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Long-term yields of oilseed rape and winter wheat in a short rotation alley cropping agroforestry system

Anita Swieter · Maren Langhof · Justine Lamerre · Jörg Michael Greef

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Abstract Alley cropping agroforestry systems (ACS) are ascribed to have manifold positive ecological effects; nevertheless their application is still limited due to uncertain productivity of the agricultural crop, especially in the tree-crop competition zone. Therefore, this study investigated the variability of oilseed rape and winter wheat yield, respectively, at different distances from the tree strip edge in 2016 and 2017 in an ACS established in 2008 in northern Germany. The ACS consisted of strips of fast-growing poplars alternating with narrow (48 m) and wide (96 m) crop alleys, each with a crop rotation including winter oilseed rape and winter wheat. Each tree strip contained 6 rows of poplars with a density of 10,000 trees per ha. Moreover, multi-year (2009–2016) crop yield data of oilseed rape and winter wheat in the narrow and wide crop alleys were compared with those of a corresponding non-agroforestry control field. In general, crop yields observed in 2016 and 2017 in the narrow crop alleys at 1 m from the tree strip edges were on average 77% (oilseed rape) and 55% (winter wheat) lower than in the middle of the crop alley. One reason for low yield close to the tree strips might be the leaf litter coverage of the seedlings in autumn. Leaf litter deposition was highest at 1 m on the windward and the leeward side of the tree strips in 2015 and on the leeward side in 2016, respectively. However, the average long-term crop yields of the narrow crop alley, the wide crop alley and the control field did not differ substantially among each other. Although oilseed rape and winter wheat yields were lower close to the tree strips, this yield reduction did not negatively influence the average long-term crop yields of the ACS.

Keywords Alley cropping · Crop yields · Winter wheat · Oilseed rape · Yield variability · Competition zone · Long-term yield · Leaf litter

Introduction

After decades of input-intensive agriculture, landscape clearing and monoculture farming in many developed countries, there is growing awareness that a transition of agricultural systems towards permanent preservation of natural resources as basis for future food security is imperative (FAO 2014). To reach this goal, crop production should be performed in a “safe space”, where food demands are met while agriculture-induced impacts on the environment are

A. Swieter (✉) · M. Langhof · J. M. Greef
Federal Research Center for Cultivated Plants, Julius Kühn-Institut (JKI), Bundesallee 58,
38116 Braunschweig, Germany
e-mail: anita.swieter@julius-kuehn.de

J. Lamerre
Agro-Transfert Ressources et Territoires, 2, Chaussée de Brunehaut, 80200 Estrées Mons, France

minimized (Bommarco et al. 2013). Recent suggestions for ecological transition in agriculture are manifold and might be seen as individual pieces of the puzzle for implementation at the landscape scale. Agroforestry systems, i.e. land use systems where trees and crops are deliberately used on the same land, might be one of these pieces, as they can reduce environmental problems, re-structure agricultural landscapes and might thus help to navigate European agriculture into the "safe space". In contrast to traditional agroforestry systems like wood pastures, modern agroforestry systems are characterized by their adaptation to modern farming practices, e.g. agricultural machinery use (Nerlich et al. 2013).

Soil enrichment, conservation of biodiversity, improvement of air and water quality, and carbon sequestration are considered to be some of the most important ecosystem services of agroforestry (Jose 2009). Moreover, when trees are arranged perpendicular to the main wind directions, the wind reducing effect of tree strips protects erosion-prone soils (Brandle et al. 2004) and reduces evaporation from the bare soil in spring, which conserves soil moisture (Tsonkova et al. 2012). As a consequence of wind breaking and modified incoming solar radiation (i.e. tree shading), the microclimatic conditions in agroforestry systems differ from those of a comparable open field (Brandle et al. 2004). Tree strips increase water infiltration and water storage, which may reduce runoff and soil loss (Anderson et al. 2009). Through litterfall, organic matter is returned to the soil, which improves physical, chemical and biological properties of the soil, thereby sustainably increasing soil fertility and protecting the soil from erosion (Pinho et al. 2012). The introduction of trees increases the structural diversity of the agricultural landscape and offers additional habitats for arthropods and beneficial insects (Stamps and Linit 1997; Glemnitz et al. 2013), small mammals (Dix et al. 1995) or breeding birds (Gruss and Schulz 2008). Agroforestry systems generally have a greater C sequestration potential through tree-based above ground as well as below ground carbon storage than comparable tree-less croplands (Quinkenstein et al. 2009; Zoner et al. 2016). Trees planted on agricultural land might contribute to reduced nutrient losses by rooting below the crop root zone and thereby increase seepage quality (Van Noordwijk et al. 2006).

Despite the above mentioned environmental benefits of agroforestry systems, their introduction in the European agricultural landscape has been relatively low, with a current area of approximately 358.000 ha (Herder et al. 2016). In short rotation alley cropping agroforestry systems (ACS), fast-growing trees like poplars and willows are used for the production of wood fuel. However, so far, "classical" bioenergy crops, i.e. maize for biogas production or oilseed rape/wheat for biofuel production, are preferred by farmers owing to the well-established cultivation techniques. Moreover, trees require additional management (planting, pruning, harvest etc.), which might be a reason for the relatively low interest in agroforestry systems among farmers (Seiter et al. 1999). A major obstacle for a wider adoption is the uncertain productivity of the agricultural crop in an ACS compared to a single crop system, especially in the tree-crop competition zone (Thevathasan and Gordon 2004). However, reports in the scientific literature on yield effects of the crop component in ACSs are rare. For example, under-yielding was found for wheat (Fang et al. 2005) and maize (Thevathasan and Gordon 2004), whereas for soybean and wheat higher or equal yields compared to the separately grown crop were found (Thevathasan and Gordon 2004). Possible reasons for reduced crop yields in ACSs are competition for essential resources for plant growth, such as light, water, nutrients and space as well as the leaf litter coverage of (winter) crop seedlings, mainly at the tree/crop interface (Batish et al. 2008; Sparkes et al. 1998). Typically, this interspecies competition for resources increases with tree growth, leading to increased shading, litter fall, and rooting.

To date, relatively few studies exist that investigated the yield of annual crops in temperate agroforestry systems over several years. Though, for the assessment of crop yield in agroforestry systems multi-year studies are necessary to consider annual weather variability. For example, the effect of wind protection or shading depends on the actual wind speed as well as the tree height. Depending on the rate of precipitation, competition for water might be more or less pronounced. Hence, to support farmers in their decision making process pro or contra the establishment of agroforestry systems on their land, the current study statistically evaluates yield data of winter wheat (*Triticum aestivum* L.) and winter oilseed rape (*Brassica napus* L.) collected at a temperate ACS in

Northern Germany over a period of 8 years (2009–2016). It was hypothesized that negative effects on crop yield are limited to a small area directly bordering the tree strips, where trees and crops compete for resources like water, nutrients, light and space. The yield in this competition zone is assumed to be of minor importance for the overall yield of the crop alley. Thus, similar yields in ACS and the control field, which is a standard tree-less agricultural field, are expected. To test this hypothesis (1) the yield of oilseed rape and winter wheat and the amount of leaf litter deposition were estimated at different distances from the tree strips in the narrow crop alleys of the ACS. (2) Average yields of oilseed rape and winter wheat were compared between ACS with narrow and wide crop alleys and a corresponding non-agroforestry control field over multiple years.

Materials and methods

Experimental site description

The study was conducted on a short rotation ACS, established in 2008 in Northern Germany at Wendhausen (North 52°19′54″, East 10°37′52″) near Braunschweig. The study site is located in a plain area at 85 m above sea level and covers an area of 30 ha. The climate is temperate with an average annual temperature of 9.8 °C and an average annual precipitation sum of 616 mm. Local soil properties are rather heterogeneous; the soil in the ACS is mainly characterized by a silty clay texture, whereas the soil in the control field is mainly characterized by a clayey loam texture. Yield potential at our study site was classified as medium to low.

The ACS includes 9 tree strips (13 × 225 m) planted with fast growing poplars for energy wood production, 5 narrow (48 × 225 m) and 3 wide (96 × 225 m) crop alleys. In the tree strips with 6 rows of trees, 3 poplar clones (*P. nigra* L. × *P. maximowiczii*, *P. maximowiczii* × *P. trichocarpa, P. koreana* × *P. trichocarpa*) were planted with a plant density of 10,000 trees/ha (0.5 m × 2 m). In order to allow for agricultural machinery use on the crop alley, the border between tree strip and crop alley was set at 1.5 m distance from the outer tree row. Three non-agroforestry control fields of about 3 hectares each are located next to the ACS. The experimental design is visualized in Fig. 1. In both, ACS and control, crop rotation included winter oilseed rape and winter wheat, with each crop being cultivated on one of the fields in each year. Both, ACS crop alleys and control fields were cultivated site-specific, tillage was carried out using a cultivator, a disc harrow and a 5-share half-turn plough with underground packer, sowing was conducted using a rotary harrow combined with drill. Crops were sown during the recommended time span for sowing, i.e. from the end of September (winter wheat) and between the middle and end of August (oilseed rape), and sowing of the same crop was done

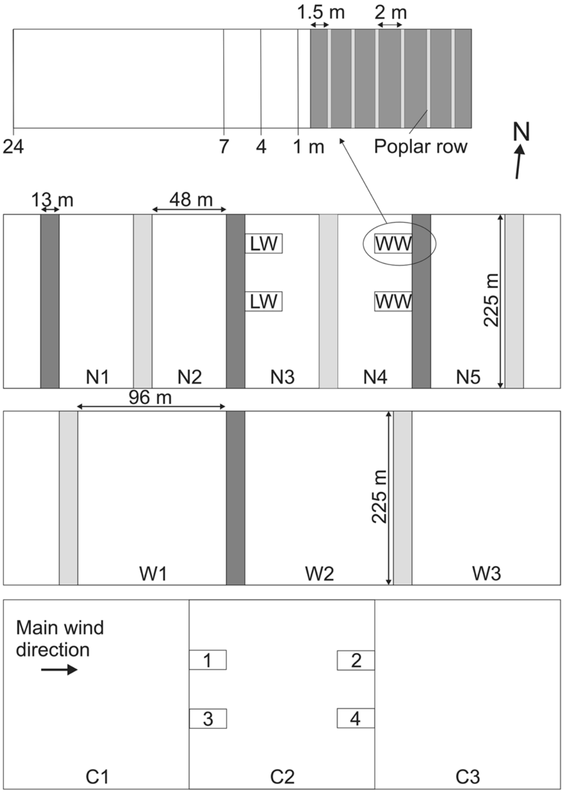


Fig. 1 Sketch of the experimental layout (not to scale). The alley cropping system consists of five narrow (N1–N5) and three wide (W1–W3) crop alleys. Light grey bars represent north–south oriented tree strips with 3-year rotation cycle and dark grey bars those with 6-year rotation cycle. C1–C3 denote the non-agroforestry control fields. In each year, both, winter wheat and winter oilseed rape were cultivated on one of the narrow crop alleys, on one of the wide crop alleys and on one of the control fields. Leeward (LW) and windward (WW) plots for the analysis of the yield variability in the tree-crop competition zone, are located in the narrow crop alleys N3 and N4. The upper part of the figure shows the layout of these plots at 1, 4, 7 and 24 m distance to the tree strip edge

at the same date. Fertilizer and crop protection products were applied according to regional recommendations and taking the actual nutrient content of the soil into account. Tree strips were harvested in a 3- or 6-year rotation cycle by a short rotation coppice harvester.

The tree strips are north–south oriented, i.e. perpendicular to the main wind direction (west/southwest). Thus, the leeward area (wind protected area) is situated on the eastern side of the crop alleys, whereas the windward area (wind-exposed area) is situated on the western side of the crop alley (Fig. 1). Wind speed and direction were recorded by the German National Meteorological Service (DWD) at a height of 10 m at Braunschweig, 15 km from the study site, and are presented for the time span of main litter fall in Figs. 5b and 6b.

Collecting yield and leaf litter data

Crop yield was measured at 1, 4, 7 and 24 meters distance from the tree strip edge (i.e. the border between tree strips and crop alleys) with four replications (two on the leeward and two on the windward side of the alley) in both crop types (oilseed rape in 2016 and winter wheat in 2017) in the narrow crop alleys of the ACS (see Fig. 1). The same procedure was followed in 2017 in the winter wheat non-agroforestry control field, with two replications on the eastern and on the western field edge, respectively. Harvest was done using a plot combine harvester with a cutting width of 1.5 m. E.g., for the observation of the 1 m distance, a strip from 0.25 m to 1.75 m from the tree strip edge/field edge was harvested. At each distance, a total area of 12.5 m^2 was harvested. After the harvest, dry matter yields of oilseed rape seeds and winter wheat grains were determined and calculated in tons per hectare.

To assess the leaf litter deposition in the crop fields, litter traps of 0.1024 m^2 size were exposed at the same plots where yield measurements were taken. The collection of litter started after sowing of the winter crops (i.e. winter oilseed rape and winter wheat) and traps were emptied weekly until the end of the litter fall period. Collected leaves were dried and weighed separately for each trap. Total leaf litter deposition was determined as the sum across six (wheat) and seven (oilseed rape) sampling events for each trap.

From 2009 to 2016, annual crop yields and grain moisture was determined using a GPS-equipped harvester. Yield measurements were conducted separately on each entire crop alley and control field, respectively. Furthermore, in each year, fields of the same crop were harvested at the same day. Due to technical problems with the harvester, oilseed rape yield data for 2013 and 2015 are not available. Yield data from the harvester were averaged for each field and year (2009–2016).

Statistical analysis

Given the low number of replications, both crop yield and leaf litter deposition in relation to the distance to the tree strip edge/field edge and the orientation of the crop alley towards the tree strip (i.e. leeward or windward) were not analyzed statistically but were described by the arithmetic mean and visualized using scatterplots.

The relationship between crop yield and total leaf litter deposition was assessed by calculating the Spearman's rank correlation coefficient.

To analyze the effect of the cropping system on the long-term average yield, separate linear mixed effect models were fitted for each crop type with the cropping system (i.e. narrow ACS, wide ACS, control field) as fixed effect and the year (2009–2016) and the field ID (1–11) as random effects. This candidate model was then compared with the null model containing only the random effects using the Akaike information criterion corrected for small sample sizes (AICc, see Burnham and Anderson 2002) and maximum likelihood estimation. A lower AICc of the null model compared to the candidate model (including the fixed effect) indicates no substantial differences in crop yield between the cropping systems. Variance components of the random effects and confidence intervals were obtained from the candidate model with restricted maximum likelihood estimation (Zuur et al. 2009).

Statistical analyses were carried out using R (R Core Team 2017) and packages Hmisc (Harrell et al. 2016), lme4 (Bates et al. 2015), lsmeans (Lenth 2016) and bblme (Bolker 2017).

Results

Crop yield and leaf litter deposition variability at different distances from the tree strip edge

The average oilseed rape yield at 1 m from the tree strip edge was 0.1 t/ha on the windward side and 1.5 t/ha on the leeward side (Fig. 2a, b). The average oilseed rape yields at 4, 7 and 24 m (i.e. in the middle of the narrow crop alley) were 3.0, 3.2 and 3.1 t/ha (windward) (Fig. 2a) and 2.3, 3.0 and 3.6 t/ha (leeward), respectively (Fig. 2b).

The average winter wheat yield at 1 m from the tree strip edge was 3.5 t/ha on the windward side and 3.1 t/ha on the leeward side (Fig. 3a, b). The average winter wheat yields at 4, 7, and 24 m varied between 5.9, 6.2 and 7.6 t/ha (windward) (Fig. 3a) and 5.0, 6.1 and 6.5 t/ha (leeward) (Fig. 3b).

On the non-agroforestry control field, the average winter wheat yield at 1 m from the field edge was 6.3 t/ha on the western side and 6.4 t/ha on the eastern side (Fig. 4a, b). The average winter wheat yields at 4, 7, and 24 m were 6.9, 7.7 and 7.5 t/ha (western side) (Fig. 4a) and 7.3, 8.1 and 6.9 t/ha (eastern side), respectively (Fig. 4b).

Overall, oilseed rape yield at 1 m from the tree strip edge was on average 77% lower than in the middle of the narrow crop alley (i.e. 24 m from the tree strip edge), whereas winter wheat yield at 1 m from the tree strip edge was on average 55% lower than in the middle of the narrow crop alley. On the non-agroforestry control field, winter wheat yield at 1 m from the field edge was on average 11% lower than at the 24 m distance from the field edge.

Total leaf litter deposition during the litter fall period of 2015 was on average 51.2 g/m^2 at 1 m from the tree strip edge on the windward side and 45.0 g/m^2 at 1 m from the tree strip edge on the leeward side (Fig. 5a, b). The average leaf litter deposition at 4, 7 and 24 m was 11.7, 6.0 and 0.0 g/m^2 (windward) (Fig. 5a) and 8.5, 0.2 and 0.0 g/m^2 (leeward), respectively (Fig. 5b). In 2016, total leaf litter deposition was on average 33.1 g/m^2 at 1 m from the tree strip edge on the windward side and 223.6 g/m^2 at 1 m from the tree strip edge on the leeward side (Fig. 6a, b). The average leaf litter deposition at 4, 7 and 24 m was 11.7, 0.0 and 0.0 g/m^2 (windward) (Fig. 6a) and 41.2, 8.1 and 0.0 g/m^2 (leeward), respectively (Fig. 6b).

For both years, the Spearman's rank correlation coefficients *k* showed a negative correlation between

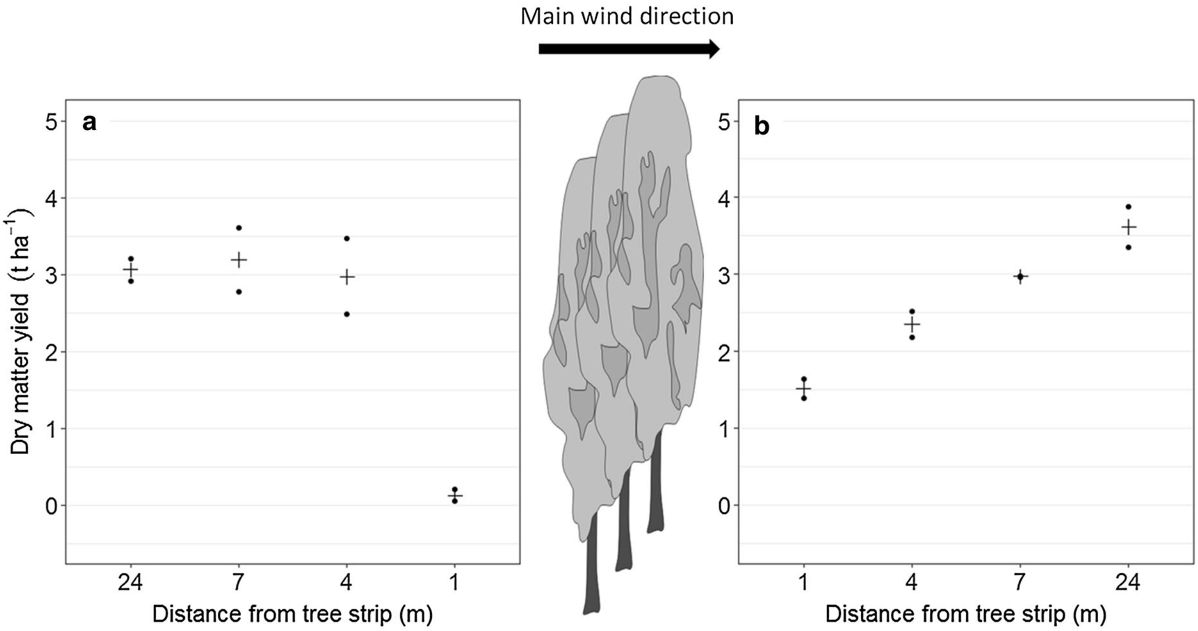


Fig. 2 Scatterplots showing oilseed rape yields at different distances from the tree strip edge on the windward (**a**) and on the leeward (**b**) sides of the narrow crop alley, respectively. Dots denote observed yields and crosses denote average yields at the respective distance from the tree strip

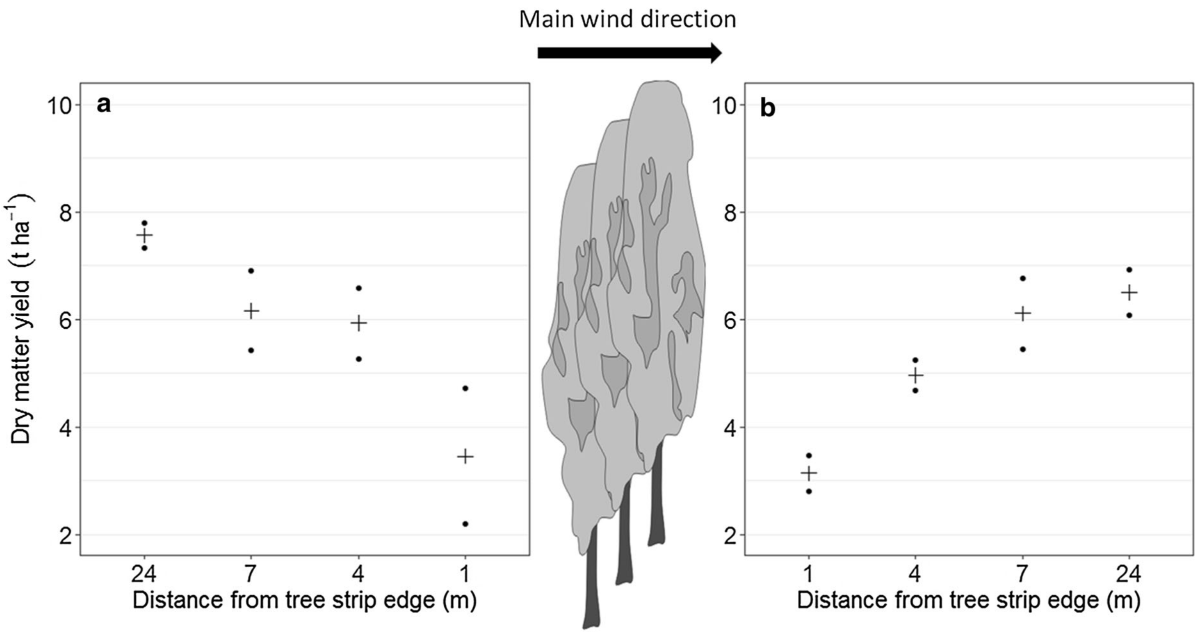
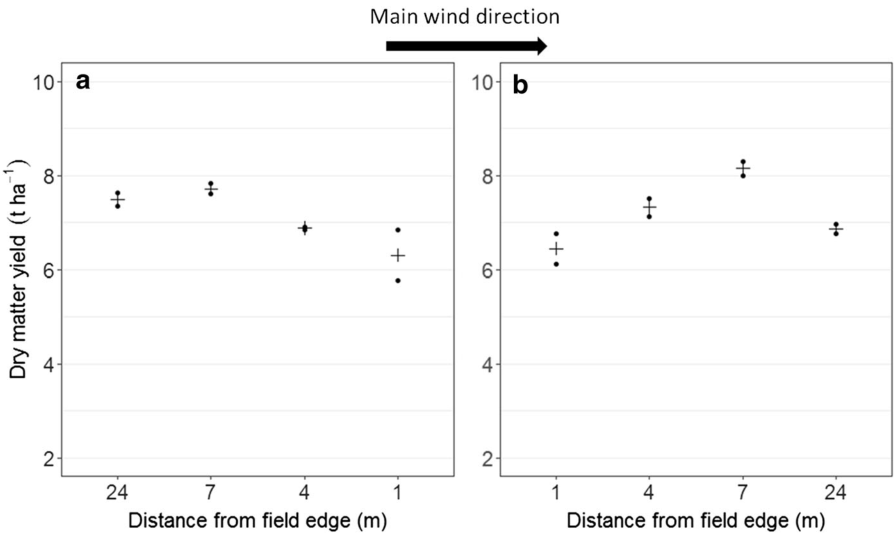


Fig. 3 Scatterplots showing winter wheat yields at different distances from the tree strip edge on the windward (**a**) and on the leeward (**b**) sides of the narrow crop alley, respectively. Dots denote observed yields and crosses denote average yields at the respective distance from the tree strip

Fig. 4 Scatterplots showing winter wheat yields at different distances from the field edge on the western (**a**) and on the eastern (**b**) sides of the non-agroforestry control field, respectively. Dots denote observed yield, and crosses denote average yields at the respective distance from the tree strip



crop yield and total leaf litter deposition in previous autumn. For the oilseed rape yield and total leaf litter deposition, k was -0.76 ($P = 0.0007$, $n = 16$), whereas for the winter wheat yield, k was -0.85 ($P = 0$, $n = 16$).

Effect of the cropping system on long-term crop yields

The long-term oilseed rape yield was on average 3.0 t/ha (narrow ACS), 3.5 t/ha (wide ACS) and 3.1 t/ha (control), respectively (Fig. 7a). The long-term winter wheat yield of the narrow ACS was on average 7.2 t/ha, whereas those of the wide ACS and the control

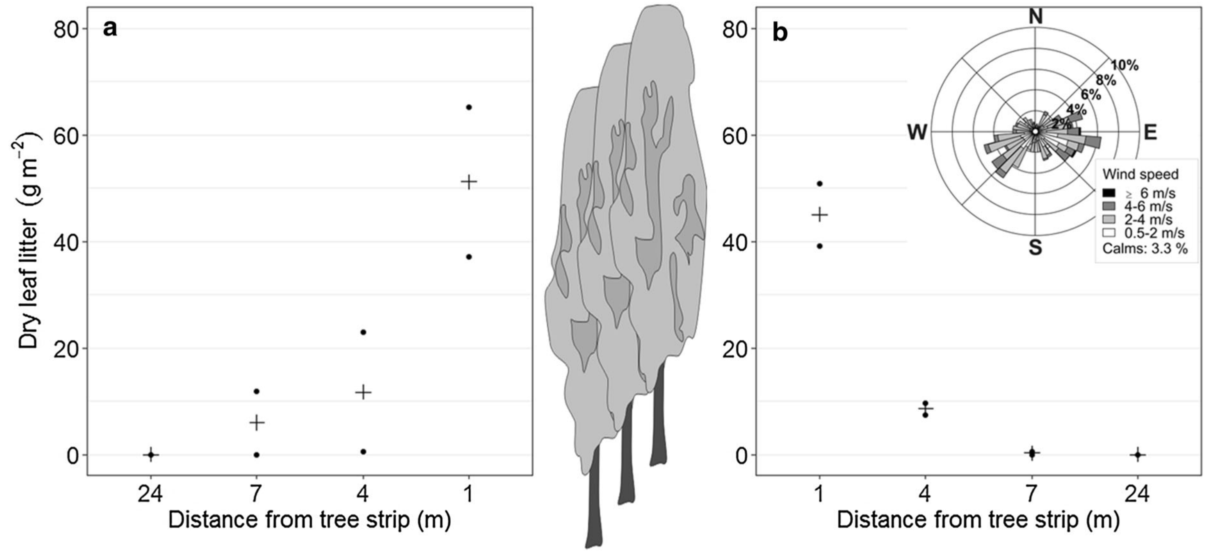


Fig. 5 Scatterplots showing accumulated leaf litter deposition in autumn of 2015 after sowing of winter oilseed rape at different distances from the tree strips on the windward (**a**) and on the leeward (**b**) sides of the narrow crop alley, respectively. Dots denote observed leaf litter deposition, and crosses denote average leaf litter deposition at the respective distance from the tree strip. Wind plot (**b**) shows frequency of wind speed and direction at Braunschweig during the period of main leaf litter deposition

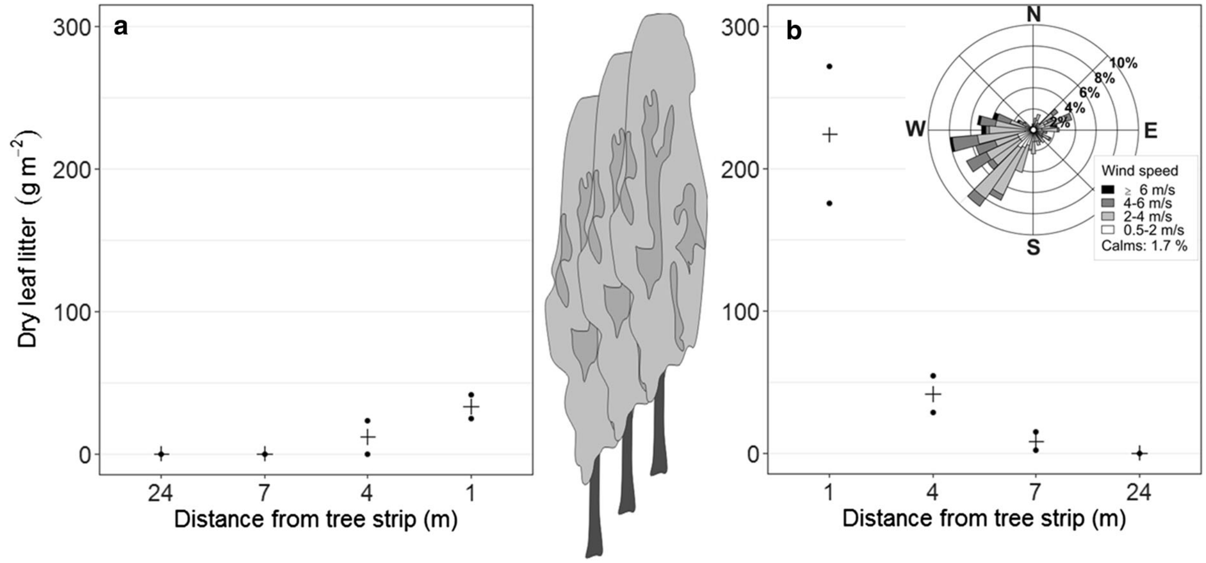


Fig. 6 Scatterplots showing accumulated leaf litter deposition in autumn of 2016 after sowing of winter wheat at different distances from the tree strips on the windward (**a**) and on the leeward (**b**) sides of the narrow crop alley, respectively. Dots denote observed leaf litter deposition, and crosses denote average leaf litter deposition at the respective distance from the tree strip. Wind plot (**b**) shows frequency of wind speed and direction at Braunschweig during the period of main leaf litter deposition

field were 7.4 t/ha (Fig. 7b). There were no substantial differences in average long-term crop yield between the cropping systems, (i.e. narrow ACS, wide ACS, non-agroforestry control field) for both crop types as indicated by lower AICc of the null model than the candidate model (Tables 1 and 2). In both candidate

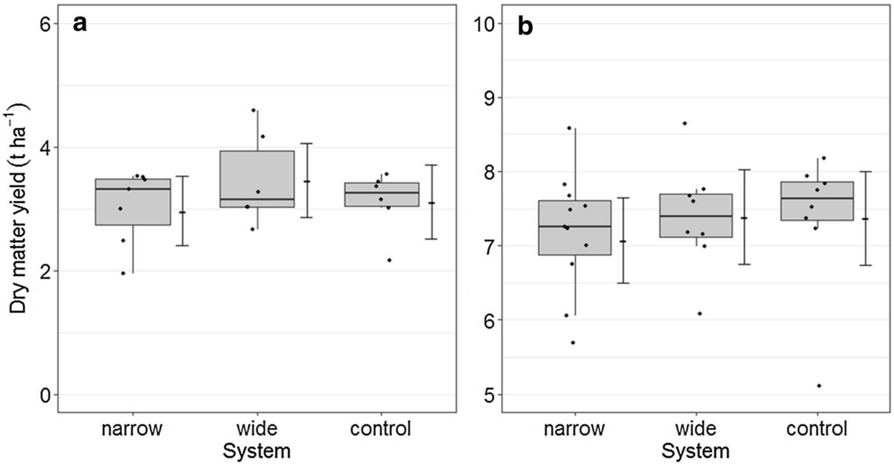


Fig. 7 Boxplots showing the average winter oilseed rape (**a**) and winter wheat (**b**) yields of the years 2009-2016 for the crop alleys in the narrow alley cropping agroforestry system (ACS), the wide ACS and the control field. Black dots represent average yield data per year and field plot; to avoid overlap of data points with the same value, data points were "jittered" horizontally. Error bars are the 95% confidence intervals of the candidate model

Table 1 AICc-values for the null model and the candidate model for the long-term winter oilseed rape yield

Model	Parameters	*n* = 19 df	AICc	Δ AICc
Null	–	4	36.5	0.0
Candidate model	Cropping system	6	40.0	3.5

Table 2 AICc-values for the null model and the candidate model for the long-term winter wheat yield

Model	Parameters	*n* = 27 df	AICc	Δ AICc
Null	–	4	73.4	0.0
Candidate model	Cropping system	6	78.9	5.5

models, variance components of the random effects were higher for year than for field (oilseed rape: 0.2968 vs. 0.0698, winter wheat: 0.1439 vs. 0.0287).

Discussion

Crop yield and leaf litter deposition variability at different distances from the tree strip edge

Decrease of crop yield from the middle of the crop alley (i.e. 24 m from the tree strip/field edge) to 1 m distance from the tree strip/field edge was greater in the narrow ACS than in the non-agroforestry control field. This indicates a negative effect of the trees in the ACS on crop growth in the competition zone between trees and crops. Tree height was approximately 5 m in 2015 and 6 m in 2016, and reduced crop yield was observed up to 7 m distance from the tree strip edges. Thus, our findings are in accordance with several earlier studies that observed yield reductions up to a distance from the tree strip/hedge of two times its height (Akbar et al. 1990; Chirko et al. 1996;

Kowalchuk and de Jong 1995; Kreutz 1973; Lamerre 2017; Puri and Bangarwa 1992).

The strong negative correlation between crop yield and leaf litter deposition in previous autumn indicates that leaf litter coverage can be a reason for the observed crop yield reduction near the tree strips. Especially in 2017, we found lower winter wheat yield at 1 and 4 m on the leeward side compared to the windward side of the tree strip edge. Correspondingly, leaf litter deposition in 2016 adjacent to the tree strips was higher on the leeward than on the windward side. In addition, in 2016, total leaf litter deposition at 1, 4 and 7 m from the tree strip edge on the leeward side was greater than in 2015, probably due to higher trees and different wind conditions during the period of litter fall: In 2015, during the main litter fall period, wind came mainly from southwestern and southeastern directions, whereas in 2016, during the main litter fall period, wind came mainly from southwest. Thus, leaf litter deposition in 2015 was similar on the windward and on the leeward side of the tree strips, whereas in 2016, leaf litter deposition was greater on the leeward compared to the windward side. In accordance with our results, Lamerre (2017) found reduced winter wheat and winter barley yields near poplar strips due to a lower number of ears per square meter. This yield reduction was caused by thick leaf litter coverage of the seedlings, especially on the leeward side of the tree strips. Batish et al. (2008) and Singh et al. (2001) suggested that reduced seedling survival due to allelopathic effect of litter cover can also be a reason for reduced crop productivity in ACSs.

Besides litter coverage, reduced crop yields near the tree strips can result from competition between trees and crops for essential resources such as light, soil water or nutrients. Mainly in temperate climates, tree shading negatively affects plant growth due to reduced photosynthetic activity (Krüger 1981). Negative effects on crop yields in agroforestry systems were reported for winter wheat in Northern China (Chirko et al. 1996) and for maize in Canada (Thevathasan and Gordon 2004). In previous studies on the ACS at our experimental site, tree shading caused developmental delay of winter wheat and winter barley plants near the tree strips, which resulted in lower plant size, grains with lower thousand grain and hectoliter weights and higher grain moisture contents, compared to the middle of the crop alley (Lamerre 2017).

We found extremely low oilseed rape yield at 1 m on the windward side of the tree strip edge in 2016, although leaf litter deposition in previous autumn at 1 m windward from the tree strip edge was only slightly higher than at the leeward side. It is thus supposed that the observed yield reduction at 1 m on the windward side of the tree strip edge was not caused by leaf litter coverage but by a very low plant density. Sowing of oilseed rape seeds at 1 m from the tree strip edge might have been hampered by the trees, resulting in areas with no or a reduced amount of seeds.

Another possible reason for the observed crop yield reduction near the tree strips could be the competition for soil water between trees and crop plants (Gillespie et al. 2000; Jose et al. 2004). Soil water tension measurements at our experimental site showed the influence of poplar roots in the crop alleys up to a distance of 3 m from the tree strips (Lamerre 2017). Trees and crop plants in the competition zone can also compete for essential nutrients, such as nitrogen, due to the proximity of tree and crop roots in the same soil strata (Van Noordwijk et al. 2006). On our experimental site, it was shown that poplar trees in edge rows produced higher amounts of biomass than trees in the middle rows due to increased space and light availability near the crop alleys (Lamerre et al. 2015).

Contrary to our expectations, we could not find a positive windbreak effect on crop yield for the oilseed rape yield in 2016 and the winter wheat yield in 2017, respectively. This might be due to the favorable climatic conditions during both experimental years. Precipitation was relatively high and thus, contrary to dry years, higher humidity due to the windbreak effect of the trees was not a decisive factor. Moreover, wind blew on average lightly, that is, ranged between 2 (light breeze) and 3 (gentle breeze) on the Beaufort scale. Thus, the windbreaking effect of tree strips in 2016 and 2017 is considered to be negligible. Several authors reported zones behind a hedge or tree strip with increased crop yield above the average yield of the crop alley. The increase in crop yield is thought to be caused by reduced evapotranspiration due to the windbreaking effect of tree strips and hedges (Brandle et al. 2004; Kort 1988; Kowalchuk and de Jong 1995; Müller 1956; Stoeckeler 1962). Often the “beneficial zone” is largest under special climatic conditions (e.g. drought) and might be absent under optimal growing conditions (e.g. Kowalchuk and de Jong 1995). For example, Kowalchuk and de Jong (1995) reported increased yields behind a hedge that reached from one and a half to three times the hedge height, whereas Müller (1956) measured highest yields at a distance from the hedge of 3 times its height. However, in the current study, yield was measured at 1, 4, 7, and 24 m. Thus, a possible increase in yield between 7 and 24 m due to the windbreak effect could not be detected.

Effect of the cropping system on long-term crop yields

Both, the average long-term oilseed rape and winter wheat yields of the narrow ACS, the wide ACS and the control field did not differ substantially among each other. Slightly lower average crop yields in the narrow ACS might be explained by a higher percentage of competition zone area (i.e. crop area close to the tree strip with reduced yields) in this cropping system compared to the wide ACS. However, the slightly lower average crop yields in the narrow ACS cannot be explained only by the width of the crop alleys, as crop yields of the narrow ACS were similar to those of the wide ACS and the control field, when trees were the tallest (in 2013). Furthermore, statistical analysis of the multi-year yield data of both crops revealed a strong year and a weaker crop alley effect on long-term crop yields. For example, in 2012, the average winter wheat yield of the control field was lower than that of the narrow and wide ACS, respectively, probably due to dry weather conditions. In that year, crops in the ACS might have benefitted from the tree strips that can have a positive effect on soil moisture, whereas in the tree-less control field, unfavorable soil properties (sandy loam) resulted in low water holding capacity (Lamerre 2017).

Yield differences/reductions might also be caused by damage during tree harvest. In 2011 and 2014, directly after tree harvest, the average oilseed rape and winter wheat yield of the narrow ACS was lower than that of the wide ACS and the control field, respectively. This might be explained by ground and crop damage caused by short rotation coppice harvesting machinery as well as harvesting related traffic by tractor and trailer on the crop alley in previous winter, especially near the tree strips (Lamerre 2017). In the narrow ACS, the percentage of the zone negatively affected by tree harvest was greater than in the wide ACS and, thus, also the effect on the total yield.

Especially in years with low precipitation, when competition for water between trees and crop plants was strongest, crop yield in the narrow ACS tended to be lower than in the wide ACS as well as in the control. Again, this yield difference might be caused by the higher percentage of the competition zone in the narrow ACS. Thus, at the experimental site at Wendhausen the wide ACS might be more favorable than the narrow ACS, especially in years with dry weather conditions. Moreover, crop alley widths greater than 50 m enhance habitats for open landscape species (e.g. field lark) (Unseld et al. 2011). However, as the narrow ACS offers a better windbreak effect (Böhm et al. 2014; Lamerre 2017) than the wide ACS, the former might be preferred in regions with high wind erosion potential.

Irrespective of the ACS width, tree strips provide the above mentioned ecological benefits, such as protection from wind erosion (Brandle et al. 2004), reduction of nutrient leaching (Böhm et al. 2013) and contribution to the habitat connectivity (Tsonkova et al. 2012).

Conclusions

This study provides robust data of annual crop yield in a temperate ACS by statistically evaluating yield data of winter wheat (*Triticum aestivum* L.) and winter oilseed rape (*Brassica napus* L.) from a period of 8 years (2009–2016). Yields of oilseed rape and winter wheat, respectively in 2016 and 2017, were lower close to the tree strips than at 4 and 7 m distance from the tree strip edge and in the middle of the narrow crop alley. It is assumed that leaf litter deposition on the first few meters of the crop field negatively influenced the development of winter crop seedlings. However, this yield reduction in the tree crop competition zone did not negatively influence the average long-term crop yields of the ACS. These results show that ACSs can contribute to a sustainable intensification of agriculture and the farm income diversification without under-yielding of the crop components winter oilseed rape and winter wheat.

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