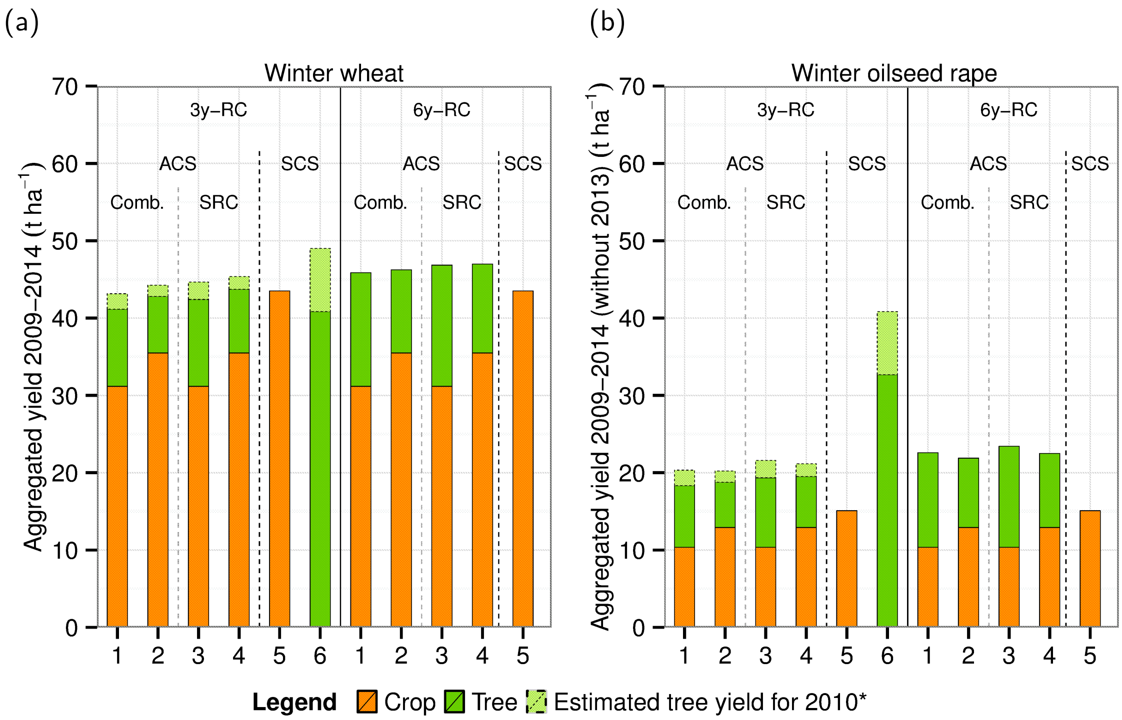
Rotation cycle	**3y-RC**				**6y-RC**	
System	**ACS**		**SCS**		**ACS**	
Design	**Combined**	**SRC**	**Cont.**		**Combined**	**SRC**
Period				**Period**		
2009/10	4.2	5.9	3.5	2009/10-2013/14	42.4	44.7
2011/12-2013/14	21.7	25.3	23.6			
2014/15	10.7	10.0	13.8	2014/15	11.4	12.8
Sum	36.6	41.2	40.8	Sum	53.9	57.5
Yearly growth	7.32	8.25	8.17	Yearly growth	8.98	9.59

In each figure of the following section (figs. 3.29 and 3.30), the biomass/energy yields aggregated over the years and calculated with the proportions presented in section 2.5.3 will be presented for each of the four compared systems (narrow alley-cropping, wide alley-cropping, sole-cropping with crop and sole-cropping with tree) with each crop (winter oilseed rape and winter wheat), each rotation cycle (3-year and 6-year) and each SRC-strip design (SRC and combined).

3.4.2 Calculated biomass production of the four systems

Considering the systems with the winter wheat (see fig. 3.29 (a)), slightly higher yields were reached in general in the alley-cropping systems (ACSs) than in the crop open field over the years (2009-2014). In the 3-year rotation cycle (3y-RC), slightly more biomass was produced in systems with the wide alley and the short rotation coppice (SRC) design (respectively for the narrow and wide alleys systems with the combined and SRC design: 43.15, 44.27, 44.67, 45.38 t ha^{-1}). Concerning the sole-cropping systems (SCSs), the value of the open field was slightly above the narrow ACS with SRC design (43.51 t ha^{-1}), whereas the value of the SRC-control field was the highest, over the ones of the ACS (49.00 t ha^{-1}). With the trees in the 6-year rotation cycle (6y-RC), the values in the ACSs were slightly higher than with the 3y-RC. The ACSs with the narrow and the wide alleys showed similar values within each SRC-strip design, but were slightly higher in the SRC design (respectively for the narrow and wide alley systems with the combined and SRC design: 45.86, 46.26, 46.86, 46.99 t ha^{-1}).

Concerning the winter oilseed rape systems, higher yields were also calculated in the ACSs than in the open field (but not than in SRC-control field), especially in the systems with the narrow alleys (see fig. 3.29 (b)). The general trend was also that systems with the SRC design produced slightly more biomass than with the combined design. In the systems with the 3y-RC and the combined design, 20.33 t ha^{-1} was reached with the narrow alleys and 20.23 t ha^{-1} with the wide alleys, whereas with the SRC design 21.59 and 21.15 t ha^{-1} was produced, respectively with the narrow and wide alleys. The open field showed only 15.09 t ha^{-1}, whereas the SRC-control field produced almost two times more biomass (40.84 t ha^{-1}) from 2009 to 2014 (but without 2013 because this value was for not available in this year for the winter oilseed rape). Concerning the systems with the 6y-RC, 22.59, 21.88, 23.42 and 22.49 t ha^{-1} were produced, respectively with the narrow and wide alleys in the combined and SRC design.



1 - Narrow alley-cropping system with combined design (27 % SRC-strip; 73 % Crop)

2 - Wide alley-cropping system with combined design (20 % SRC-strip; 80 % Crop)

3 - Narrow alley-cropping system with SRC design (27 % SRC-strip; 73 % Crop)

4 - Wide alley-cropping system with SRC design (20 % SRC-strip; 80 % Crop)

5 - Crop open field (100 % Crop)

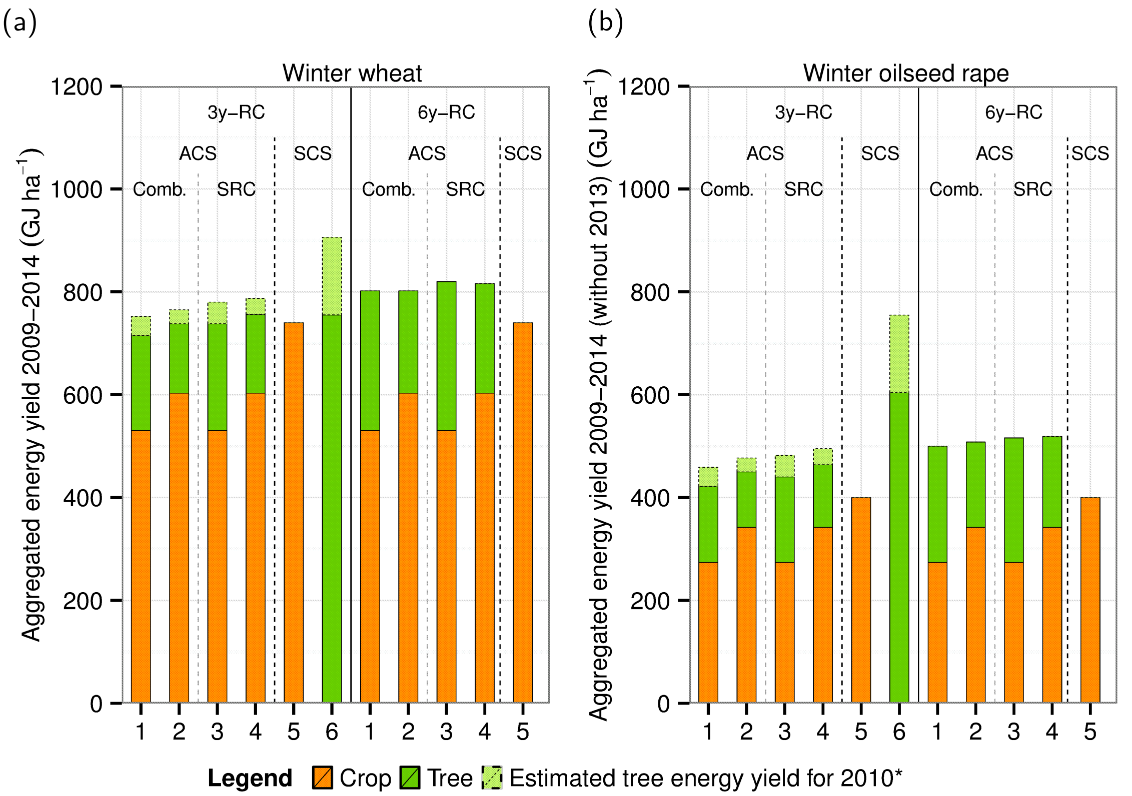
6 - SRC-control field (100 % SRC)

Figure 3.29. *Aggregated grain and wood dry yield (t ha^{-1}) from 2009 to 2014 (without 2013 for the winter oilseed rape) for the alley-cropping systems (ACS) with narrow and wide alleys, the crop open field and the short rotation coppice (SRC)-control field of the sole-cropping systems (SCS), with winter wheat (a) and winter oilseed rape (b), with SRC-strips in the 3-year rotation cycle (3y-RC) and the 6-year rotation cycle (6y-RC) and the combined (Comb.) and SRC (SRC) designs (*the 2010 yield of the tree component in the 3y-RC was estimated because of missing values).*

3.4.3 Calculated energy production of the four systems

In fig. 3.30, the converted aggregated biomass yields into energy yields (in GJ ha^{-1}) is presented. In the winter wheat systems, the trends of energy yields were quite similar to the ones of the biomass yields. Concerning the 3-year rotation cycle (3y-RC), greater yields were observed with the wide than the narrow alleys and, generally, in the alley-cropping systems (ACSs) than in the open field (see fig. 3.30 (a)). The energy yields in the ACS ranged from 751 to 766 GJ ha^{-1} for the combined design and from 780 to 786 GJ ha^{-1} for the short rotation coppice (SRC) design (narrow and wide alleys, respectively). The energy production was much lower in the open field (740 GJ ha^{-1}) than in the SRC-control field, where it was the highest (907 GJ ha^{-1}). In the 6-year rotation cycle (6y-RC), the values were also higher than in the 3y-RC, similarly to the biomass yield. The lowest energy production was identified in the systems with the narrow and wide alleys and the combined design (802 and 803 GJ ha^{-1}, respectively). The highest energy yield was measured in the systems with the SRC design (820 and 816 GJ ha^{-1}, respectively for the narrow and wide alleys).

After converting the winter oilseed rape yields into energetic outputs, the values were closer to the ones of the winter wheat than for the aggregated biomass yields (see fig. 3.30 (b)). Moreover, the share of the crop in total energy production was higher than when considering grain biomass yield. In the 3y-RC, the highest energy yield was measured for the SRC-control field, which was almost the double of the yield in the open field (respectively, 755 and 400 GJ ha^{-1}). In the ACSs, the values were higher in the systems with the wide alley and the SRC design (respectively for the narrow and wide alley systems with the combined and SRC design: 459, 477, 482, 495 GJ ha^{-1}). In the 6y-RC, the values of the ACSs were slightly higher than in the 3y-RC. The energy yields were also slightly higher in systems with the wide alleys and the SRC-design than with the narrow alleys and the combined design (respectively for the narrow and wide alley systems of the combined and SRC designs: 501, 508, 516 and 519 GJ ha^{-1}).



1 - Narrow alley-cropping system with combined design (27 % SRC-strip; 73 % Crop)
2 - Wide alley-cropping system with combined design (20 % SRC-strip; 80 % Crop)
3 - Narrow alley-cropping system with SRC design (27 % SRC-strip; 73 % Crop)
4 - Wide alley-cropping system with SRC design (20 % SRC-strip; 80 % Crop)
5 - Crop open field (100 % Crop)
6 - SRC-control field (100 % SRC)

Figure 3.30. *Aggregated grain and wood energy yield (GJ ha^{-1}) from 2009 to 2014 (without 2013 for the winter oilseed rape) for the alley-cropping systems (ACS) with narrow and wide alleys and the crop open crop field and short rotation coppice (SRC)-control field of the sole-cropping systems (SCS), with winter wheat (a) and winter oilseed rape (b), with SRC-strips in the 3-year rotation cycle (3y-RC) and the 6-year rotation cycle (6y-RC), and the combined (Comb.) and SRC (SRC) designs (*the 2010 yield of the tree component in the 3y-RC was estimated because of missing values).*

3.4.4 Summary of the overall evaluation of the systems

Except in 2014, higher wood biomass yields were recorded in the short rotation coppice (SRC)-strips than in the SRC-control field, especially with the SRC design. For the winter wheat, the yield was in general slightly higher in the open field and in the wide alleys, except for 2012 and 2013. For the winter oilseed rape, the yield was the highest in the wide alleys, except in 2009 and 2014.

Concerning the system evaluation, from 2009 to 2014 (without 2013 for the winter oilseed rape), higher biomass (crop grain and wood) and energy yields were reported in the alley-cropping systems (ACSs) than in the crop open field, but the highest were produced in the SRC-control field. Better results were reached with SRC-strips in a 6-year rotation cycle (6y-RC) than in a 3-year rotation cycle (3y-RC), and in systems with winter wheat than in the systems with winter oilseed rape.

Furthermore, for the winter wheat systems with the 3y-RC, higher biomass and energy yields were calculated for the wide ACS with the SRC design, whereas with the 6y-RC, similar biomass and energy values were observed with both alley widths, but in general also slightly more in the SRC design.

Concerning the systems with winter oilseed rape, lower biomass yields were produced in the wide ACS than in the narrow ACS, with both rotation cycles and both designs, and even less in the crop open field. The greatest biomass and energy yields were observed in the sole-cropping system with the SRC-control field, without crop component. In both rotation cycles, slightly more energy was produced in the ACS with the SRC design than in the combined design and also with the wide crop alleys.

4 Discussion

The several measurements carried out at the experimental site of the Julius Kühn-Institute aimed at assessing the modifications of the growing conditions (mainly regarding microclimate, light and leaf coverage) in the alley-cropping system (ACS), and especially in the competition zone, at the tree/crop interface. Moreover, the productivity of the tree and crop components and of the whole system was assessed. In the following sections, these issues will be discussed: the description of the modified growing conditions, their effects on the productivity of each component, as well as on the productivity of the whole system. The results presented in the previous sections also allow to discussing the different designs and arrangement options in ACSs, in order to maximize the productivity of ACSs.

4.1 Modifications of growing conditions in the alley-cropping system

4.1.1 Modifications of wind velocity

The wind velocity reduction on the leeward side (wind-sheltered area) of the crop alley was substantial in 2013, when the short rotation coppice (SRC)-strips were the tallest. In 2014, as the SRC-strips were much smaller because of the previous harvest, almost no wind velocity reduction occurred, in any direction. As expected, these results show that the presence of SRC-strips on the crop field creates a windbreak effect, depending on the height of the SRC-strip. Böhm et al. (2014), who also assessed the windbreak effects in ACSs, observed similarly that wind velocity reduction increased with tree height. Besides, less wind velocity reduction was observed during winter 2013 than during summer. This effect is attributed to the increased porosity due to the absence of leaves, which determines the amount of wind velocity reduction (Cleugh, 1998).

Several authors who studied the effect of hedges and windbreak on wind velocity stated that on the leeward side, the quiet zone extends mostly up to 10 to 20 h, where h is the tree height (Cleugh, 1998; Brandle et al., 2004). The leeward zone could even extend up to 30 h (Röser, 1995; Wang and Takle, 1995; Cleugh, 1998). Kreutz (1952) considered that 15 h would rather be the average under German conditions. 20 to 30 h would be the leeward zone length with multirow windbreak, such as an ACS with several SRC-strips. During summer 2013, the SRC-strips on the western side of the wind velocity measurements (leeward side) at the experimental site were 6 m high on average. According to the studies cited above, the quiet zone should have been given up to at least 60 m (10 h) from the leeward SRC-strip. When considering the wind from all directions, in the wide crop alley, the open field velocity (100 %) was reached at 35 m (5 h), whereas in the narrow alley with 48 m width (8 h) it was not reached at all. Thus, only the results of the narrow alley are quite in line with the literature concerning the size of the quiet zone. Besides, Kreutz (1973) estimated that there is a wind protection up to 50 % of the open field wind velocity. Stoeckeler (1962) observed a wind reduction $>$ 50 % up to 10 h on the leeward side, with a hedge porosity of 50 %. In the studied ACS, during summer 2013, 50 % of the open field wind velocity was measured up to approximately 25 m (4 h), in both alley widths with north and west winds, and up to approximately 5 and 15 m (1 and 2.5 h) regarding the wind from all directions, respectively for the wide and narrow alleys. The size of the wind-protected area in the present ACS was thus lower than the observations of other authors.

These results show that the narrow alley offered a better wind protection than the wide alley. This is notably explained by the fact that the measurements in the narrow alleys were situated behind several SRC-strips, whereas only one strip was present in front of the wide alley measurement. This indicates a better wind protection behind several SRC-strips, which was also confirmed by measurements carried out in early autumn 2013 and the observations of Kreutz (1952). The fact that the size of the leeward zone was smaller than in the observations of other authors is probably due to the low velocities observed on the experimental site in general. Furthermore, in the studied ACS with north-south oriented SRC-strips, the greatest wind reduction was observed with west winds, which are the main winds in long-term measurements at the experimental site. This result corresponds to the statements of Kort (1988) who suggested that the wind velocity reduction is optimized when the strip is oriented perpendicular to the main winds.

4.1.2 Modifications of light

Another important interaction in ACSs is the competition for light (Jose et al., 2004): trees are shading crops in their vicinity, and this phenomenon increases with tree height. The results of the calculation of solar radiation conducted in this study reflected this shading effect, as a greater light reduction was measured next to the SRC-strip and when trees were the tallest in 2013. In this year, the shade of the SRC-strips was cast up to 20 m into the crop alley, on the leeward and windward sides, for both crops and both alley widths. But the greatest light reduction ($>$ 90 % of open field solar radiation) was measured up to 10 m into the crop alley. The size of the shade was the greatest on the leeward side of the winter wheat narrow alley because trees were the highest there, due to the different rotation cycles of the SRC-strips. The absence of shade on the windward side of the winter wheat wide alley in 2013 and of the winter barley wide alley in 2014 is simply due to the absence of SRC-strip there. According to Krueger (1981), in the shaded area, mainly orange, yellow, green and infra-red rays reach the crop, which are photosynthetically less active than red and blue light rays. Thus, a yield reduction was expected in the shaded area, especially in a zone of 10 m, at least in 2013.

4.1.3 Modifications of air temperature and relative humidity

The air temperature and relative humidity (RH) values over the crop alley, separately analyzed for different day periods and different day conditions, differed most from the values in the open field, but also between the measurement points, in 2013, when trees were the tallest. This suggests that, as a consequence of wind velocity and light reduction, the presence of the SRC-strips had an effect on these parameters. Several authors reported that hedges, and by extension SRC-strips, influence microclimate by increasing temperature (several degrees celsius) and humidity in the wind reduction zone, up to 8 h on average (where h is the strip height) (McNaughton, 1988; Grace, 1988; Cleugh, 1998; Brandle et al., 2004). According to these authors, the zone of increased temperature and RH was expected to be 48 m wide for 6 m high trees in 2013, which is the width of the narrow alley.

However, when the hourly temperature and relative humidity (RH) values were averaged over the measurement period, almost no differences were observed between the measurement points in the alley-cropping system (ACS), and between the measurement points and the open field (see appendix C). The differences just appeared when the values were separately analyzed for different day periods (morning, noon, afternoon) and different weather conditions (cloudy, sunny). As the results showed, the temperature and RH values mainly followed the course of the shadow. In the morning, as the sun rose in the east, the leeward side of the crop alley received the solar radiation first and warmed up, while the windward side was still in the shade and stayed cool. At noon, when the sun was at its zenith, there was almost no shade, and the temperature and humidity was quite similar throughout the whole alley. In the afternoon, the shadow was cast on the leeward side of the crop alley, resulting in a decrease of temperature there, while the temperature increased on the windward side, where the sun shone. The RH followed the opposite trend of the air temperature (where the air temperature increased, the RH decreased). Due to the important effect of light on microclimate modifications, these effects were stronger on sunny days than on cloudy days.

The above mentioned results differ completely from what was observed for hedges by McNaughton (1988), Grace (1988), Cleugh (1998) and Brandle et al. (2004), i.e. higher temperature and humidity in the vicinity of the SRC-strip. Several explanations are proposed. Cleugh (1998) suggested that the shade modifies the heating in the quiet zone and, depending on the orientation of the windbreak, can offset the warming there. In that case, shade could be a more important factor for the modification of microclimate than wind reduction. Besides, at the Wendhausen site, the wind velocity values in the open field were quite low in summer 2013 (between 0.59 and 1.91 m s^{-1}), as this site is surrounded by a forest and other hedges. So it is assumed that the wind velocity reduction was not so relevant for the modification of the microclimate but rather the shading effect. Moreover, Bätjer et al. (1967) indicated that the microclimate changes behind a hedge are especially identifiable close to the ground level, but the present measurements were conducted at 1.5 m height above ground level.

Furthermore, the differences between temperature and RH values are only notable, when they exceed the measurement error, which was 0.4 °C for the temperature and 0.8 % for the RH in this study. In both years, differences up to 5 °C between the ACS and the open field values were measured, mainly on sunny days. In 2013, these differences might have influenced plant growth, as the observed values in ACS lay out of the range for optimum growth of winter wheat (between 15 and 20 °C, Diepenbrock et al. (2005)). However, as sunny days represent only few days in the vegetation period, this effect was probably only small on total yield. Moreover, as the incoming solar radiations and the tree heights differ from year to year, this effect cannot be generalized. In 2014, the temperature and RH differences between the sunny and cloudy days were also observed, however, they were smaller than the ones observed in 2013 and were only present at 3 m from the SRC-strip. At this measurement point, no wind reduction but reduced solar radiation was measured, as trees were already between 1.2 and 1.5 m tall at the end of the vegetation period, resulting in the lower temperature and higher RH there. Once more, these findings support the theory that shade was more responsible for the microclimate modifications than the windbreak effect on the experimental site.

Within the SRC-strip, the temperature and the RH followed similar trends than the measurement points in the shaded area in 2013: on sunny days, values were lower than the ones of the open field, but on cloudy days, they were quite similar to the ones of the open field. Similar results were reported by Ringler et al. (1997). In 2014, as the measurement was conducted at 1.5 m height in the SRC-strip (i.e. over the trees), air temperature and RH values were not so representative for the SRC-strip and more similar to the ones measured in the crop alley.

4.1.4 Modifications of potential evapotranspiration

Conversely to the effects presented in Cleugh (1998) and Brandle et al. (2004), who always observed reduced evaporation on the leeward side of a windbreak, the potential evapotranspiration (pET) parameter in this study followed the same tendencies as the air temperature and RH over the crop alley and over the day, i.e. it showed the highest values on sunny days and the lowest on cloudy days and in the shaded area, on the windward and leeward sides. The reason for this contrast is similar to the ones proposed for the temperature and relative humidity (RH) parameters: the shading effect was more responsible for the modification of the microclimate parameters than the windbreak effect on the experimental site. Cleugh (1998) affirmed in his study that shading may reduce evaporation and pointed out the complexity of the changes of microclimate parameters on evaporation. The pET is not only affected by temperature and RH, but also by radiation.

The results of the pET should be, however, interpreted carefully. Since the data were separated into day periods, it was not the temperature and the RH values at 2:00 pm that were used (as described in the method of Haude (1955)), but the mean temperature and the mean RH for each day period. It was important to divide the data into day periods in order to be able to find out whether different effects exist at different times of the day, depending on shade. Moreover, each used sensor has its own measurement error, which cannot be corrected (approximately 0.4 °C for air temperature and 0.8 % for RH). For this reason, it must be kept in mind that this error could be also included in the final calculated pET value. Furthermore, poplar roots could have had a considerable competition for water with crops, and thus influence the microclimate. But the effect of the poplar roots could not be taken into account in the calculation of the pET because no month factor was available for this crop.

4.1.5 Modifications of soil water tension and leaf ground coverage

The soil water tension indicates the energy which plants need to extract soil water (Webster, 1966) and thus provides information on the presence of roots in the assessed soil layer. A tension value of 0 means a wet soil, whereas a higher value (in this study up to 200 cBar) indicates a drier soil. Within each assessed depth beneath the trees, the soil dried out homogeneously over the measurement period. This demonstrates that the poplar roots grew down to at least 90 cm depth. As already reported in International Poplar Commission (1979), poplars show a high proportion of horizontal surface roots from which develop vertical plunging roots, which can grow very deep, depending on water table and soil texture. Furthermore, it is common knowledge that poplars have a large water requirement and a great need for light and oxygen especially regarding their roots (International Poplar Commission, 1979; Dillen et al., 2011). The soil layer at 90 cm depth under the short rotation coppice (SRC)-strip could have been influenced by ground water, explaining the fluctuations of soil water tension.

In the crop alley, at 3 m into the leeward zone, the soil dried out especially at the depths of 30 and 60 cm, indicating the presence of roots in both soil layers. The barley plants around the sensors were damaged during the instrument installation and thus grew badly at this spot, explaining the very low soil water tension values at 15 cm. In the middle of the crop alley, most of the soil water was absorbed in the first soil layer, down to 30 cm. Thus, the winter barley plants were probably taking water down to 30 cm depth but not at 60 and 90 cm, testifying to the presence of winter barley roots down to at least 30 cm depth, but not at 60 cm depth anymore. However, in the measurement at 3 m from the SRC-strip, it was observed that at 60 cm depth, the soil dried out, although winter barley roots did not reach this depth. This suggests that poplars rooted under the winter barley at this depth, 3 m away from the SRC-strip. Crow and Houston (2004) also observed that poplar roots mostly develop in the plowed soil horizon, and that poplars in outer rows tended to develop larger roots. Thus, they could have been in a direct competition for water and nutrients with the adjacent cultivated crop, as suggested in previous paragraphs and by (Jose et al., 2004) more generally for agroforestry systems. Some decreases in the soil water tension values were observed in the upper soil layers of the three measurement points, almost at the same dates, corresponding with precipitations.

Poplar leaves were identified mostly up to 8 m next to the SRC-strip, in the autumn of both years, and especially in 2013, shortly before the harvest of the SRC-strips, when trees were taller than in autumn 2012. At the experimental site, poplar leaves showed surfaces up to 176 cm^{-2} and a leaf area index of 2 (data not shown), indicating big sizes of leaves. This is due to the fact that the poplars clones used in this study were bred to have great leaves in order to catch as much light as possible. This property of poplar leaves, but also their known allelopathic interference (Singh et al., 2001), could have caused damage to the young cereal and oilseed rape plants, which were just emerging at the time of litter fall. This effect was especially strong on the present experimental site, because here, the sowing is carried out very early, just before litter fall, due to the low traffic ability from October.

To sum up, the main abiotic stresses in the vicinity of trees were in this study the lack of light (especially on sunny days, resulting in reduced temperature), leaf coverage and eventually root competition. This competition zone was observed approximately up to 10 m into the crop alley. The effects of these modifications on yield will be presented in the following section.

4.2 Effects of modified growing conditions in the alley-cropping system on yield and quality parameters in crop alleys

In this section, the effects of the modified growing conditions, as discussed in section 4.1, on the yield and quality parameters of the crop alleys will be presented.

4.2.1 General effects on yield and quality parameters in crop alleys

Effects of assessment year and distance from short rotation coppice-strips

The model predictions of 2013 and 2014 presented bell-shaped curves for yield and inverted bell-shaped curves for grain moisture content (MC), regarding both crops (winter wheat and winter barley) and both alley widths (48 and 96 m) in the alley-cropping system (ACS). These shapes were more curved in 2013 than in 2014, suggesting a stronger effect in 2013, when the trees were the tallest. Conversely, the curve shapes in the open fields (without trees) in 2013 and 2014 and in the summer barley of the ACS in 2008 (when trees were just planted) were straight lines without slope, showing the absence of effect there. This suggests that the short rotation coppice (SRC)-strips had an effect on both, the yield and the MC. The significant effects of distance, alone and in interaction with the alley width and the crop, which were detected for both, the yield and the MC models of the ACS, are also consistent with this effect. The other measurement parameters, related to crop yield and quality (yield components, phenological stages, aphid infestation and hectoliter weight) were also more affected by the SRC-strips in 2013 than in 2014, especially in their vicinity. However, it is assumed that the bell-shaped curve of the predicted for the winter barley in the ACS and the quite high MC values at 40 m in the narrow alley of the winter barley, both observed in 2014, were not directly an effect of the SRC-strip, but of a compaction damage. During the tree harvest in winter 2013/14, the trailer drove over the crop alley, next to the SRC-strip. As the frozen soil started to thaw after a while, a compaction damage was created on the soil and the crop.

Kreutz (1973) as well as Kowalchuk and de Jong (1995) stated that a negative effect on yield should appear up to 1.5 h (where h is the strip height) from the hedge. Akbar et al. (1990), Puri and Bangarwa (1992) and Chirko et al. (1996) measured wheat yield reductions up to at least 5 m from the trees. Müller (1956) also observed the lowest yield next to the hedges, for different crops. Bruckhaus and Buchner (1995) reported a yield depletion of winter cereal crops within 2 h for wet years. For cereals, Marxen-Drewes (1987) observed a reduced yield at the field edges, in both fields, with and without hedge, but a greater reduction next to the hedge. In the present study, a yield reduction zone was identified on both. the leeward and windward sides of the crop alley, next to the SRC-strip. In 2013, yield values below the mean were mainly observed on the leeward side up to 10 m into the narrow alley of the winter wheat. This distance corresponds to approximately 1 h, as the SRC-strip was 9.4 m high. Thus, the results of the present study are consistent with other studies. Moreover, the yield reduction zone corresponds to the size of the competition zone identified on the experimental area, where the growing conditions were modified. Therefore, the yield reduction next to the SRC-strips can be attributed to these modifications, and notably the reduction of incoming solar radiation, also suggested by Chirko et al. (1996), high leaf ground coverage and air temperature on sunny days, as concluded in the previous sections.

Effects of crop species and strip height

Independently of the SRC-strip effect, higher yields and hectoliter weights were observed for winter wheat than for winter barley, which is common under German conditions (Diepenbrock et al., 2005). The significant effects of the crop species which were detected in 2013 and 2014 in the models of yield and MC are consistent with these conclusions. Concerning the yield components of the winter barley in 2013, both, the ear number per m^2 (EN) and the thousand grain weight (TGW), significantly affected the total grain weight (GW), whereas the GW of the winter wheat was only affected by the EN or the TGW. This shows that the lower GW of the winter wheat was due to a lower EN. The winter wheat had indeed a higher tiller number at 8 m than at 3 m from the SRC-strip, which is attributed to the shading effect at 3 m during tillering and later on during stem elongation, as similarly found by Marxen-Drewes (1987). Conversely, the winter barley produced a higher tiller number and reached higher yields than the winter wheat, already at 3 m distance from the SRC-strip. This crop might have been less affected by the shading effect than the winter wheat, due to the earlier tillering in the growing season before the full development of the poplar leaves.

The width effects observed on yield and MC distribution and also on quality parameters in 2013 were mostly a result of the different SRC-strip heights. The SRC-strips next to the winter wheat and winter barley were in different rotation cycles on the leeward and the windward sides of the crop alley, in both, the narrow and the wide alleys of the ACS. This explains that for winter wheat, the yield reduction was greater on the leeward than on the windward side in the narrow alley (strip heights were 9.4 m on the leeward and 6.8 m on the windward side). However, it was decided to keep both crops in the models in order to obtain more information about the general effect of the SRC-strips on crop productivity. Also because of the different strip heights, the points of the narrow and the wide alleys were pooled together in the yield components analysis. This was carried out for both crops, in order to obtain comparability in the analysis. Thus, no width effect could be tested on yield components.

In the following paragraphs, the yield modifications will be discussed separately for the competition zone in the vicinity of the SRC-strips, where the strongest effects were observed, and for the middle of the crop alley, where the weakest effects were observed.

4.2.2 Effects of modified growing conditions on yield and quality parameters in the competition zone

Modifications of plant development, yield and yield components

Wheat and barley plants are the most vulnerable to abiotic stress in the early reproductive phase: from floral meristem development to anthesis (flowering) (Dolferus et al., 2011). According to the scale of Meier (1997), the stage of flowering is represented by the phenological stage number 60. In 2013, this phenological stage was reached in the middle of the crop alley and in the open field at the end of May for the winter barley, and in the middle of June for the winter wheat. Fischer (2011) stated that May is the month with the best growth in Northern European latitudes. However, in both months, the trees already had their full leaves. Thus, it can be assumed that the wheat and barley plants suffered from the shading effect at that time, at least shortly before the flowering. This effect probably explains the delayed plant development and thus the lower yield observed in the vicinity of the short rotation coppice (SRC)-strips than in the middle of the crop alley and in the open field. Puri and Bangarwa (1992) also found out that the development of winter wheat was delayed under trees and Marxen-Drewes (1987) observed a different plant growth between the edge and the middle of the field, in both fields, with and without hedges.

In 2013, the total grain weight (GW), the ear number per m^2 (EN) and the thousand grain weight (TGW) of the winter wheat and the winter barley were lower on the leeward and the windward sides than in the middle of the crop alley and in the open field, and those of the winter wheat showed a greater value range. The closer correlation between the GW and the EN than the one between the GW and the TGW of both crops observed on the leeward and windward sides shows that yield reduction in the vicinity of the SRC-strip was mainly caused by the reduction of the EN per m^2, especially for the winter wheat. As suggested by Friend (1966), the lower EN, as a result of a lower plant number per m^2, can be attributed to the lower light intensity and temperature in the vicinity of the SRC-strips. Similarly, Marxen-Drewes (1987) observed at an experimental site in Northern Germany that the number of winter wheat and winter barley plants was reduced in the vicinity of the hedge compared to a measurement point at 66 m from the hedge. Moreover, Dufour et al. (2013) also observed a yield decrease due to shading in an alley-cropping system (ACS), as a result of the reduction of both, the grain number per ear and the total grain weight, whereas the mean grain weight per ear was affected only moderately. This is consistent with the statements of Dolferus et al. (2011). According to them, the grain number per m^2 is the main component directly linked to the yield in cereals like wheat. Marxen-Drewes (1987) found out that the number of ears was decisive for the yield, but also that the TGW decreased with increasing tree height. The TGW provides the best indications about grain size. Furthermore, a grain sample with low TGW will have a high hectoliter weight (Milatz, 1970), which is consistent with the observed results. This suggests that the grains harvested next to the trees were smaller than in the middle of the crop alley.

At the experimental site in Wendhausen, the winter cereals have to be sown very early, at the end of September, because of the low traffic ability on the field from October. Consequently, the winter crops are already at the stage of small plants when the poplar leaves start to fall. Poplars are characterized by big leaves, resulting in great leaf ground coverages next to the SRC-strips. Thus, these high leaf ground coverages observed in the vicinity of the SRC-strips might also have been responsible for a lower number of plants, and thus a lower EN. This effect is even stronger for the winter wheat in both years during which greater leaf coverage and tree height were reported. Thus, it seems that the leaf coverage effect increases with increasing strip height. The trees were harvested in January 2014 and thus were tall from September 2013 (sowing) until January 2014 and quite small until the harvest in July 2014. Nevertheless, in 2014, there was still an effect of the EN on the GW for both crops, confirming the important influence of leaf coverage at the beginning of the plant development. But until now, no study exists to confirm the present results. This important effect of leaves on productivity could be avoided by later sowing dates, after the litter fall, and the incorporation of leaves in the soil. However, this depends on the soil traffic ability of the field in winter.

Singh et al. (1998) observed a yield reduction of wheat up to 12 m away from the shelterbelt (less than 1 h, where h is the strip height) in the southern area (with maximum incoming light) of an east-west oriented *Populus deltoides* tree row of 16 m height, compared to the unsheltered zone (further away). This reduction was attributed to potentially because of a competition and phytotoxic interference with poplar trees. The allelopathic effect of poplar leaves could also explain the negative effects on yield but was not directly assessed in this study. The influence of weed competition could also be a reason for yield depression in the competition zone. According to other observations in this study (data not shown), more weeds were detected in the margin between the SRC-strip and the crop alley than within the crop alley.

Modifications of aphid population density

In the growing season of 2013, when no insecticide was applied, greater populations of aphids and slightly more beneficial insects (mainly ladybug and its larva, green lacewing and its larva and syrphid flies) were recorded next to the SRC-strip than in the middle of the crop alley and in the open field. Winged aphids can better control their landing when the air does not move (Dixon, 1998) and can thus land more easily in the vicinity of the SRC-strips (Lewis and Stephenson, 1966), as the wind velocity is reduced there. Moreover, because the plants in the shaded area were delayed in their development, they stayed green for a longer time and thus were more appropriate for aphids than the plants in the middle of the crop alley which became senescent earlier. Consistently with the present results, Marxen-Drewes (1987) observed that the infestation of aphids was higher at the field edge, independently of the height of the hedge. In the middle of the crop alley and in the open field in 2013 and everywhere in 2014, the number of aphids only had a negligible effect on crop growth, as it was clearly below the economic threshold (approximately 20 per tiller, Dixon (1987)).

Modifications of quality parameters

In 2013, higher grain moisture content (MC) values were measured and predicted in the vicinity of the SRC-strips than in the middle of the crop alley. Moreover, the grain MC was higher in the narrow alleys than in the wide alleys. Some MC values in the narrow alleys and next to the trees were even > 17 %, which could have led to a bad grain storage (Diepenbrock et al., 2005). These results can be attributed to the modified microclimate conditions, especially the higher relative humidity (RH) and lower potential evapotranspiration (pET) next to the SRC-strips. As a matter of fact, due to the weak air movement and evaporation in this zone, but also because the plants remain in an earlier stage of development, the grains cannot dry as fast as in the middle of the crop alley (Röser, 1995). The MC values in the winter wheat wide alley were higher on the leeward than on the windward side, as there was no SRC-strip at this place. Furthermore, the influence of SRC-strips on the MC is supported by the fact that all observed values in the open field were similar over the subplot.

Concerning the hectoliter weight, it was reduced next to the SRC-strips, suggesting smaller grains and/or higher grain moisture contents there than in the middle of the crop alley (Milatz, 1970; Egger, 1989). In Germany, this parameter is used to set the price of fodder cereals and the minimum value that should be reached for winter barley is 63 $kg.hL^{-1}$ (Diepenbrock et al., 2005). However, values over this threshold were measured only at a few measurement points in 2013.

Other quality parameters of cereals, which were not assessed in this study, might also be affected by SRC-strips. For instance, the reduced pET and higher RH next to the SRC-strips observed on sunny days could contribute to increased disease infestation (Brandle et al., 2004). Furthermore, five years after the tree planting, Jung et al. (2014) measured an increased protein content in summer barley grains directly next to the SRC-strip. These authors reported an increased mycotoxin content next to the SRC-strip, even though it was below the critical value set by the European legislation.

4.2.3 Effects of modified growing conditions on yield in the middle of the crop alleys

Many authors reported the positive effects of wind protection on the yield in the non-shaded area of the crop alley, which should be above the field mean, due to the reduction of potential evapotranspiration (pET). For instance, Kowalchuk and de Jong (1995) observed an increase of yield above the field mean between 1.5 and 3 h from the hedge (where h is the strip height) under dry conditions. Stoeckeler (1962) recorded a small but consistent yield increase of 2 % up to 10 h from the hedge, and mostly in the first 5 h. Müller (1956) observed the highest yield at 3 h, and then a constant decrease of the yield down to the mean with increasing distance from the hedge. Furthermore, Kort (1988) reported in his review that shelterbelts always have positive effects on winter wheat and barley. These positive effects appear up to 20 h, but are most pronounced between 3 and 10 h, which correspond to the quiet zone on the leeward side defined by Cleugh (1998). Bruckhaus and Buchner (1995) supposed that the yield increase should occur only in dry years.

At the experimental site, in 2013 and for both crops, the predicted yield and sometimes the measured yield was above the mean of the measured yield in the middle of the narrow alleys and at 20 m from the leeward short rotation coppice (SRC)-strip in the wide alleys (approximately 3-4 h). These findings are in line with previous studies. However, it is problematic to attribute this yield increase to the effect of the wind protection, as it is not possible to directly compare the values observed in the middle of the crop alleys with the values of the open field. On the experimental site of this study, the crop alleys and the crop open fields show different soil textures and as a consequence potentially different water holding capacities. However, this parameter influences the yield. Further research with similar soil conditions in both, the alley-cropping system (ACS) and the open field, is necessary to find out whether the yield increase in the middle of the crop alleys is really above the potential yield of the open field.

4.2.4 Influence of soil conditions and spatial location of the crop alley on yield and grain moisture content distribution

The soil apparent electrical conductivity (EC) was measured at the experimental site and integrated in the models for yield prediction. This parameter provides information about soil differences as it is influenced by soil parameters, such as soil moisture, pore size and distribution, temperature of soil water and the amount of colloids and their composition (McNeill, 1980). Moreover, this parameter is also strongly influenced by soil temperature, bulk density and soil texture (especially clay content) (Domsch and Giebel, 2004; Sudduth et al., 2001). Consequently, the EC is supposed to be directly correlated to the yield (Anderson-Cook et al., 2002). This is consistent with the fact that the smoother for soil conductivity $(f_4(nEC_{25i}))$ was a significant term in almost all models used to predict the yield in the crop alleys and the open field. By including the mean normalized soil apparent electrical conductivity corrected to 25°C value (nEC_{25}) of each crop alley as parameter in the model for the yield predictions, the effect of the soil heterogeneity within the alleys and open fields at the experimental site could be partly corrected. In doing so, the predicted yield within one alley or subplot should only be influenced by the distance from the short rotation coppice (SRC)-strips.

In 2013, the smoother $f_4(nEC_{25i})$ significantly influenced the yield, whereas only nEC_{25} as linear factor was significant for the grain moisture content (MC). This is due to the fact that the grain MC is probably less influenced by soil conditions than the yield, but more directly by the SRC-strip itself, mainly through shading. This also explains the lower variation in the MC data than in the yield data. In 2008, almost no effect of the SRC-strip on the yield was detected and the slight curved line that was predicted is attributed to soil heterogeneity because all fields were pooled together. The great data variation is also attributed to this effect.

Moreover, as a spatial auto-correlation was detected in the yield and the MC data, the spatial smoother $(f_5(X_i, Y_i))$ was included in the models used to predict these parameters. This was done in order to correct the effects caused by the position of the points in the alley and over the whole area, similarly to the considerations for the soil heterogeneity with the EC. However, this sometimes created predicted yield and MC values which deviated from the measured values, resulting in a curve following another trend than the curve of the measured values, as for instance, for the yield values in the wide alleys of the winter wheat and the barley in 2013. There, the predicted yield was strongly influenced by the small zone of Kolluvisol-Gley in the crop alley 8, which affected the yield negatively. This also explains why the predicted yield was sometimes slightly higher than the actual measured mean.

The effects on the yield of the SRC-strips as a consequence of the modified growing conditions will be discussed in the next section.

4.3 Effects of modified growing conditions in the alley-cropping system on yield of short rotation coppice-strips

4.3.1 General effects of modified growing conditions and rotation cycle on yield of short rotation coppice-strips

In general, tree growth and biomass production were different between edge and middle rows within the alley-cropping system (ACS) and between the ACS and the short rotation coppice (SRC)-control field, in the different assessed years. These effects were already detected on the diameters at breast height (DBHs) in 2009, as trees were two years old. In 2014, after the first harvest of the SRC-strips in the 6-year rotation cycle (6y-RC) and the second harvest of SRC-strips in the 3-year rotation cycle (3y-RC), small differences on DBH and height were detected between rows. The greatest differences between rows and systems, however, were detected in 2013, but statistical significant differences were only observed in 2009 and 2014, when the numerical differences were the smallest. This absence of statistical effect is attributed to the great data range in 2009 and 2013.

The greatest differences between both rotation cycles were observed in 2013 for the DBHs. They were much larger in the 6y-RC than in the 3y-RC. The number of shoots per tree also differed in both rotation cycles. Trees in the 6y-RC showed mostly only one shoot, whereas trees in the 3y-RC had more than 4 shoots per tree. Indeed, as trees in the 3y-RC were already coppiced, they regrew in a shrub-like shape (Sennerby-Forsse et al., 1992). Thus, the differences between the rotation cycles can be mainly attributed to the fact that one rotation cycle was already harvested once.

Even though the rotation cycles presented different structures, this did not affect much the yearly biomass production of trees, which was very similar between both rotation cycles. However, as Auclair and Bouvarel (1992a) suggested that biomass production is greater after coppicing and Herve and Ceulemans (1996) found better intrinsic growth performance on coppiced trees, a greater biomass production was expected in the 3y-RC. This different result is attributed to the higher mortality observed in this treatment after the first harvest (data not shown). The change in phenol content after coppicing (less phenols predispose to rot fungi and thus mortality) (Sennerby-Forsse et al., 1992), but also the fact that poplars are highly susceptible to disease and insect infestations (Dillen et al., 2011) can explain this effect. The results of 2014 showed similar regrowth in both rotation cycles in the first year after the harvest. Further observations are thus needed to find out how the rotation cycle influences the yield over the years.

Similarly to the results of the crop alleys, the effects of the modified growing conditions on SRC-strips will be discussed separately for the outer (leeward and windward) rows, in the competition zone, and the middle rows.

4.3.2 Effects of modified growing conditions on edge rows of short rotation coppice-strips

In 2013, in both designs, the outer rows of the poplar short rotation coppice (SRC)-strips within the alley-cropping system (ACS) showed larger diameters at breast height (DBH) than the middle rows. This result is attributed to the bigger available space next to the alley boundary, which is known to influence poplar shoot diameters positively (Cannell, 1980; Auclair and Bouvarel, 1992b; DeBell et al., 1996; Benomar et al., 2012). The high biomass production in edge rows is thus a result of the large DBHs, as this parameter was proportional to diameter growth in this study, but also of the high number of shoots (Lamerre et al., 2015). This effect was already observed for the same clone in the study of Gamble et al. (2014). Higher survival rate of branches for large plant spacing was also measured by DeBell et al. (1996) for the poplar hybrid *P. trichocarpa x P. deltoides*. These findings confirm the importance of increased space availability at edge rows for the positive impact on biomass production.

Light is also an important factor for poplar growth (Farmer, 1963; International Poplar Commission, 1979). The higher light availability at edge rows led to a higher number of shoots but lower shoot heights, as suggested by Ringler et al. (1997). Furthermore, poplars show a high apical dominance and an important phototropism and thus incline in the direction of the light intensity (International Poplar Commission, 1979). This reaction was also observed on the experimental field (data not shown), confirming the important impact of light in growth differentiation between rows in the present ACS. It should be mentioned, that this effect is only valid for the north-south orientation.

Even though the SRC-strips were not fertilized in this study, it was expected that a higher nitrogen concentration could be available at the edge rows, due to the proximity of the fertilized crop alley and the casual use of centrifugal fertilizer spreader with low precision (Lamerre et al., 2015). Nitrogen should positively enhance poplar biomass production, as reported by Curlin (1967), Liu and Dickmann (1992), Heilman and Fu-Guang (1993) and Hofmann-Schielle et al. (1999). These last authors found, however, positive effects on biomass production of a balsam poplar clone only in the first rotation period, while Heilman and Fu-Guang (1993) observed a decisive role of nitrogen until the third rotation period. But the effect of fertilization differs with site characteristics (Kauter et al., 2003). Moreover, according to Wühlisch and Chauhan (2011), poplars should be able to fix nitrogen with the help of endophytic bacteria. For these reasons and as the middle rows of the combined design did not receive fertilizer and still produced great biomass, it can be considered that the effect of nitrogen in this study was minimal compared to the positive effects of light and space.

Furthermore, in 2013, in the 6-year rotation cycle SRC-strips, leeward rows tended to produce slightly more biomass and showed larger DBHs than the windward rows. A favorable effect on poplar growth in the leeward rows can be attributed to the casual higher temperature observed on sunny days, which would contribute to a higher growth rate and higher leaf area index (Grace, 1988). Conversely, higher wind speeds on the windward side would cause higher transpiration rates of trees (Taylor et al., 2001), as well as potential damage of the leaf cuticle (Dixon and Grace, 1984), explaining the slower tree growth observed there. However, the higher diameters observed on the windward rows than on the leeward rows in the 3-year rotation cycle contradict the previous results, and can be mostly attributed to shading effect. As formerly concluded for the effects on crop alleys, the wind velocity reduction probably did not play an important role at the experimental site of Wendhausen, as the wind speeds were quite moderate, and the assessed SRC-strips were already situated in a protected area behind several SRC-strips. This supports the conclusions that light and space explain the present results.

4.3.3 Effects of modified growing conditions on middle rows of short rotation coppice-strips

In both rotation cycles, the middle rows of the short rotation coppice (SRC)-strips in the SRC design were characterized by a low number of shoots with small diameters, contributing to the low biomass production measured there compared to the edge rows. The reduced available space in these rows compared to the one available for the edge rows can partly explain this effect. As poplars are considered as shade intolerant (Farmer, 1963; International Poplar Commission, 1979), the reduced light availability in the middle rows of this design might also have been implicated in the reduced biomass production. Narrow spacing for trees also means higher competition for others resources such as water, which was identified as relevant for poplar growth in SRC (Ceulemans and Deraedt, 1999). This increased competition could be also responsible for the low biomass production in these rows. The same explanation can be given for the results of the SRC-control field, which were similar to the ones observed in the middle rows of the SRC design.

Concerning the combined design, the biomass production in the middle rows was different in the 3-year rotation cycle (3y-RC) and in the 6-year rotation cycle (6y-RC). This result is unlikely to be linked to the rotation cycle, but rather to the SRC-strip structure at the time of measurement. A greater distance between aspen and poplars trees was provided, leading to more space for the poplar trees in the middle rows of the combined design. The high biomass production of the middle rows in the 6y-RC is thus consistent with our expectations, but the low biomass production of the middle rows in the 3y-RC are not. As an explanation, it is suggested that these trees could have suffered from the shading of aspen trees after the first harvest.

4.4 Effects of modified growing conditions and system design on total productivity of the alley-cropping system compared to the sole-cropping systems

4.4.1 Effects of system and crops species

Regarding biomass and energy production purposes, the alley-cropping systems (ACS) with narrow and wide alleys produced higher aggregated crop grain and tree yield over the years than the crop sole-cropping system (SCS). These results are generally attributed to the higher yields of trees than of crops (only grain yield was considered). The higher yields observed in some years in the crop alleys in comparison to those measured in the open field, and the higher yields observed in the short rotation coppice (SRC)-strips, especially in 2009, compared to the ones measured in the SRC-control field, also explain these results.

However, these observations should be interpreted with caution, notably because a strong year effect was perceived in the data. Moreover, different soil conditions were present between the ACS, the open field and SRC-control field. The lower winter wheat yields observed in the open field compared to the ones measured in the ACS in 2012 can be explained by soil differences and the dry weather conditions, that could have been less unfavorable in the ACS due to the high clay content and subsequently its high water holding capacity. Furthermore, the straw production of wheat and winter oilseed rape, that can also be used for energy production, was not included in the calculation. The reason for this choice is notably that the straw was not harvested in the present context but stayed on the field to be incorporated in the soil. However, if the straw was included, the yield proportion of the crop component would have been doubled in each system, as both crops have a minimum of 50 % straw content.

The grain yields and energy yields in the system evaluation were higher for winter wheat than for winter oilseed rape, which commonly produces lower grain yield than winter wheat (Diepenbrock et al., 2005), but shows a higher calorific value in grain (Döhler, 2009). In winter wheat systems, the trends between the systems for energy yields were similar to those for biomass yields, because poplar and winter wheat have similar calorific values. Interestingly enough, concerning the winter oilseed rape system in the 3-year rotation cycle (3y-RC), the highest energy production was reached with one hectare of poplar SRC. Thus, even though the winter oilseed rape grains have high calorific values, the yields are still too low to compete with a SRC plantation. Stone and brown coal still present higher calorific values (respectively 29.7 and 20.6 GJ t^{-1}) than poplar wood and winter wheat grain (Döhler, 2009), and would thus stay more competitive in terms of energy production than an ACS. However, they have quite high ash contents (Döhler, 2009). Including the straw production in the system calculation would double the total biomass and energy production of the ACS with winter oilseed rape, which would be subsequently similar to the production of a SRC plantation.

4.4.2 Effects of alley width and strip design

Regarding both crops, higher summed grain yields were observed in the wide alleys than in the narrow alleys of the alley-cropping system (ACS) over the years. However, as trees were the tallest (in 2013), similar yields were measured in both alley widths. Thus, these differences were rather attributed to a year effect than to a width effect. Different cultivars were used in 2008-2011 compared to 2012-2014, but these cultivars had similar properties. Concerning the winter wheat, *Mulan* and *Arezzo* are both adapted to marginal sites such as Wendhausen, show an early ripeness and should thus have similar yields. The winter oilseed rape cultivars *Taurus* and *Visby* are both characterized by high yields and early ripeness. The differences observed between the narrow and the wide alley-cropping systems in the system evaluation of winter wheat are thus attributed to the different yields measured over the years in both alleys widths (higher biomass and energy production in the wide alleys), mostly due to the different weather conditions. Furthermore, as the differences between the narrow and the wide alley-cropping systems in the system evaluation of the winter oilseed rape were smaller than for the winter wheat, the greater values of the tree component in the narrow alleys might explain the greater biomass and energy production of this system. Further measurements should be done in the future to find out whether there is a width effect on total productivity.

Concerning the short rotation coppice (SRC)-strips, the SRC design, in general, produced more biomass than the combined design. This is due to the low biomass production of the aspen trees per hectare, notably caused by their low planting density. Moreover, aspens have a different inherent growth pattern and considerable biomass increment was recorded first in the eighth to tenth year of growth on other sites (Liesebach et al., 1999). Slightly higher yields were reached in the systems with the 6-year rotation cycle than in the systems with the 3-year rotation cycle, which is explained by the slightly higher yearly biomass production of poplars observed in this rotation cycle. These results marginally differ from the precedent results of the biomass estimation conducted in 2013, notably because a different method of estimation was used. The rotation cycles should be compared carefully because the average yearly growth in 2010 was only estimated.

4.4.3 Conlusions on the system evaluation

In general, it can be concluded that the yields/energy outputs (grain and wood yield) of ACSs with narrow or wide alleys can be similar to the ones of sole-cropping systems, and even higher than the ones of an crop open field. However, the results on the economic level could be different. Each component of an ACS needs specific inputs and harvest techniques, which can be accompanied by additional costs. Moreover, poplar trees have a considerably higher water content when harvested (approximately 55 %) than winter wheat grains (approximately 14 %) and winter oilseed rape grains (approximately 9 %), which can cause additional costs for the transport. The customer should be situated in the close area of the ACS in order to avoid long transports of wood chips. All these parameters should be taken into account to analyze the presented systems on the economic level, which is decisive for the adoption of ACSs. The present study provides the basis for such an analysis.

4.5 Limits of the study

4.5.1 General limits of the study site

Alley-cropping systems (ACSs) such as the one assessed in this study are difficult research objects, as suggested by Stamps and Linit (1999). The observed yield effects are the result of several interactions between trees and annual crops. These interactions were only partly assessed in this study because not all of them can be integrated in such a study work. For this reason, any final conclusions about which single factors mostly influenced the yields cannot be drawn. Furthermore, the year effect cannot be excluded from the results. This work only aimed at the description of some selected above-ground interactions between the trees and the annual crops and their effects on the yield of both components. Some coherency was found between the mechanisms that modified growing conditions and the yield effects, however, this has to be interpreted with caution. Moreover, it should be clear for the reader that the present conclusions are only valid for the experimental field assessed in this study, notably because of its special soil conditions, and cannot be generalized to other soil and climate conditions. A process-based model such as "Yield-SAFE" (Van der Werf et al., 2007) would be necessary to be able to predict the yield of each component in each design situation for different site characteristics. However, this model is not appropriate for short rotation coppice (SRC)-strips yet.

A major difficulty in designing experimental agroforestry systems is to ensure the independence of treatments by randomization (Stamps and Linit, 1999). Moreover, real statistical replications of the systems would implicate their reproduction somewhere else in the landscape, which is not possible for obvious financial reasons. Some questions were difficult to answer due to certain arrangements of the design of the ACS in Wendhausen. As the rotation cycle of every second SRC-strip was different, it was not possible to compare windward and leeward effects in one crop alley due to divergent tree heights on both sides. Additionally, the fact that all crops were cultivated each year favored the repeatability of the measurements over the years, but prevented the use of real statistical repetitions (one in several fields). The use of different crop cultivars over the years also limited data comparability.

The sole-cropping systems (SCSs), the open field and the SRC-control field, used to compare performance of crop alleys and SRC-strips, were situated south and west of the ACS. However, as presented in section 2.1.4, different soil types characterize both areas, are also differ from the ones in the ACS. This soil effect probably influenced the results of the system evaluation, which should be thus only interpreted as tendencies. Moreover, one of the fields is influenced by a hedge and another one by the near forest on the western side (see appendix A). Concerning the yield component analysis, the values in the ACS and in the open field should also be compared with caution, as small-sized samples, used in this assessment, are even more influenced by soil differences than big sample areas. The place of sampling was always carefully selected to avoid turnaround paths or damaged area, but the variability in such a big field is still great and probably influenced the final results.

4.5.2 Limits of the employed methods

Since the study was only conducted over two years, a year effect is included in the main observed yield effects. Furthermore, the methods of assessment in this study are also debatable. As suggested by Müller (1956), the soil conditions along the transect from the windbreak should be exactly the same, in order to only assess the effects of the modified microclimate on yield. As it was not possible to fulfill this condition, it was decided to measure the soil apparent electrical conductivity (EC) and to integrate this parameter into the yield and grain moisture content (MC) models, in order to correct different soil conditions. The EC offers the possibility to rapidly assess local soil differences in high resolution, but a complete soil cartographic assessment in very high resolution would be more precise. However, this was not manageable due to limited time and resources. In the end, it was only possible to describe a tendency regarding the yield distribution over the crop alley, because the yield was also influenced by other parameters than the EC, for example the nutrient availability.

In the solar radiation calculation, which was carried out in the period between sowing and harvest, the growth of trees over the season was not included, as well as the fact that from the sowing of the crop to the harvest of trees at the end of 2013 trees were taller than between January 2014 and July 2014. It was assumed that the reduction of light was less important in autumn than in spring. For this reason, the tree heights measured between May and June 2013 and 2014 were used for the calculation. The obtained values should be mainly indicative for the potential light reduction next to the SRC-strips and its extension into the crop alley, but cannot totally represent the reality.

Concerning the biomass estimation of trees, only four short rotation coppice (SRC)-strips were selected in the alley-cropping system (ACS) in order to keep data collection feasible. These strips were chosen because they showed a good and homogenous growth. It was also important that these strips were situated next to each other to have similar soil conditions. But, as a result, they were all situated in the area most protected from the wind (eastern part of the ACS). For this reason, the presented results of the SRC-strips may not be applicable to windy conditions.

In the overall system evaluation, only the grain yield of winter wheat and winter oilseed rape was considered, although the straw is also a component of the system. This was decided in order to stay in line with the production scheme at the experimental site, where only grains and wood are exported and the straw is incorporated into the soil. Obviously, if the straw had been taken into account, different results would have been obtained. Moreover, the analysis was performed with only one crop over years, which was cultivated on different fields. This situation is clearly far from reality and an analysis including the different crops of the rotation would have made more sense. However, this was not possible notably because some yields were missing over the years.

It was decided to leave out an economic analysis of the different systems assessed in the overall system evaluation. However, this would have delivered helpful results to promote the implementation of ACS in the agricultural landscape of Germany and Europe. But such an economic analysis would only make sense if all steps of production were included and this would have been too time-consuming and would not correspond to the scope of this thesis.

From the results discussed in the previous parts, conclusions can be drawn regarding optimum designs of ACSs. Different options to improve the productivity of alley-cropping systems will be discussed in the following section.

4.6 Options to improve the productivity of alley-cropping systems

In order to optimize crop growth and erosion protection in alley-cropping systems, several parameters should be taken into account, such as strip height, porosity, orientation and alley width (Kort, 1988). The height of the short rotation coppice (SRC)-strip is determined by the rotation cycle and defines the distance up to which the wind speeds are reduced, whereas porosity, influenced by the planting density and strip width, affects the amount of wind velocity reduction (Cleugh, 1998). Brandle et al. (2004) argued that height and length together determine the total wind-protected area. Moreover, the continuity of the hedge (no gaps) also influences the wind protection. To contribute to biodiversity conservation, agroforestry systems should moreover maximize habitat heterogeneity and enhance landscape connectivity (Jose, 2009). These design options are discussed in the following section, in connection with the results of this study.

4.6.1 Strip orientation and length

As also found by Wang and Takle (1995), the results of this study showed the importance of the SRC-strip orientation in relation to the main wind direction for efficient windbreak, as the greatest wind reduction was observed for the main winds (west) at the experimental site.

However, according to Röser (1995), a north-south oriented windbreak hedge has a different influence on the incoming light in the crop alley than an east-west-oriented hedge. A north-south oriented tree rows generate shading effects on both, western and eastern sides of the crop alleys, whereas an east-west-oriented tree rows mostly cause shading on the northern side (Röser, 1995). Regarding east-west oriented windbreak hedges, Stoeckeler (1962) observed a better crop growth, an increased temperature and an earlier ripening south of the windbreak compared to its northern side. Thus, when selecting the strip orientation, it is important to find a compromise between wind protection and shading effect (Röser, 1995). If the area considered for the installation of the alley-cropping system (ACS) is already quite wind protected, such as in the studied site where the field surrounded by a forest, an east-west SRC-strip orientation could be an interesting alternative to maximize light and thus optimize crop yield. However, the effects of this orientation on the productivity of the SRC-strip should be investigated. In this study, the north-south orientation had a positive effect on the productivity of the outer rows of the SRC-strip, but an east-west orientation could bring different results because of the different light distribution (mainly on the southern side). If the ACS is implanted on a sloping field, the best orientation against water erosion would be along the contour lines (Dupraz and Liagre, 2008).

Cleugh (1998) pointed out the importance of considering the length of the windbreak, in order to ensure optimal wind protection also from oblique winds (that do not blow directly perpendicular to the windbreak). In the studies collected by this author, fences with a length greater than 40 h (where h is the windbreak height) and a porosity of 43 % provided an optimum windbreak effect. However, depending on the geometry of the field, it is not always possible to obtain such long strips. The strip length will usually be determined by the field length. Brandle et al. (2004) recommended a minimum length of 10 h in order to reduce the effects of wind flows around the ends of the windbreak. Dupraz and Liagre (2008) proposed to have a minimum field length of 100 m for single tree rows as the turnarounds of the agricultural machines at shorter field length are too time-consuming. An area, at least as wide as the biggest machine of the farm that has to turn around the SRC-strip, should be available at the end of each strip, which additionally reduces the actual length of the strip.

4.6.2 Rotation cycle of short rotation coppice-strips

A major result of this study is that the strip height directly influences the size of the competition zone in the crop alley (mainly through shading and leaf coverage). According to Brandle et al. (2004), it also determines the size of the area which is wind-sheltered and in which the microclimate is modified. Rotation cycle length is thus an important tool to control tree height and as a result the productivity of the system. Choosing short rotation cycles could ensure small trees and thus high crop productivity.

According to the present findings, the yearly biomass production of the short rotation coppice (SRC)-strips in a 3-year rotation cycle (3y-RC) is similar to the one of the SRC-strips in a 6-year rotation cycle (6y-RC). However, short rotation cycles reduce the survival potential of the trees and as a result their productivity over time (Sennerby-Forsse et al., 1992). The competition with weeds, to which poplar is sensitive in the first years of growth (Otto et al., 2010), could increase after each harvest. Additionally, frequent harvests could negatively influence biomass yield (Sage, 1999). Moreover, each time the trees are cut, the windbreak effect is lost for a while. A solution to counter the reduced wind protection after the harvest could be to harvest only each second strip (Böhm et al., 2014). This should, however, stay profitable for the farmer and would probably only make sense in big ACSs with many SRC-strips. Regarding nature and biodiversity protection, Unseld et al. (2011) recommended to harvest only some parts of the strips, in order to preserve habitats for present species, even though the costs would increase. Moreover, these authors supposed that longer rotation cycles would reduce greenhouse gas emissions.

It should be kept in mind that harvest time has to be chosen in the first place for maximum biomass yield. The optimal rotation cycle for biomass production in SRCs with high planting densities is 3 to 4 years (Ceulemans and Deraedt, 1999; Armstrong et al., 1999; Deckmyn et al., 2004; Nassi O Di Nasso et al., 2010). Poplar is considered to be a low quality wood for energy purposes, notably due to a high amount of branches (Dillen et al., 2011), which could rise with increased number of harvests. More research on the effect of the rotation cycle on SRC-strip yield after several harvests should be thus carried out in order to identify the optimal rotation cycle in ACS, including all these parameters. But certainly, waiting too long for the harvest would result in very high harvest costs, because automated harvesting becomes impossible and traditional felling must be implemented (Kauter et al., 2003).

4.6.3 Width and design of the short rotation coppice-strip

In this study, the biomass yield of the outer rows of the short rotation coppice (SRC)-strips was higher than the biomass yield of the middle rows (Lamerre et al., 2015). To reduce strip width while increasing the length and number of SRC-strips would thus increase the productivity of the SRC-strips per area (Lamerre et al., 2015). However, such a design of the SRC-strips should be adapted to each field on which the alley-cropping system (ACS) is established to ensure the profitability of the system, as a higher number of narrow SRC-strips could increase the harvest duration. Moreover, some rules should be respected to get basic payments for the SRC-strips: each strip must have a minimum size of 0.3 ha (European Parliament and Council, 2013c), which is not the case in the investigated ACS in this study. For this reason, the selected field for the ACS should be big enough, in order to allow for this minimum strip size.

Moreover, edge rows of the SRC-strips in the present ACS produced a higher number of shoots than middle rows, which could, however, negatively influence wood quality (Lamerre et al., 2015). According to Kenney et al. (1990), following parameters are involved in the efficiency of energy conversion processes for poplars and willows: "The ratio of bark to wood, moisture content, specific gravity, calorific or heating value, and the relative content of extractives, a-cellulose, hemicellulose, and lignin". Notably high bark content produces more ashes, which is undesirable in biomass power plants (Kauter et al., 2003). The concentration of potassium, sodium, calcium, magnesium and silicon oxide in bark influences the ash melting behavior, whereas the chlorine contained in bark can lead to corrosion processes (Kauter et al., 2003). Bark proportion decreases with increasing shoot diameter (Guidi et al., 2008) and thus should be higher in edge rows than in middle rows, because of the high amount of thin shoots. The poplar wood quality increases when the tree diameter exceeds 4 cm (Guidi et al., 2008). Moreover, more branches growing horizontally were observed in edge rows (data not shown), which could be problematic for the harvest. These horizontal branches cannot be harvested most of the time, but when they are, they cannot be well chipped and also negatively influence the quality of wood chips.

The porosity of the strip is an important factor for wind protection. It decreases with increasing permeability of the windbreak (Nägeli, 1946). A porosity around 40 % should be provided to ensure good wind-sheltered areas (Cleugh, 1998), but it could be between 30 and 50 % (Röser, 1995). Klingbeil et al. (1982) warned that tree strips with too many gaps between trunks or in the crown area, as well as very short strips, are less effective regarding wind protection. In the present study, the importance of porosity for the amount of wind velocity reduction was observed during winter 2013, when trees were bare and less wind protection was given directly on the leeward side. Thus, very narrow SRC-strips could be less suitable for wind protection.

Additionally, according to Knauer (1993), reducing the width of SRC-strips would limit the ecological value. The diversified structure of a strip and the presence of gaps in its structure, such as in the combined design in this study (great plant spacing between aspens and poplars), enhances biodiversity (Unseld et al., 2011). However, the combined design investigated in this work was less productive than the SRC design. Some predator arthropods benefit from a single-row strip because of its high proportion of edge, whereas other predators, such as insectivorous birds, prefer larger, wider windbreaks (Dix et al., 1995). According to Unseld et al. (2011), the allelophatic effects of poplars can have a negative influence on the diversity of the flora. More generally, Huxley (1985) stated that if the tree/crop interface has an overall positive biological effect, the amount of interface should be maximized with many narrow strips. Otherwise, it should be minimized with less but wider SRC-strips.

Planting density also strongly influences the regrowth and performance of shoots (Sennerby-Forsse et al., 1992). For wood chip production, Bärwolff et al. (2012) recommends a density between 10,000 and 13,000 plants per ha under German conditions. Moreover, the space within a row should be minimum 0.4 m and the space between rows minimum 2 m by these densities. As it was observed in this study, the middle rows of the poplar SRC-strips were less productive than the outer rows, notably because of the competition for light and water (Lamerre et al., 2015). A reduction of the planting density could be a possibility to increase shoot yield in these rows. On the other hand, lower planting densities could lead to higher porosity, which could reduce wind protection but enhance biodiversity. Including an aspen tree row in the middle of the SRC-strip, such as in the combined design in this study, reduces the total productivity of the SRC-strip, notably because the aspen trees do not produce much biomass, even though the middle poplar rows are influenced positively. But the greater space between the poplar rows and the aspen rows favor the infestation by weeds and aspens suckers, which could negatively affect poplar productivity in the long run.

In order to reduce the potential infestation of fungi, which is common in coppice plantations, Sennerby-Forsse et al. (1992) recommended to mix species. This could additionally improve microclimate and biodiversity within the strip. Knauer (1993) also mentioned that hedges of only one species, even with several rows, have a low ecological value. However, according to the regulation DirektZahlDurchfV (2014), only few genera are allowed to be planted in SRC-plantations/strips, and even less species (12) are permitted for the ecological focus area (EFA, see section 1.2.5). To enhance biodiversity, native species such as linden or hazelnut trees would be relevant, however, basic payments cannot be solicited concerning these species. Moreover, planting costs by a species mix are higher (Unseld et al., 2011).

4.6.4 Alley width

In general, in systems which are cultivated with modern agricultural machines, such as alley-cropping systems (ACS), the alley width should be proportional to the maximum machine's width used on the farm. In order to optimize crop productivity, Dupraz and Liagre (2008) suggested that the minimum alley width between single tree rows should be two times the adult tree height, in order to minimize competition between both system components. In the investigated ACS in this study, similar yields were obtained in the narrow and wide alleys. However, in some years, the negative effects on yields observed in the vicinity of the short rotation coppice (SRC)-strips could become stronger. Thus, it could be advantageous to select a wide alley, in order to reduce the proportion of the competition zone in the crop alley and thus increase area productivity. Moreover, alley widths greater than 50 m enhance habitats for open landscape species (e.g. field lark) (Unseld et al., 2011). Thus, greater widths should be selected if these species should be protected. Concerning wind protection, it was observed by Böhm et al. (2014) and in this study that the narrow alley (50 m) offered a better windbreak effect.

Bruckhaus and Buchner (1995) recommended laying out grass borders along hedges, to improve the habitat for predatory animals but also the acceptance of farmers, as these borders that are taken out of the production, could reduce the competition of the system components in the direct vicinity of the strip. However, it should have less than 2 m width, in order to not become a *landscape feature*, as foreseen in the article 8 of the regulation AgrarZahlVerpflV (2014). These features are not only ineligible for basic payments and submitted to management constraints, but also unproductive. But the presence of a small border (1.5 m in the investigated ACS in this study) can contribute to increase SRC-strip productivity because it allows for more space for the trees. Moreover, the adjacent crop is influenced less negatively because less crop surface is situated in the shade. It is, however, recommended not to select a border narrower than the space that should be available for one tree row (here 1 m next to the last tree row). Another possibility to reduce the size of the competition zone could be the tree/root pruning (Jose et al., 2004). However, as this operation must be repeated regularly, it could have a negative impact on tree survival (Stoeckeler, 1962).

4.6.5 Other considerations

In this study, the effects of short rotation coppice (SRC)-strips on the quality of cereal crops were tested only using the hectoliter weight and the grain moisture content (MC). However, some other modifications may occur, e.g. a modification of protein content (Jung et al., 2014), notably because light conditions are modified next to the SRC-strip. In order to counter these modifications, precision fertilization with selected nitrogen doses could be applied, as the plants in the competition zone next to the SRC-strip probably require less nitrogen because of their limited growth. Moreover, due to the higher aphid population that was observed in 2013 on the winter barley, it can be recommended to apply phytosanitary products specifically next to the SRC-strips, whereas this application could be avoided in the middle of the crop alley. Precision farming could be thus a chance to help implementing ACSs.

Moreover, as more diseases could potentially infect the crops in the very close area of the SRC-strip compared to the middle of the crop alley, special resistant cultivars could be sown there. Brandle et al. (2004) stated that crop cultivar is an important factor that contributes to crop response to shelter effect, because most of the available cultivars were selected under exposed conditions. Cultivars, which are better adapted to the conditions in the sheltered area, such as short and thicker-stemmed plants (shade tolerant) should be preferred. Moreover, C3-plants should perform better in shade and thus in agroforestry systems than C4-plants, as their photosynthetic rate is limited even when light increases further (Jose et al., 2004). If possible, it is recommended to sow winter crops after leaf fall, which will suppress the effect of leaf coverage and thus increase crop productivity in the competition zone.

In general, it is helpful to choose a field with a regular outline. On fields with an irregular outline, it is preferable to suppress one strip instead of increasing the number of complicated operations (Dupraz and Liagre, 2008). On a stretched field, the tree strips need to be oriented along the length. The longer the field, the easier the machine operations will be (Dupraz and Liagre, 2008).

But not all fields are compatible with the implementation of an alley-cropping system (ACS) with SRC-strips, notably regarding the ecological effects. For instance, in landscapes where trees are already dominant, as well as in typical open landscapes or marsh areas, the establishment of SRC-strips would endanger the survival of rare species adapted to these biotopes (Unseld et al., 2011). In order to enhance the biodiversity, according to these authors, SRC-strips should be placed to close gaps in the biotope network and increase structural diversity.

The assessed site, for instance, was already well wind-protected because it was surrounded by forests and hedges. Therefore, another strip arrangement could have been selected, such as in the form of a connection between these forest and hedge, instead of an arrangement parallel to the main wind direction. The renunciation of pesticides and fertilizers would also be optimal for nature conservation and help to reduce greenhouse gas emissions (Unseld et al., 2011). These authors stated that not only for nature conservation but also for nature scenery, the structure of an ACS should be diversified and well integrated in the landscape.

Nevertheless, ACSs are not the only possible cropping systems to reach environmental objectives in the agricultural landscape. For instance, if the main problem to counter on the field is erosion, maybe the implementation of mulch-sowing would be sufficient and would not require such high time and money investment as an ACS.

4.7 Further research needed

The findings of this study should be tested over the years, because the conditions will change, notably at the below-ground level. As short rotation coppice (SRC) plantations show different yields at different ages (Sennerby-Forsse et al., 1992), the results found here are not applicable for the whole life time of the system. The root system will develop further, whereas the above-ground biomass should always follow the same cycle, because of the periodical harvests. Notably the below-ground effects of SRC-strips on crop yield and the impact of deep rooting systems on soil fertility should be assessed. Indeed, root competition for water and nutrient could play an essential role in yield reduction.

The deep rooting of poplars could also bring some advantages, in the form of the “nutrient pump” and “safety net” roles, as described by Van Noordwijk et al. (2006). Bringing up nutrients to the topsoil which are not available for the alley crops (“nutrient pump”) and catching leached nutrients (“safety net”) would positively influence the sustainability of the system. In trees, the relocation of nutrients into the leaves is relatively low compared to the one in the bark and as a result a removal of biomass after each harvest of poplar could reduce soil fertility (Dillen et al., 2011). Quantifying these inputs would help to better understand and thus better design alley-cropping systems (ACSs), but also to reconsider fertilization management, notably next to SRC-strips. Especially in Wendhausen, where the soil is rich in clay, roots of cereal crops grow shallowly, whereas trees could be able to reach deeper layers.

In order to further assess the productivity of differently designed ACSs, a process-based model such as Yield-SAFE could be implemented. This model has to be first adapted to short rotation wood biomass production. Additionally, it could be useful to assess the 3D shape of different SRC-strips, as proposed by Van Thuyet et al. (2014) and Zhou et al. (2002), with different numbers of rows, rotation cycles, clones and designs, as this can influence the windbreak effect. Many data are already available in Germany as some institutions have already established such

ACSs. The next steps of research should thus aim at modeling and subsequently implementing these systems by farmers, using recommendations obtained from long terms observations.

At last, an economic evaluation of the system would help farmers to design the ACS and should comprise all the steps of production. The productivity results of system components obtained in this study with different designs offer therefore a basis for such an analysis.

5 Conclusions

The main objective of this thesis was to study the modifications of the growing conditions, as a result of above-ground interactions, and simultaneously, yield effects on both, tree and crop components, in the alley-cropping system (ACS) established in 2008 at the Julius Kühn-Institute in Wendhausen (Lower Saxony, Northern Germany). Furthermore, this work aimed at determining whether the productivity of the whole ACS was positively or negatively influenced by interactions of trees with agricultural crops by evaluating the effects of the yield modifications on the total productivity of ACSs.

Concerning the modifications of the growing conditions at the above-ground level, the following effects were observed. In 2013, as the trees were the highest, a strong wind reduction occurred on the leeward sides and especially in the narrow alley. However, a change of air temperature and relative humidity (RH) next to the short rotation coppice (SRC)-strips could be observed only on sunny days. After the harvest of all strips, no wind reduction and almost no change in air temperature and RH were detected over the crop alley. The incoming light was reduced in the vicinity of the SRC-strips due to tree shading, especially in 2013, while the leaves were blown up to 8 m into the crop alley and covered the ground in the first 3 m of the crop alley on the leeward side almost completely (in autumn 2012 and 2013). At this distance from the leeward SRC-strip, poplar roots were detected in 2013, suggesting a potential competition for resources such as water and nutrients at the below-ground level.

Next to the SRC-strips, the yield of winter barley and winter wheat was reduced, mainly by a reduced number of ears per m^2, due to the high leaf ground coverage during emergence of the crop. The reduction of solar radiation in the vicinity of the trees caused a slight delay in the normal phenological development there: the plants remained small and developed grains with lower thousand grain and hectoliter weights than in the middle of the crop alley. Up to 10 m into the alley, grain moisture contents were above the alley mean. More aphids, but also more aphid mummies and beneficial insects were observed on cereal plants in direct vicinity of the SRC-strips. The outer rows of the SRC-strips (windward and leeward) in both, the SRC and combined designs, showed a higher shoot number and larger diameters, which resulted in higher growth rates and thus greater biomass production than in the middle rows. These effects were mainly caused by an increased light and space availability. The middle rows of the combined design showed a high yearly biomass production in the 6-year rotation cycle, which was attributed to the grater space available between aspens and poplars. In conclusion, the above-ground interactions at the tree/crop interface positively influenced the productivity of the SRC-strips, whereas crop productivity was reduced in this zone. The below-ground interactions, which were not assessed in this study, could also have had an effect on productivity and should be examined in the future.

The biomass/energy production of the different design arrangements in the ACS available in Wendhausen was compared to the one of the sole-cropping systems (SCS) (only crop or tree component). In general, higher wood yields were recorded in the SRC-strips than in the SRC-control field, especially for the SRC design. Concerning the winter wheat, the yield was slightly higher in the open field and in the wide alleys in general, whereas for the winter oilseed rape, the yield was generally the highest in the wide alleys. Even though the trends were different in each year, between 2009 and 2014, higher aggregated yields were observed in the ACSs (grain + wood yield) than in the open field, but the greatest aggregated yield was produced in the SRC-control field. Better results were achieved for SRC-strips in the 6-year than in the 3-year rotation cycle, and in systems with winter wheat than with winter oilseed rape.

Thus, the agroforestry system investigated in this study can contribute to "sustainable intensification" in agriculture, because the yields are comparable to those in the sole-cropping systems, whereas the structural diversity is increased with potential positive effects on biodiversity. In order to reach high productivity, the width of the SRC-strip should be reduced to maximize the proportion of outer rows. At the same time, the crop alley width should be in a balanced relation to the total area of the agroforestry field, to limit the proportion of the tree/crop interface area with lower productivity for annual crops. In order to reach optimal wind protection, the strip number, orientation and length should be adapted to the local wind directions. The rotation cycle length should be selected to reach maximal wood biomass while keeping trees small to reduce the shading effect (3 to 4 years). Further research should be done to assess the productivity of the presented ACS over time and also of differently designed ACSs.

In general, it is important to select carefully which system arrangement and design could be best adapted to the soil-climate conditions of the field, as the site is a key factor for the profitability of ACSs (Unseld et al., 2011). Moreover, as this study showed, the design of ACSs influences its productivity. But many administrative rules must be respected to keep the field eligible for subsidies and reduce the design possibilities. Further adaptation of the regulation will be necessary to increase the acceptance of ACSs in Germany: the article 23 of the EU regulation 1305/2013 should be accepted and simultaneously, the limit of 100 trees per hectare and a limited number of species should be repealed, to allow for the use of SRC-strips in ACSs. The economic context is also decisive for the implementation and arrangement of ACSs. To keep this production profitable, there should be a local possibility to commercialize the wood chips, as too long distances would result in high transport costs.

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Appendices

A. Aerial picture of the experimental site in Wendhausen

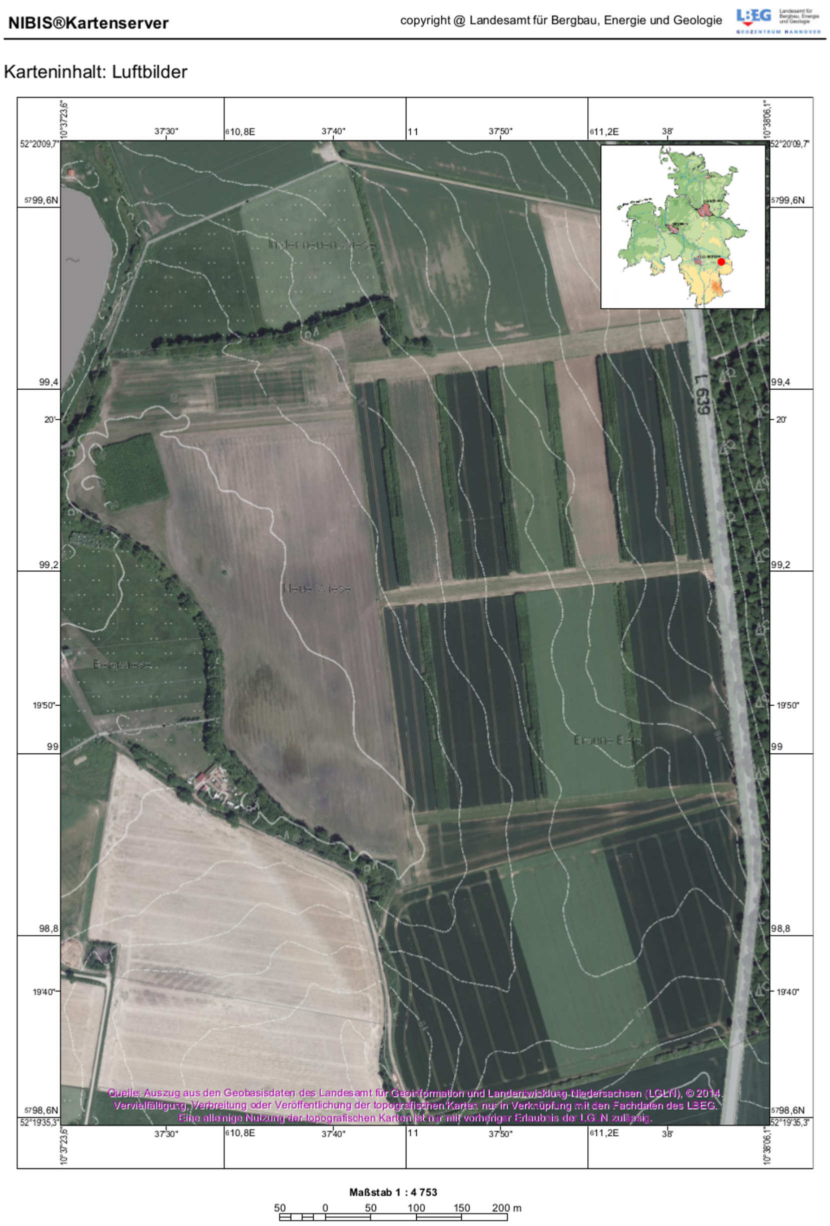

Figure A.1. *Aerial picture of the experimental site in Wendhausen, with the height lines and the coordinates (NIBIS (R) KARTENSERVER, 2014).*

B. Position of the subplots in the crop open field C1-C3

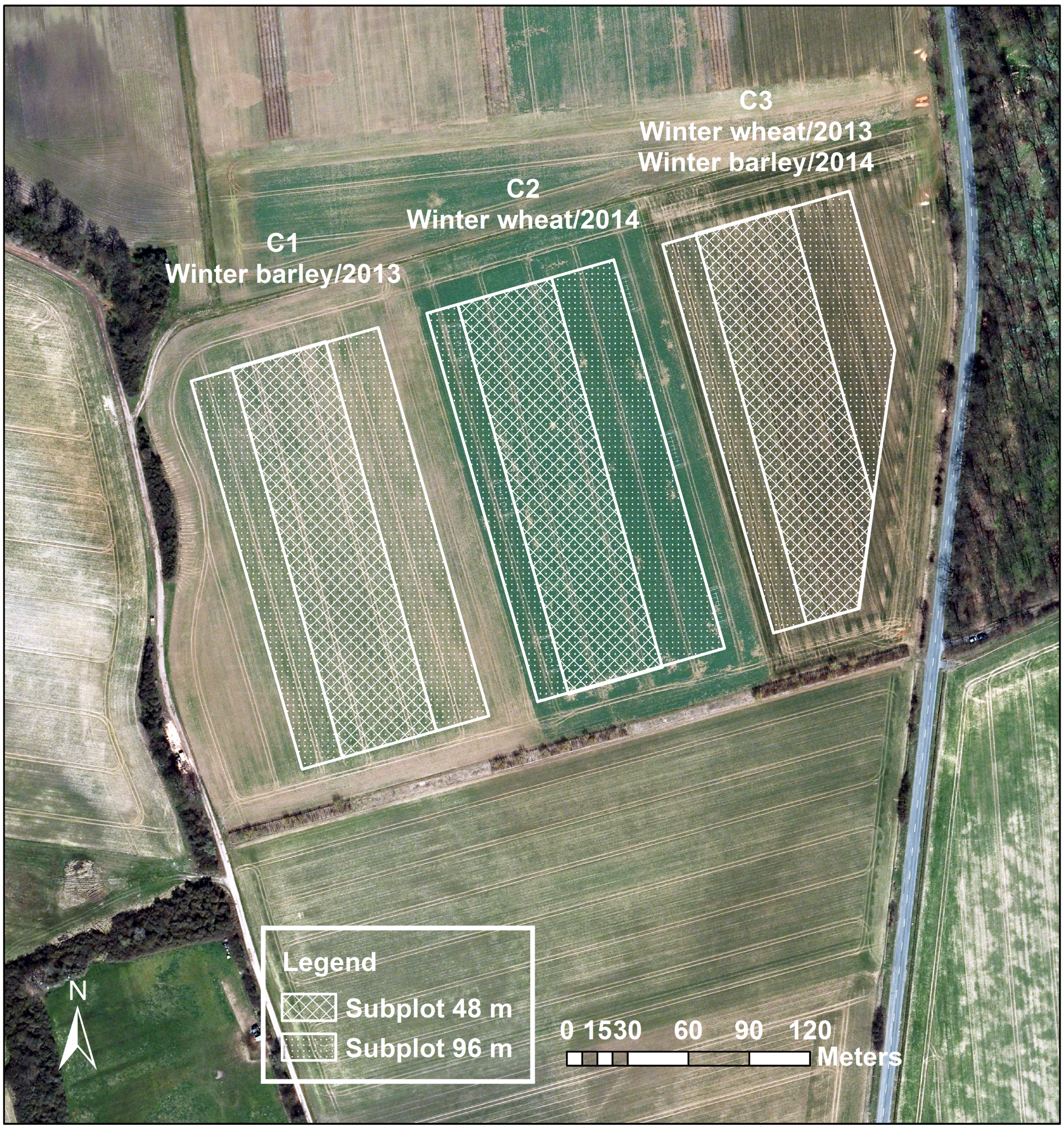

Figure B.1. *Position of the subplots (48 and 96 m widths) in the crop open fields C1-C3, used for the yield and grain moisture content distribution models.*

C. Air temperature and relative humidity values in 2013 and 2014

Table C.1. *Mean ± standard error, minimum (min.) and maximum (max.) air temperature and relative air humidity values in the short rotation coppice (SRC)-strip, at several distances from the leeward SRC-strip (3, 11 ,25.5, 40 and 48 m) and in the open field, during the two measurement periods in 2013 and 2014 (mean ± standard error) (ND: No data).*

Measurement period	Distance from leeward SRC-strips (m)	Air temperature (°C)			Relative air humidity (%)		
		mean	min.	max.	mean	min.	max.
Summer 2013 (06/02-07/11/13)	SRC-strip	16.7 ± 0.2	16.5 ± 0.2	16.9 ± 0.2	72.3 ± 0.6	70.7 ± 0.6	74.0 ± 0.6
	3	16.8 ± 0.2	16.5 ± 0.2	17.1 ± 0.2	73.1 ± 0.7	70.1 ± 0.7	74.0 ± 0.7
	11	17.0 ± 0.2	16.6 ± 0.2	17.3 ± 0.2	73.4 ± 0.7	71.5 ± 0.8	75.4 ± 0.7
	25.5	16.8 ± 0.2	16.4 ± 0.2	17.1 ± 0.2	73.6 ± 0.7	71.8 ± 0.8	75.4 ± 0.7
	40	16.8 ± 0.2	16.5 ± 0.2	17.2 ± 0.2	ND	ND	ND
	48	16.6 ± 0.2	16.3 ± 0.2	16.9 ± 0.2	74.4 ± 0.7	72.6 ± 0.7	76.2 ± 0.7
	Open field	16.6 ± 0.2	16.3 ± 0.2	16.9 ± 0.2	ND	ND	ND
Summer 2014 (05/22-07/08/14)	SRC-strip	15.8 ± 0.2	15.0 ± 0.2	16.6 ± 0.2	77.1 ± 0.6	73.9 ± 0.7	80.3 ± 0.6
	3	15.6 ± 0.2	14.8 ± 0.2	16.3 ± 0.2	81.5 ± 0.6	77.7 ± 0.7	85.1 ± 0.5
	11	15.7 ± 0.2	14.9 ± 0.2	16.6 ± 0.2	80.5 ± 0.6	77.1 ± 0.7	83.8 ± 0.6
	25.5	15.6 ± 0.2	14.8 ± 0.2	16.5 ± 0.2	80.5 ± 0.6	77.1 ± 0.7	83.8 ± 0.5
	40	15.6 ± 0.2	14.7 ± 0.2	16.5 ± 0.2	ND	ND	ND
	48	15.6 ± 0.2	14.8 ± 0.2	16.5 ± 0.2	80.6 ± 0.6	77.3 ± 0.7	83.9 ± 0.5
	Open field	15.6 ± 0.2	14.8 ± 0.2	16.4 ± 0.2	80.4 ± 0.6	77.0 ± 0.6	83.6 ± 0.5

D. Statistical results

D.1 Models used for the spatial distribution of yield and grain moisture contents in 2008, 2013 and 2014.

Yield models

See table D.1.

Grain moisture content models

See table D.2.

Table D.1. *Parameters estimates, their significance levels, the correlation coefficients and the number of observations used for each selected model to predict the grain yield in the alley-cropping system and the crop open fields in 2008, 2013 and 2014. Significance levels: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1, n.s.: not significant. (edf: effective degree of freedom (a high value means a highly non-linear curve and 1 means a straight line); - : not used in the model; ND: No data; SE: standard error; R^2: correlation coefficient).*

System		Alley-cropping system			Crop open field		
Year		2008	2013	2014	2008	2013	2014
Intercept γ (estimate ± SE, significance level)		56.0 ± 1.4***	93.5 ± 11.5***	84.3 ± 3.3***	ND	83.1 ± 0.4***	91.0 ± 0.2***
Smoother terms (edf, significance level)	$f_1(Distance_i)$	1.67**	3.7***	3.4***	ND	-	1.0n.s.
	$f_2(Distance_i : Width_{narrow})$	-	2.0*	-	ND	-	-
	$f_2(Distance_i : Width_{wide})$	4.8***	-	-	ND	4.5***	-
	$f_3(Distance_i : Crop_{winterwheat})$	-	4.9***	-	ND	-	-
	$f_3(Distance_i : Crop_{winterbarley})$	-	-	4.9***	ND	-	-
	$f_4(nEC_{25i})$	5.4***	5.3***	3.7***	ND	-	-
	$f_5(X_i, Y_i)$	8.5***	7.8***	8.6***	ND	8.5***	8.3***
Linear effects (estimate ± SE, significance level)	$Crop$	-	-	-	ND	-	-
	$Width$	-	-	3.4 ± 2.3n.s.	ND	-	-
	nEC_{25}	-	-	-	ND	-	-
Adjusted R^2		0.30	0.67	0.48	ND	0.67	0.18
Number of observations		2495	1451	1418	ND	1150	1181

Table D.2. *Parameters estimates, their significance levels and the correlation coefficients and the number of observations used for each selected model to predict the grain moisture content in the alley-cropping system and the crop open fields in 2008, 2013 and 2014. Significance levels: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1, n.s.: not significant. (edf: effective degree of freedom (a high value means a highly non-linear curve and 1 means a straight line); - : not used in the model; SE: standard error; R^2: correlation coefficient).*

System		**Alley-cropping system**			**Crop open field**		
Year		**2008**	**2013**	**2014**	**2008**	**2013**	**2014**
Intercept γ (estimate±SE, significance level)		15.9 ± 0.3***	17.6 ± 0.18***	15.7 ± 0.2***	ND	18.9 ± 0.5***	13.5 ± 0.1***
Smoother terms (edf, significance level)	$f_1(Distance_i)$	3.9***	3.9***	3.4***	ND	-	1.0***
	$f_2(Distance_i : Width_{narrow})$	2.0**	4.9***	5.0***	ND	-	-
	$f_2(Distance_i : Width_{wide})$	-	-	-	ND	-	-
	$f_3(Distance_i : Crop_{winterwheat})$	-	-	-	ND	-	4.7***
	$f_3(Distance_i : Crop_{winterbarley})$	-	4.7***	4.1***	ND	4.6***	-
	$f_4(nEC_{25i})$	-	-	-	ND	-	-
	$f_5(X_i, Y_i)$	8.1***	-	8.3***	ND	8.8***	-
Linear effects (estimate ± SE, significance level)	$Crop$	-	-	-	ND	-	-
	$Width$	-	-	-	ND	-	0.2 ± 0.03***
	nEC_{25}	0.6 ± 0.1***	0.3 ± 0.1***	0.03 ± 0.08n.s.	ND	-	-0.2 ± 0.1*
Adjusted R^2		0.22	0.95	0.71	ND	0.86	0.84
Number of observations		2495	1451	1418	ND	1150	1181

D.2 Results of the analysis of variance for the yield components

See table D.4.

D.3 Results of the analysis of variance for the diameters at breast height

Table D.3. *Results of the analysis of variance for the diameters at breast height measured in winter 2009/10, 2013/14 and 2014/15 in both rotation cycles (except in 2009/10). Significance levels: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1., n.s.: not significant. (3y-RC: 3-year rotation cycle; 6y-RC: 6-year rotation cycle; n: number of observations) (H_0: All diameters are the same at the different row positions).*

Winter	**2009/10**	**2013/14**		**2014/15**	
Rotation cycle	-	3y-RC	6y-RC	3y-RC	6y-RC
F-value (for the row position)	7.3	1.0	2.2	4.1	4.1
Significance levels	***	n.s.	n.s.	***	**
n	140	593	132	996	713

D.4 Equations' and correlation coefficients of the biomass estimation models

See table D.5.

Table D.4. *Results of the analysis of variance for the yield components of the winter wheat and winter barley assessed in 2013 and 2014 at all measurement points and additionally at the leeward (L), windward (W) and middle (M) points. Significance levels: *** p<0.001, ** p<0.01, * p<0.05, . p<0.1., n.s.: not significant. (EN: ear number per m^2; TGW: thousand grain weight; R^2: correlation coefficient) (H_0: the factors EN, the TGW and the interaction of EN and TGW (EN:TGW) do not affect the total grain weight).*

	Crop	**Winter wheat**							**Winter barley**						
	Year	**2013**				**2014**			**2013**				**2014**		
	Position	L	W	M	All	L	M	All	L	W	M	All	L	M	All
Significance level of factors	EN	n.s.	***	n.s.	***	***	n.s.	*	**	***	***	***	***	*	*
	TGW	***	n.s.	n.s.	**	n.s.	n.s.	*	*	*	*	***	n.s.	n.s.	*
	EN:TGW	***	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	**
Adjusted R^2 of fixed effects		0.99	0.97	0.78	0.91	0.85	0.69	0.87	0.48	0.72	0.42	0.57	0.86	0.84	0.89
Adjusted R^2 of fixed and random effects		0.99	0.97	0.78	0.92	0.85	0.78	0.87	0.64	0.84	0.64	0.71	0.86	0.85	0.91

Table D.5. *Equations' coefficients and their lower and upper confidence intervals (CI) at 95 % and the correlation coefficients of the biomass estimation models for the different row positions (leeward, middle, windward), designs (SRC: short rotation coppice), combined and control field) and rotations cycles (3y-RC: 3-year; 6y-RC: 6-year).*

Rotation cycle	**Row positions**	**Coefficient α**			**Coefficient β**			**Correlation coefficient $\mathbf{R}^2$**
		Lower CI	α	Upper CI	Lower CI	β	Upper CI	
3y-RC	Leeward control field	0.08	0.11	0.14	2.05	2.19	2.32	0.98
	Control field	0.08	0.09	0.13	2.12	2.28	2.44	0.97
	Windward	0.08	0.10	0.11	2.15	2.26	2.37	0.99
	Middle SRC design	0.05	0.06	0.07	2.48	2.65	2.81	0.98
	Middle combined design	0.08	0.09	0.10	2.21	2.31	2.41	0.99
	Leeward	0.07	0.10	0.14	1.96	2.23	2.51	0.92
6y-RC	Windward	0.11	0.16	0.25	1.81	2.06	2.31	0.93
	Middle SRC design	0.09	0.10	0.12	2.19	2.29	2.40	0.99
	Middle combined design	0.08	0.11	0.14	2.14	2.30	2.46	0.98
	Leeward	0.08	0.09	0.11	2.28	2.38	2.48	0.99

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[1] The research project "AgroForstEnergie II" was funded from 2012 to 2015 and aimed at evaluating the sustainability of producing energy wood in alley-cropping systems. The following work is a part of the third sub-project. Further information is available at: www.agroforstenergie.de/en.

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[2]Das Forschungsprojekt "AgroForstEnergie II" wurde von 2012 bis 2015 gefördert und zielte die Evaluierung der Nachhaltigkeit von der Energieholzerzeugung in Alley-Cropping Systemen. Weitere Informationen können unter www.agroforstenergie.de/de erhalten werden.

Erklärung

Hiermit erkläre ich, dass ich diese wissenschaftliche Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Braunschweig, 28. April 2017

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Lebenslauf

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EDV	Sehr gute Kenntnisse in Microsoft Office, ArcGIS, R und LaTex.
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Braunschweig, 28. April 2017