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Competition, stress and benefits: Trees and crops in the transition zone of a temperate short rotation alley cropping agroforestry system

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Abstract

Tree strips on agricultural production sites offer many economic, ecological and social advantages. However, the introduction of trees creates a transition zone between tree strips and crop land. Here, trees and crop plants compete for resources such as space, nutrients, water and light, which causes stress in the low-competitive system. On the other hand, facilitation such as additional nutrient input through tree leaf litter and fine roots are possible. This study aims to provide indications for competition and benefits that can arise for plants growing in the transition zone of a temperate short rotation alley cropping agroforestry system (SRACS). Various climatic and plant-growth parameters were investigated between 2013 and 2019 at different positions of an SRACS with fast-growing poplars in northern Germany. Reduced yield of wheat, oilseed rape and silage maize close to the tree strip was associated with greater soil water tension in 30 and 60 cm soil depth due to the presence of poplar roots, reduced solar radiation due to tree shading and leaf litter coverage. In contrast, poplars growing in the outer rows produced more biomass than those in the inner rows due to the additional availability of space, light and nutrients taken from the crop field. Trees in the transition zone seem to be competitive with arable crops, but without effect on the average long-term yield of arable crops.

KEYWORDS

competition stress, fast-growing poplar, fine roots, leaf litter, microclimate, yield

1 | INTRODUCTION

In short rotation alley cropping agroforestry systems (SRACS), strips of fast-growing trees alternate with strips of crops or grassland. In temperate climate zones, the tree component in such systems is dominated by poplars planted for energy purposes whereas common annual grain crops for temperate agriculture, such as wheat, maize or soybean, dominate the crop component (Wolz & DeLucia, 2018). This division of the cropping system offers many advantages to the farmer, the agroecosystem, the climate through carbon sequestration and substitution of fossil fuels and also the society (IPCC, 2019; Jose et al., 2012). Introduced landscape elements like tree rows add heterogeneity to monotone agricultural production sites, as these elements differ substantially from cropland, for example due to their height, perenniality or management practices. The intention in the establishment of SRACSs is to use their positive synergistic effects for an increase in overall productivity. By offering various ecological services, such as erosion control and reduction in soil evaporation, trees on cropland can be an adaptation measure to current or future stressors because of climate change (Schoeneberger et al., 2012; Sheppard et al., 2020). However, instead of producing only positive effects on the arable crops with the introduction of trees, a transition zone is created where the two unequal components meet. Here, they compete with each other, and this competition creates stress in the low-competitive system. Due to the linear arrangement of crop and tree components in SRACSs, transition zones extend over the entire strip lengths.

The size of the transition zone in an SRSRACS is neither static nor fixed, but depends on the design of the agroforestry system, that is tree species, tree age and orientation of the tree strip, as well as the variable under investigation. For example, the spatial extend of modified microclimatic conditions can be large for wind speed but might be smaller for air temperature (Foereid et al., 2002; Schmidt et al., 2017). Moreover, the spatial extend for the same variable (e.g., shade) might be different during the course of the day (sun position), the season (foliated vs. defoliated trees) or in different weather conditions (sunny vs. rainy days). Thus, according to Schmidt et al. (2017), in this paper, we define the transition zone in SRACSs as a spatio-temporal variable entity with functional and structural gradients in between adjacent crop and tree strips.

Growth conditions of crops and trees depend on the availability of light, water, nutrients and space, which might be modified in the transition zone of SRACSs compared with the pure stand of crops and trees. Concerning solar radiation, tree height, canopy density and orientation determine the magnitude of solar radiation penetration on the cropped area over the day (Schmidt et al., 2019). The reduction in the photosynthetic active radiation because of shading from tree rows can cause yield and quality loss to crops. In agroforestry related literature, this has been shown, for example for wheat (Artru et al., 2017; Dufour et al., 2013; Sparkes et al., 1998) or maize and soybean (Reynolds et al., 2007). However, during stress periods of heat and drought, plants in the transition zone can benefit from tree shading due to reduced soil evaporation (Lin, 2010) and crop transpiration. Temperature-related stress negatively affects photosynthesis, stomatal conductance and crop development (Moore et al., 2021). Moreover, quality traits such as protein content of wheat grains can be enhanced in agroforestry systems (Temani et al., 2021). Currently, the positive effect of shading has a greater impact in Mediterranean or tropical countries. In the future, due to the climatic change with an increased frequency of drought and elevated temperatures, positive effects of shading in terms of reducing heat stress might be also relevant in temperate climate zones.

At the below-ground level, there might be found both competition and complementarity between tree and crop roots (van Noordwijk et al., 2015). Annual crops are, in general, shallow-rooting crops with 50% of roots in the upper 20 cm of the soil and 95% of root biomass in a soil depth of 100 cm (Fan et al., 2016). Trees, on the other hand, have a wider and deeper extending root system due to their perenniality (van Noordvijk et al., 2015). Root architecture varies with tree species and soil conditions. Competition for water (and nutrients) between forest and crop elements can occur due to overlapping root systems and their associated rhizospheres when precipitation is a limiting factor (Livesley et al., 2000). Although in a deep soil trees are capable of rooting beneath crop roots to access water and nutrients that are out of reach of crop roots, there is evidence that trees such as poplars prefer to uptake water, if available, from the upper soil layer (Luedeling et al., 2016; van Noordwijk et al., 2015). In times where water is scarce, trees take up water from deeper soil layers or groundwater (Bayala & Prieto, 2019). Especially in their early developmental phase, young trees access water from the cropping zone. Competition for water in the transition zone can also occur early in the season when trees consume water prior to spring crop sowing, which might result in yield losses of these crops in drier environments or during drought periods (Luedeling et al., 2016). The occurrence of competition for water depends on the phenology of crops and trees in an agroforestry system. At the above-ground level, the amount of rainfall reaching the soil surface in transition zones is influenced by canopy interception of tree vegetation. A part of the rainfall that is intercepted by the tree vegetation is lost by evaporation from the plant surface to the atmosphere, whereas another part can reach the soil surface due to throughfall or stemflow (e.g., David et al., 2006).

In drier environments, shallow-rooting crops can benefit from the redistribution of water by trees from deeper to upper soil layers. The amount of water that is redistributed by this hydraulic lift is estimated to amount to 5%–30% of the daily evapotranspiration (Luedeling et al., 2016).

In the transition zone of SRACSs, because of the above-mentioned horizontal and vertical overlap of the root systems of crops and trees, there might be competition for nutrients. On the other hand, deep-rooting trees also have an important role in the uptake and transfer of nutrients to the top soil. According to the safety-net hypothesis, in rooting beneath the crop root zone, trees can intercept mobile nutrients from below the crop root zone and return these to the top soil with litterfall and thereby reduce nutrient leaching (Bayala & Prieto, 2019; Bergeron et al., 2011; Cadish et al., 1997; Rowe et al., 1998). Relatively immobile nutrients can also be uptaken from deeper soil layers and can be incorporated into upper soil layers after litterfall and decomposition. In this sense, trees act as a 'nutrient pump' (Jobbágy & Jackson, 2004). Moreover, in the transition zone of SRACSs, higher nutrient availability and soil organic carbon contents, as compared to a treeless crop field, might result from tree fine root and leaf turnover (Berhongaray et al., 2019; Pardon et al., 2017).

In the transition zone of SRACSs, there is competition for space between trees and annual crops, both at the below- and above-ground level. Competition for space is closely linked to the above-mentioned competition for light, water and nutrients. At the below-ground level, the trees have a clear advantage because their perennial root system is already established when annual crops are sown. Above the ground, trees profit from the space availability at the tree strip edge. Poplars growing in the edge rows have been shown to produce more biomass than those growing in the middle of the tree strips (Gamble et al., 2014; Lamerre et al., 2015).

Stress in crop plants due to altered microclimate or growth conditions in the transition zone of SRACSs can be reduced by several management options or adaptation of agroforestry designs. These include, for example root pruning (Jose et al., 2012; Wajja-Musukwe et al., 2008), crown pruning (Jose et al., 2012), modification of tree density, tree strip orientation or the cultivation of shade-tolerant crop species or cultivars (Arenas-Corraliza et al., 2019; Lin et al., 1999).

Only few published studies are available on this transition zone in SRACS, in which the tree strips are managed in short rotation. It is, however, an important form of agroforestry management in Germany.

This paper aims thus to provide indications for competition between trees and crops as well as benefits that can arise for plants growing in the transition zone of a temperate SRACS. It covers various climatic and plant-related measurements that have been carried out at different positions within the crop and the tree strip of an SRACS established in 2008 near Braunschweig in the northern part of Germany.

We hypothesize that trees benefit from the conditions of the transition zone while annual crops are exposed to various stress factors. This stress might result in reduced yield and quality in a small area close to the tree strips, which is of minor importance for the total yield of the whole crop strip (strip widths 48 and 96 m). We expect ecosystem services in the transition zones of SRACSs due to the importance of trees for nutrient cycling and nutrient retention.

2 | MATERIALS AND METHODS

2.1 | Description of the experimental site

The presented measurements were conducted on a short rotation SRACS, established in 2008 in Northern Germany in Wendhausen (North 52°19’54’’, East 10°37’52’’) near Braunschweig. The study site is situated 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. The soil in the SRACS is mainly characterized by a silty clay texture, whereas the soil in the control field is mainly characterized by a clayey loam texture. The site-specific yield potential at the study site, which describes the property of the soil that ensures sustainable productivity, is medium to low.

The SRACS consists of nine tree strips (13 × 225 m) planted with three clones of fast-growing poplars (*Populus nigra L. x P. maximowiczii, P. maximowiczii x P. trichocarpa, P. koreana x P. trichocarpa*) for energy wood production, five narrow (48 × 225 m) and three wide (96 × 225 m) crop fields between the tree strips. The tree strips, which have a distance of 48 and 96 m, respectively, and a plant density of 10,000 plants per ha, are north-south oriented, that is almost perpendicular to the main wind direction, which is west/south-west. In order to allow for agricultural machinery use on the crop fields, the border between tree strip and crop field was set at 1.5 m distance from the outer tree row (‘zero line’) at both sides of the tree strip. Adjacent to the SRACS, at least 50 m from the woody structures, are three non-agroforestry control plots of approximately 3 ha each. Both SRACS crop and control fields were managed in the same conventional and site-specific way, with each crop being cultivated on one of the fields each year. Tree strips were harvested in a 3- or 6-year rotation cycle. Swieter et al. (2019) give more detailed information on the experimental design and management practices.

2.2 | Leaf litter deposition and nutrient content

In order to assess leaf litter deposition, litter traps were positioned within the tree strips and at the same distances from the zero line where crop yield measurements were taken, that is 1, 4, 7 and 24 m distance with two replications on the wind-protected/leeward side and two replications on the wind-exposed/windward side of the field in two of the narrow crop fields of the SRACS. The collection of leaf litter was conducted weekly from beginning to end of litterfall period in 2015, 2016, 2017 and 2018. Collected leaves were dried to constant weight at 60°C for 2 days, weighed separately for each trap and calculated in g/m^2 (more details in Swieter et al., 2019).

To determine nutrient composition of the collected leaves and calculate the potential nutrient input with leaf litter decomposition into the soil, a composite sample was prepared from the leaves collected at each measurement point on several sampling dates throughout the litterfall period, ground to 1 mm using a rotor mill (Brabender) and analysed in the laboratory. Nitrogen (N) contents were determined according to the Dumas method using the vario-MAX cube (Elementar) whereas contents of P, K, Ca and Mg were determined by microwave digestion using the Start 1500 (MLS) and inductively coupled plasma optical emission spectrometry (ICP-OES) using the Thermo Icap 6300 Duo (Thermo Scientific). Afterwards, the nutrient amounts in the leaf litter of each trap were calculated by multiplying its total litter dry mass with the determined nutrient contents.

2.3 | Root distribution, nutrient contents

The horizontal and vertical distribution of the poplar fine roots in the transition zone of the crop field was assessed. A total of 18 drill cores with a diameter of 8 cm and a length of 160 cm were removed in June of 2018 on the windward side of the same wide crop field where soil nitrate (NO_3^-) and ammonium (NH_4^+) was analysed (see section 2.4). Three replicate samples were taken directly at the zero line and at 1, 2, 3, 4 and 7 m distance into the crop field. The drill cores were divided into 10 cm sections, and poplar fine roots with a diameter of ≤2 mm were separated manually from these sections, washed with distilled water and dried to constant weight at 60°C for

2 days. Fine root dry mass was expressed as g/m^3 soil separately for each 10 cm section.

To determine nutrient composition of the separated fine roots and calculate the potential nutrient input with fine root decomposition into the soil, a composite sample was prepared from all the separated fine roots, poured over with liquid nitrogen, crushed with a mortar and analysed in the laboratory using the same methods that were used for the nutrient determination of the collected leaf litter. Nutrient contents were multiplied with the dry mass of separated poplar fine roots, separately for each drill core.

2.4 | Mineral nitrogen sampling

To assess NO_3^- and NH_4^+ contents in the soil, soil samples were taken in early March of 2019 and 2020 (before first fertilizer application) on the windward side of one of the wide crop fields of the SRACS, directly at the zero line and at 7 m distance from the zero line. In 2019, soil samples were taken with a dustpan at two recently dug soil profiles in different depths of the topsoil and of the subsoil, respectively. A composite sample was prepared for each soil profile and each soil horizon. In 2020, soil samples were taken in 0–30 cm, 30–60 cm and 60–90 cm soil depth with four replications using a geological drill (the so-called 'Pürckhauer'). The same procedure was followed in the non-agroforestry control field, on the eastern field edge. NO_3^- and NH_4^+ contents of fresh soil samples were analysed in the laboratory using the San++ Continuous Flow Analyser (Skalar; Breda). To calculate NO_3^- and NH_4^+ contents in kg per ha, determined values were multiplied with thickness of the soil layer and bulk density. The latter was determined using samples of soil sampling rings that were dried for 24 hr at 105°C and then weighed. The bulk density was obtained by dividing the dried sample by the volume of the plug-in cylinder. Stone content at soil depths of 0–90 cm is very low at our study site and, therefore, was neglected.

2.5 | Water tension

To determine the soil moisture status, the soil water tension (SWT) was measured using watermark sensors (PESSL Instruments). SWT is the force that plant roots need to draw water from the soil. Sensors were installed at three positions within the SRACS (in the tree strip, at the leeward side of one of the narrow crop fields at 1.5 and 24 m from the zero line) in four soil depths (15, 30, 60 and 90 cm). The crop field was planted with winter barley; measurements were conducted over a period of 6 weeks from 1 June 2013 to 11 July 2013 (Lamerre, 2017).

2.6 | Reduction in solar radiation, air temperature and relative humidity

In order to quantify reduction in solar radiation due to the tree strips, the incoming global solar radiation on the crop field with and without the tree strips was calculated using the 'Area Solar Radiation' function of the Spatial Analyst Tools in Esri® ArcMap™ 10.2 and given as global radiation in watt hours per square metre. Global radiation is calculated as the sum of direct and diffuse radiation from all solar map or sky map sectors. The spectral range of global radiation is in the short-wave range (approx. 290–4,000 nm). With cloudless skies, the proportion of the photosynthetically active radiation (i.e., 400–700 nm) of the global radiation is in the range of 40%–50%. The tree strips shapes (considered as walls with defined heights) were added to the digital elevation model of the Wendhausen site. To simplify the calculation it was assumed that tree height and density did not change throughout the growing season. The solar radiation tool calculates the solar radiation over a specified geographic area by using location, elevation slope, orientation and atmospheric transmission as the most important input parameters. The default settings of the solar radiation tool were used. The reduction in incoming light is thus given as the percentage of solar radiation with the tree strips compared to the value obtained without the tree strips and was calculated over the whole growing season (from sowing to harvest). The analysis was carried out for two narrow (i.e., 48 m wide) crop fields of winter wheat and winter barley in 2013 and 2014.

Air temperature and relative humidity (RH) were measured at 1.5 m above-ground level with combined thermometers and hygrometers (Hygroclip 2; Rotronic Messgeräte GmbH). Sensors were installed in the tree strip and at the leeward side of one of the narrow crop fields at 1.5, 9.5 and 24 m as well as at the windward side at 1.5 m from the zero line. In addition, at 9.5 m from the zero line at the windward side as well as in the control field, temperature was measured using a temperature sensor (SMT16030; PESSL Instruments). The crop field was planted with winter barley; measurements were conducted over a period of 6 weeks from 2 June 2013 to 11 July 2013.

2.7 | Crop and tree yield

Crop yield was measured from 2016 to 2019 at 1, 4, 7 and 24 m distance from the zero line with two replications on the wind-protected/leeward side and two replications on the wind-exposed/windward side of the field in three crop types (oilseed rape in 2016, winter wheat in 2017 and 2018 and silage maize in 2019) in two of the narrow crop fields of the SRACS. The same procedure was followed in 2017, 2018 and 2019 in the control field, with two replications on the eastern and on the western field edge, respectively. Harvest was conducted using a plot combine harvester with a cutting width of 1.5 m. After the harvest, dry matter yields were determined by drying the crops to constant weight at 105°C for 2 days and calculated in t/ha (more details in Swieter et al., 2019).

Wood yield of the tree strips was estimated in winter season 2013/2014, separately for both rotation cycles (6-year-old non-coppiced poplar trees and 3-year-old coppiced poplar trees on 6-year-old stool), the outer rows (leeward and windward) and the middle rows. In each variant, diameters of breast height (DBH) of 40% of the trees were measured. From all measured data, 25 representative DBH were selected, and the corresponding shoots were manually harvested 10 cm above the ground, chipped and weighed (Lamerre et al., 2015). Allometric power equations were used to predict dry mass from DBH (Verwijst & Telenius, 1999). Based on the average shoot dry mass and the number of shoots per hectare, the yearly wood production per hectare was estimated, according to the mean stool method (Hytönen et al., 1987).

2.8 | Statistical analysis

Nutrient composition of poplar leaf litter and fine roots, horizontal distribution of leaf litter and crop yield in relation to the zero line and the orientation of the crop field towards the tree strip (i.e., leeward or windward) were described by the arithmetic mean (horizontal distribution of leaf litter, crop yield) and visualized using scatterplots.

To analyse the effect of the distance from the zero line and soil depth on the mass of the poplar fine roots, linear mixed-effect models were fitted with the distance from the zero line (0, 1, 2 and 3 m) and the soil depth (0–160 cm) as fixed effects and the number of replications (1–3) as random effect. Model selection was done using the Akaike information criterion corrected for small sample sizes (AICc, see Burnham & Anderson, 2002) and maximum likelihood estimation. The lower the AICc was, the more suitable the model was. Confidence intervals were obtained from the selected model with restricted maximum likelihood estimation (Zuur et al., 2009). To detect differences between the investigated distances from the zero line and soil depths, respectively, the Tukey post hoc test was used.

To check for a side effect (leeward/windward) in each rotation cycle, we performed linear mixed-effects models with the random effects tree ID, nested within strip ID (for details, see Lamerre et al., 2015). We also checked graphically for normal distribution and variance homogeneity of residuals. Probability level was set at .05.

Statistical analyses were carried out using R (R Core Team, 2019) and packages nlme (Pinheiro et al., 2020), bbmle (Bolker & R Development Core Team, 2020) and emmeans (Lenth, 2021).

3 | RESULTS

3.1 | Space: Litter and root distribution

Overall, leaf litter deposition during the litterfall periods of 2015–2018 was the greatest within the tree strips (T) and decreased towards the middle of the crop field, with 70%–97% of the leaf litter being deposited between the tree strip and 1 m distance from the zero line (Figure 1). In addition, amounts of leaf litter deposited on the soil were similar in 2015, 2016 and 2018, while leaf litter deposition was considerably lower in 2017. At 24 m of the zero line, in the middle of the crop field, no leaf litter was deposited, neither on the windward nor on the leeward side in 2015, 2016 and 2017 (Figure 1).

About three quarters of the poplar fine roots were found close to the tree strip at the zero line (0 m), which were on average 5,256 g/m^3. At 1, 2 and 3 m from the zero line, we found on average 819, 662 and 154 g fine roots m^{-3} respectively. From a distance of 4 m,

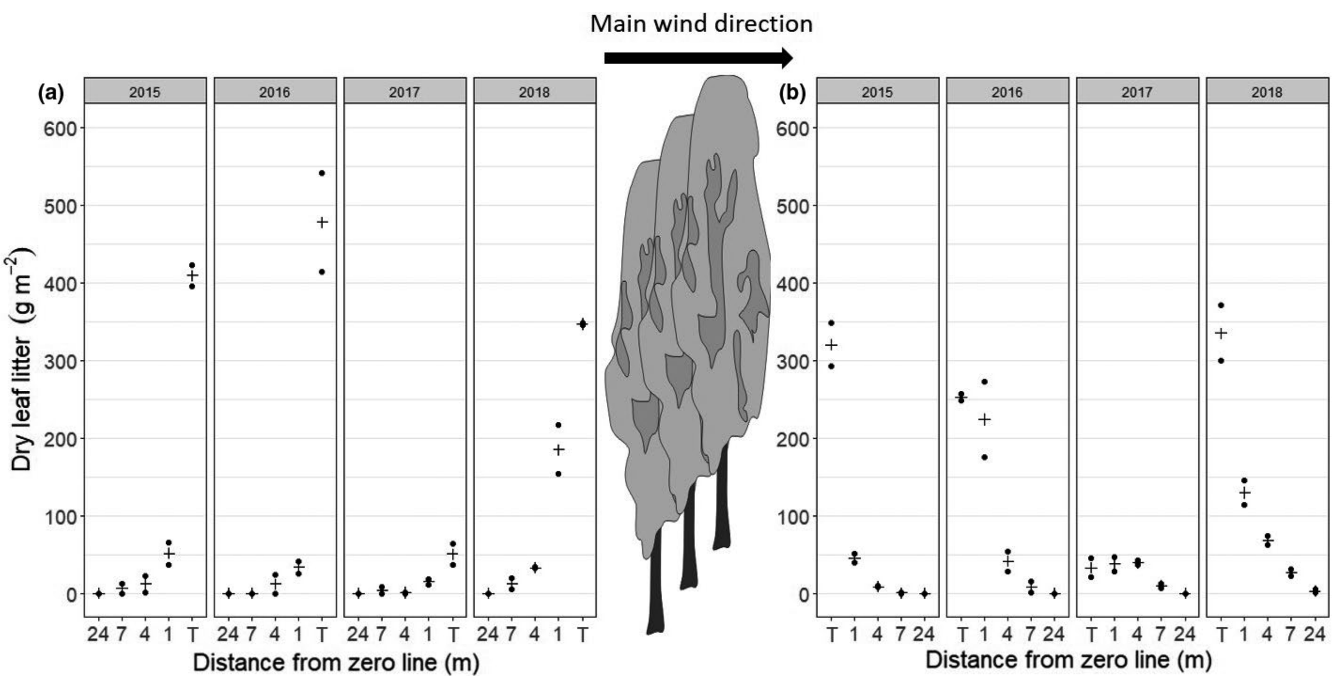

FIGURE 1 Scatterplots showing accumulated leaf litter deposition in autumn of 2015–2018 within the tree strip (T) and at different distances from the zero line on the windward (a) and on the leeward (b) sides of the crop fields, respectively. Dots denote observed leaf litter deposition, and crosses denote average leaf litter deposition at the respective distance from the zero line

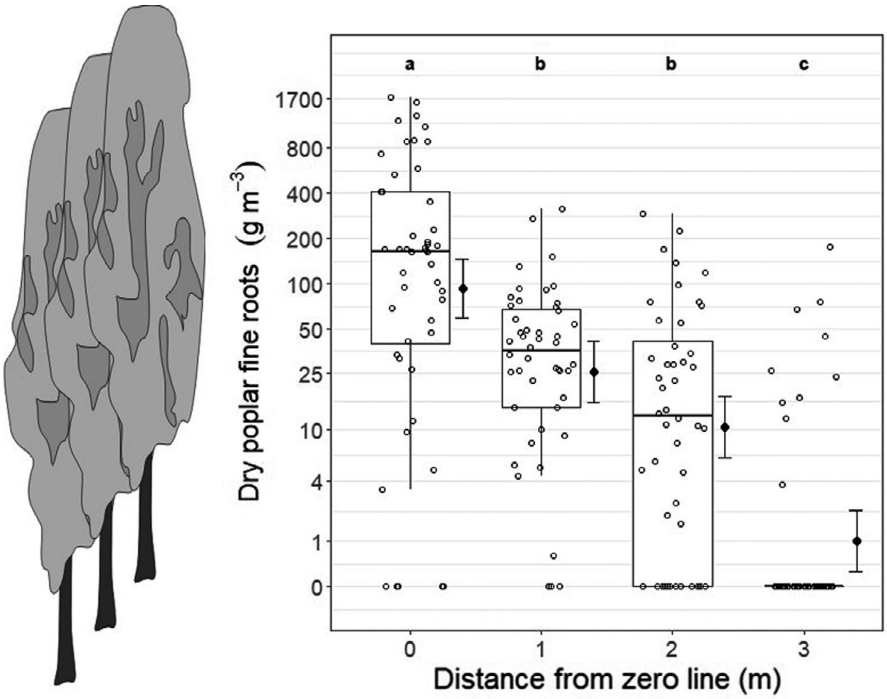

FIGURE 2 Boxplot with overlaid scatterplot showing dry mass of poplar fine roots directly at the zero line (0 m) and at different distances from the zero line, independently of the soil depth. Unfilled dots represent measured fine root masses, error bars are the confidence intervals of the candidate model with filled dots as predicted mean values. Different letters represent a significant difference between poplar fine root dry masses at the distances, according to the Tukey test

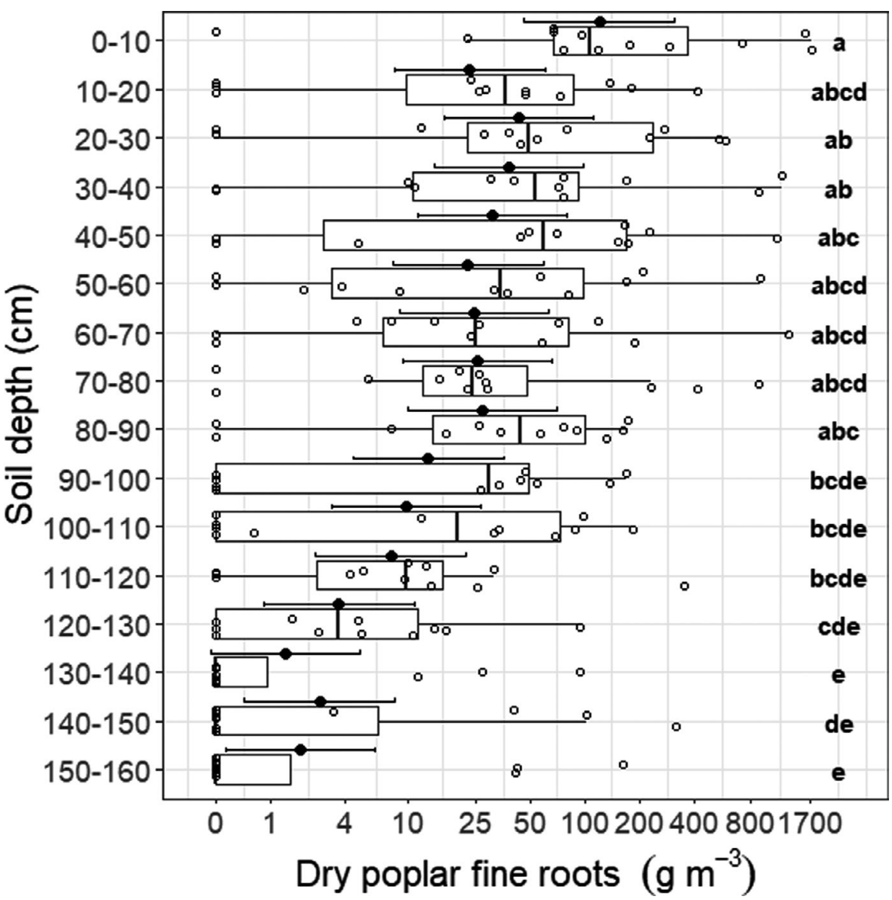

FIGURE 3 Boxplot with overlaid scatterplot showing dry mass of poplar fine roots in different soil depths, independently of the distance from the tree strip. Unfilled dots represent measured fine root masses, error bars are the confidence intervals of the candidate model with filled dots as predicted mean values. Different letters represent a significant difference between poplar fine root dry masses at the soil depths, according to the Tukey test

no tree fine roots were found in the drill cores. Overall, biomass of poplar fine roots decreased with increasing distance from the tree strip (Figure 2) and soil depth (Figure 3): Fine root density close to the tree strip was significantly higher than at greater distances, and we found significantly more fine roots in a soil depth of 0–90 cm than at greater soil depths.

3.2 | Nutrients: Nutrient contents in litter and roots, mineral nitrogen in the soil

Nutrient amounts added to the soil with the leaf litter depended on the litter dry mass and the nutrient composition of the leaf litter. Accordingly, the highest amounts of nutrients were measured within the tree strip (T) and decreased towards the middle of the crop field (Figure 4). Nutrient composition of the leaf litter composite sample was 0.66% N, 0.23% P, 0.76% K, 5.0% Ca and 0.15% Mg. According to this composition, the nutrient amounts varied greatly at different distances from the zero line (Figure 4). Overall, the amounts of nutrients deposited on the soil with the leaf litter were similar in 2015, 2016 and 2018, while in 2017 considerably less nutrients were deposited. At 24 m from the zero line, in the middle of the crop field, no nutrients were deposited with the leaf litter, neither on the windward nor on the leeward side in 2015, 2016 and 2017 (Figure 4).

Nutrient composition of the composite sample of poplar fine roots was 0.65% N, 0.16% P, 0.70% K, 2.08% Ca and 0.24% Mg. According to the total dry mass of poplar fine roots found directly at the zero line (0 m) and at 1, 2 and 3 m distance from the zero line, the amounts of nutrients deposited in the soil with the fine roots varied from on average 98.7 (Ca) to 7.59 (P), 15.4 to 1.18, 12.4 to 0.96 and 2.90 to 0.22 g/m² respectively (Figure 5).

In March 2019, average plant available mineral nitrogen contents (i.e., ammonium and nitrate) in the soil of the SRACS crop field were similar at the zero line (0 m) in both soil depths and in 0–30 cm soil depth at 7 m distance from the zero line, with a mean between 12.87 and 14.98 kg/ha. At 7 m from the zero line, a high level of nitrate was measured in the soil in 30–100 cm depth, resulting in a mean nitrogen content of 90.01 kg/ha (Figure 6a). In March 2020, the spatial distribution of average plant available mineral nitrogen contents in the soil of the SRACS crop field at 7 m from the zero line and in the control field was similar. Nitrogen contents were the lowest in 0–30 cm soil depth with a mean between 16.55 and 22.91 kg/ha and increased with soil depth to 43.92–71.35 kg/ha. In contrast, at the zero line, nitrogen contents in the SRACS crop field remained approximately the same over the measured soil depths with a mean between 10.24 and 14.22 kg/ha (Figure 6b).

3.3 | Water: soil water tension

Overall, the soil water tension increased with time at nearly all soil depths and sample positions (Figure 7). With just 16 mm, precipitation in June 2013 was well below the 30-year mean for June of 60.6 mm. Precipitation during the six weeks of measurement from 1 June to 11 July 2013 totalled 22.8 mm. Appreciable amounts of rain (between 5 and 7 mm) fell on 13 June, 29 June and 1 July, which is partly reflected by a decline in water tension (Figure 7).

In the tree strip, the mean daily soil water tension was relatively similar in the different soil depths (15, 30, 60 and 90 cm) on the same day. In the crop field at 1.5 m from the zero line, the tension increased up to 114 cBar at 30 cm and up to 72 cBar at 60 cm soil depth. At 15 cm soil depth, the increase was small, and at 90 cm, the soil water tension stayed around 0 cBar. In the middle of the crop field, at 24 m from the zero line, 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). At both 60 and 90 cm soil depth, the water tension was low (maximum 14 cBar).

3.4 | Light: solar radiation, air temperature and relative humidity

At the end of the growing season 2012/2013, trees with a 6-year rotation cycle were harvested for the first time, those with a

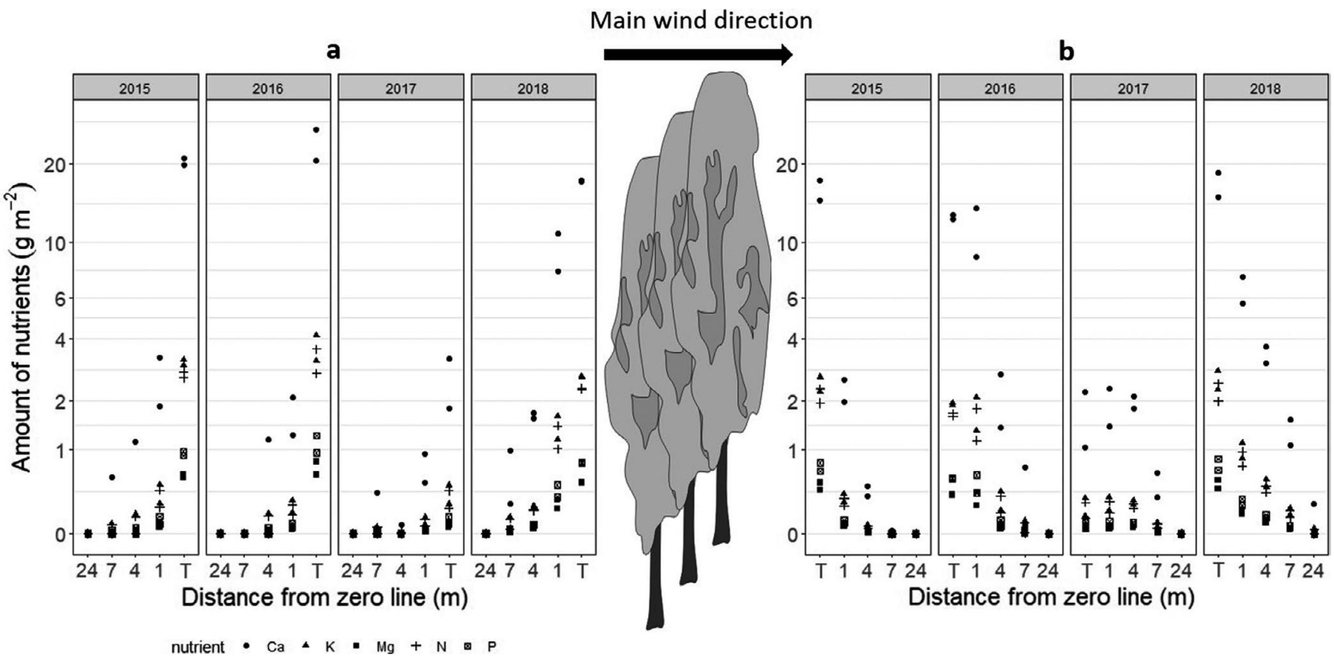

FIGURE 4 Scatterplots showing amounts of nutrients, deposited with the leaf litter in autumn of 2015–2018 within the tree strip (T) and at different distances from the zero line on the windward (a) and on the leeward (b) sides of the crop fields, respectively. Symbols denote different nutrients

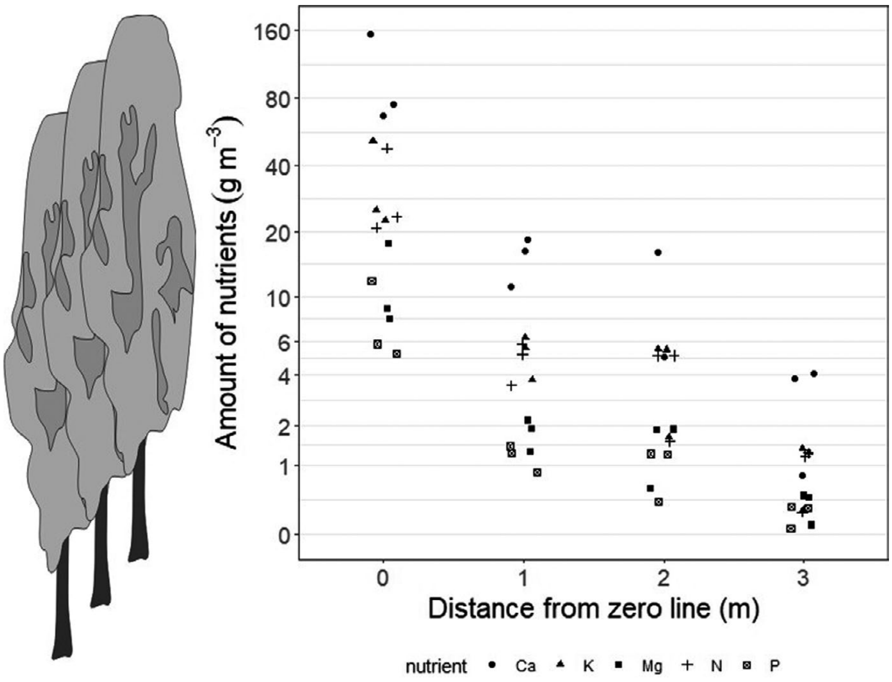

FIGURE 5 Scatterplot showing the amounts of nutrients deposited in the soil with the poplar fine roots found at the zero line (0 m) and at 1, 2 and 3 m distance from the zero line. Symbols denote different nutrients

3-year cycle for the second time. Depending on the rotation cycle, average tree heights were thus between 5.8 and 9.4 m. Compared with the open field, relative solar radiation (RSR) was always the lowest next to the tree strips and increased towards the crop field centre. The largest reduction was observed in the western part of the wheat field, where the trees were the tallest with an average height of 9.4 m. RSR was 44% and 54% at 1 and 3 m into the field, respectively, whereas in the barley field (average tree height 5.8 m), it was 50 and 67%. At the eastern side of both, the wheat and the barley crop field, RSR was quite similar due to comparable tree heights. In both fields, 100% RSR was not achieved; maximum RSR was 98% (wheat) and 99% (barley), respectively. In contrast, during the growing season 2013/2014, just after the tree harvest, 100% RSR was already reached between 6 and 8 m into the field. An appreciable reduction in the solar radiation (i.e., relative solar radiation <95%) was just observed in the first 3 and 1 m of the western and eastern part of the fields respectively. As trees just started to regrow and reached an average height of 1.2 to 1.5 m, RSR was generally higher compared with the 2012/2013 growing period.

The tree strips are north-south oriented, that is the shading of the crop fields' changes with the course of the sun during the day: In the morning, the windward crop area is shaded, at noon, there is almost no shade on the crop field and in the afternoon, the leeward crop area is shaded. Therefore, data on air temperature and relative humidity (RH) were analysed separately for morning (hours 5–12), noon (hours 12–15) and afternoon (hours 15–21) to take into account the effect of shading on the measured parameters.

In the morning, the air temperature was in general lower in the crop field and the SRC strip than in the control field. Differences were the greatest for hot and sunny days (Figure 8). At noon, most differences in the crop field were positive, that is higher than in the control field, except those for the cloudy day as well as the SRC strip during all periods. In the afternoon, all differences were positive, with the greatest differences measured on the hot and sunny days (Figure 8).

Overall, the greatest differences in RH were recorded for the hot and sunny days (Figure 8). At 1.5 m from the zero line in the morning, RH was about 3% lower in the sunny zone, whereas it was about 3% higher in the shaded zone. At noon and in the evening, RH was the highest within the tree strip. On cloudy days, RH differences were generally relatively small (Figure 8).

3.5 | Yield: crops and trees

Overall, crop yield in 2016 (oilseed rape) and 2017 (winter wheat), when average tree height was 4.78 and 7.25 m, respectively, decreased from the middle of the crop field (i.e., 24 m from the zero line) to 1 m distance from the zero line. This decrease was greater in the SRACS than in the control field. However, there were no substantial differences in average long-term crop yield between the narrow SRACS, the wide SRACS and the non-agroforestry control field, neither for oilseed rape nor for winter wheat (Swieter et al., 2019).

In 2018 and 2019, average winter wheat and silage maize yields also decreased from the middle of the crop field to 1 m distance from the zero line/field edge. This decrease was again greater in the SRACS than in the control field (Table 1).

Overall, in the SRACS, winter wheat yield at 1m from the zero line was on average 81% lower than in the middle of the crop field, whereas silage maize yield at 1 m from the zero line was on average 97% lower than in the middle of the crop field. On the control field, winter wheat yield at 1 m from the field edge was 13% lower than at 24 m distance from the field edge, whereas silage maize yield at

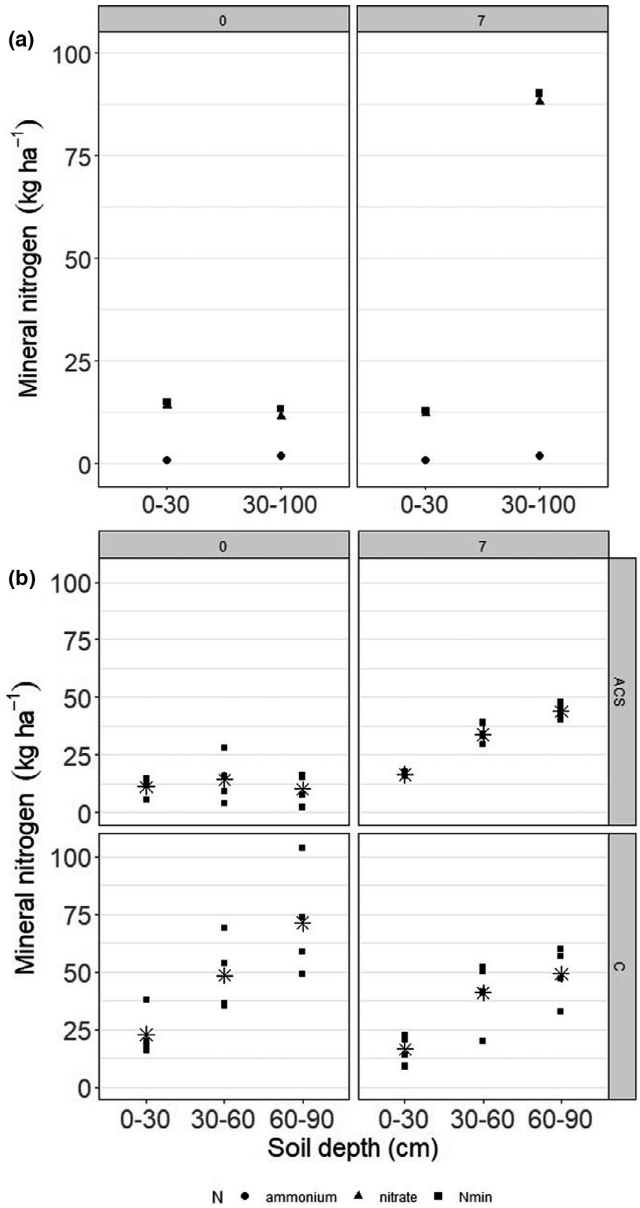

FIGURE 6 Scatterplot showing the mineral nitrogen contents in the soil of the SRACS crop field in March 2019 at the zero line (0) and at 7 m distance from the zero line (7) in the soil depths of the top soil (i.e., 0–30 cm) and of the subsoil (i.e., 30–100 cm) (a) and the mineral nitrogen contents in the soil of the alley cropping system (SRACS) and in the control field (C) in March 2020 at the zero line/border of the field edge (0) and at 7 m distance from the zero line/border of the field edge (7) in different soil depths (b). Symbols denote the sum of nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen contents in the respective soil depth, asterisks denote average mineral nitrogen contents

1 m from the field edge was 10% lower than at 24 m distance from the field edge.

Tree biomass production of outer tree strip rows was significantly higher than in the respective middle rows, in both the 3-year and 6-year rotation cycle (Table 2). Calculated dry matter biomass yield of these rows was up to 16 t/ha^{-year}. In the 6-year rotation cycle, yearly biomass production of the windward rows was significantly lower than that estimated for the leeward rows (Lamerre et al., 2015).

4 | DISCUSSION

4.1 | Competition for space between trees and crops

The leaf litter biomass results and our field observations showed that in autumn and winter, leaf litter of the poplars covers the surrounding soil. Winter crop seedlings in particular may lack the space and light to develop when covered with leaf litter. Litter deposition in all years decreased from the tree strip towards the middle of the crop field, up to a distance of 7 m from the zero line. These results are in accordance with our previous study, in which we showed that amount and area of leaf litter deposition depended not only on tree height, but also on wind speed and direction during the period of leaf litterfall (Swieter et al., 2019). The analysis of litterfall distribution in an agroforestry system (AFS) with 6/7 years old poplars in the North temperate region of Canada showed that about 80% of the leaves fell within 2.5 m from the tree row (Thevathasan & Gordon, 1997), which is consistent with our results. Leaf litter coverage of the winter wheat seedlings in autumn of 2017 may be a reason for the reduced winter wheat yields close to the tree strip in 2018, which corroborates earlier studies (Batish et al., 2008; Lamerre, 2017; Singh et al., 2001). The considerably lower leaf litter deposition measured in 2017 was due to strong winds at the time of litterfall, which blew the leaves over a greater distance. Reduced yields can further be explained with a reduced seedling survival due to possible allelopathic effects of the poplars. From laboratory studies, there is evidence that the genus *Populus* possesses allelopathic activity. Leaf extracts from *P. nigra*, *P. tremula* and *P. deltoides* have been shown to reduce germination of cereals and other plant species (Hachani et al., 2019; Inayat et al., 2019, 2020; Singh et al., 2012; Zubay et al., 2021).

Root competition for space, water and nutrients between crops and trees might be limited to a narrow area at the zero line, compared with the whole field width. Poplar fine roots were found up to 3 m from the zero line. Comparable results were found in an 11 years old AFS with poplars in England, where fine root mass density of the poplars decreased significantly with increasing distance from the tree row and soil depth (Upson & Burgess, 2013). Three years after tree planting, poplar fine roots were found up to a distance of 5 m from the tree row and 150 cm soil depth. However, eight years later, poplar fine root mass density still decreased with increasing soil depth, but the lowest fine root mass was found between 3 and 4 m from the tree row, whereas greater fine root masses were found in smaller and larger distances from the tree strip (Upson & Burgess, 2013). In an AFS with 13 years old poplars in Southern France, biomass of the poplar fine roots decreased from 0 to 7 m from the tree row, and fine root concentration was higher in the first soil layer (0–10 cm) compared to the deeper soil layers (Jha, 2017), which is in line with our results.

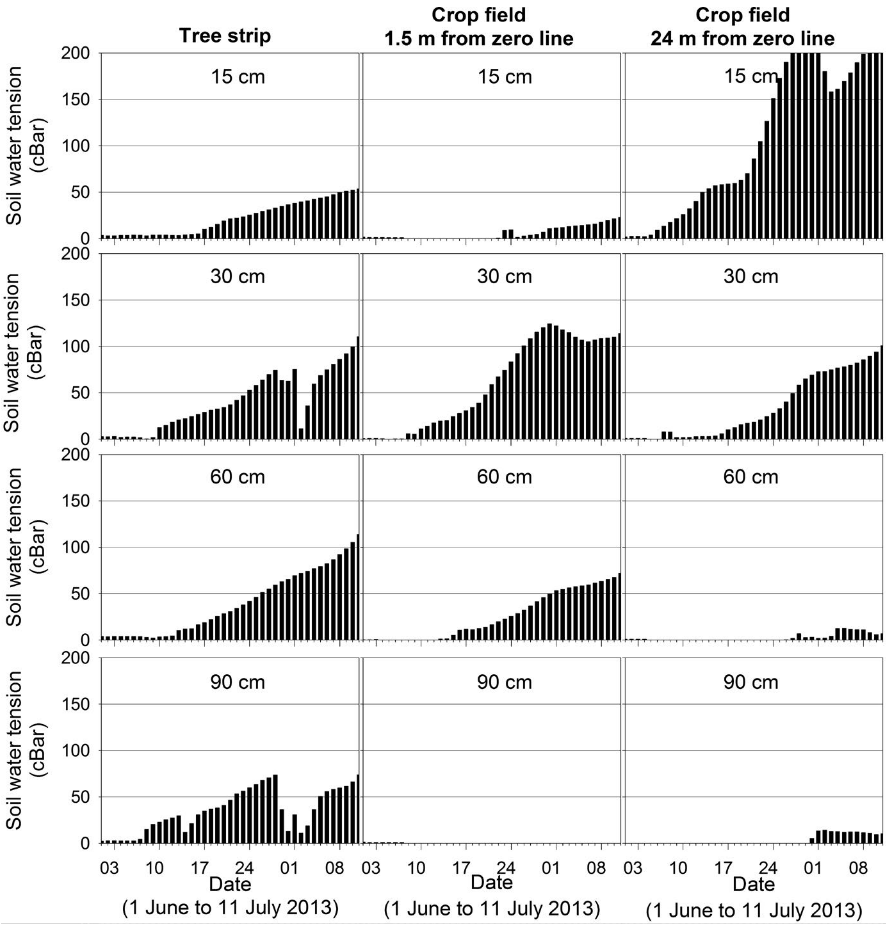

FIGURE 7 Mean daily soil water tension (cBar) in 15, 30, 60 and 90 cm soil depth in the tree strip and in the crop field at 1.5 and 24 m from the zero line from 1 June to 11 July 2013

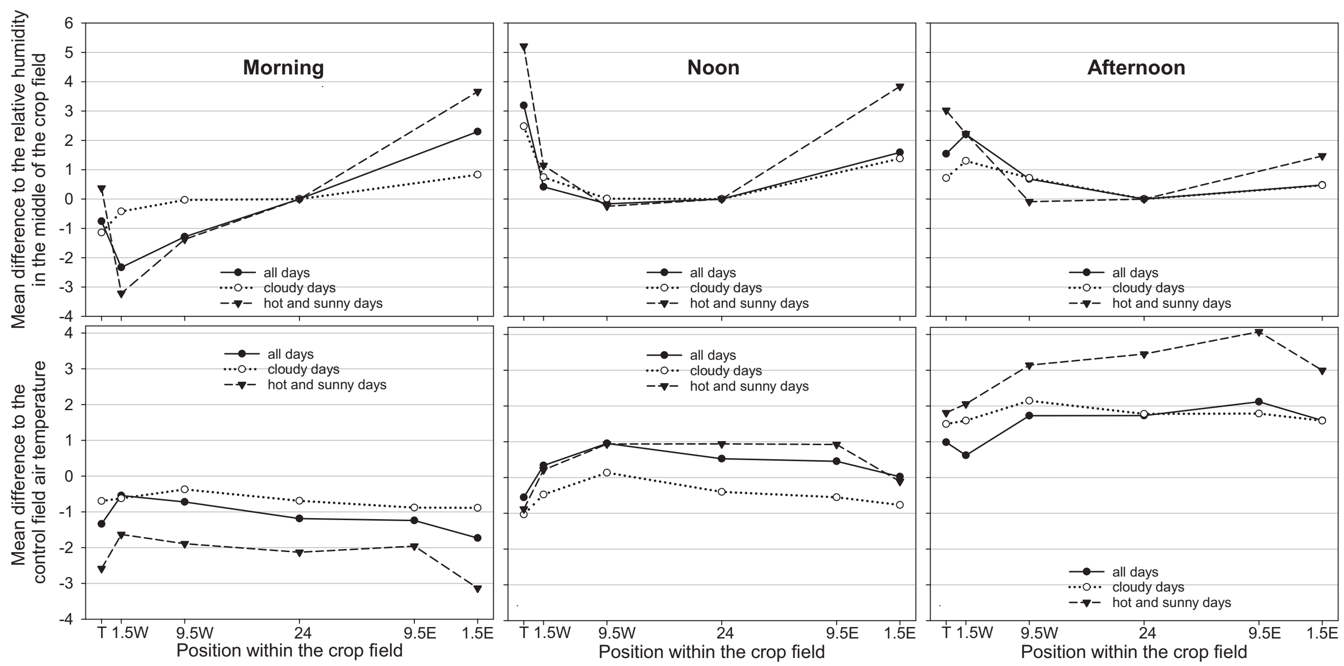

FIGURE 8 Mean differences to the control field air temperature and to the relative humidity in the middle of the crop field (i.e., 24 m from the tree strips) at different positions within the crop field as well as within the SRC strip. Data are shown for the whole measurement period ('all days', i.e., 2 June 2013 to 11 July 2013), cloudy days (solar irradiance < 3,000 W/m², i.e., 14 and 25 June, 10 July 2013) and hot and sunny days (24-hr mean >20°C and solar irradiance > 5,000 W/m², i.e., 3, 5–8, 17–20 June and 6–9 July 2013), separately for morning (hours 5–11), noon (hours 11–15) and afternoon (hours 15–21). The sensors failed from 26 June to 5 July

TABLE 1 Average winter wheat (WW) and silage maize (SM) yields of 2018 and 2019 at different distances from the zero line on the windward/western (left) and on the leeward/eastern (right) sides of the narrow crop field of the SRACS and of the control field respectively

Crop & Year	Cropping system	24 m (t/ha)	7 m (t/ha)	4 m (t/ha)	1 m (t/ha)	1 m (t/ha)	4 m (t/ha)	7 m (t/ha)	24 m (t/ha)
WW 2018	SRACS	7.53	6.59	5.91	1.48	1.44	5.23	5.97	7.55
WW 2018	C	7.93	7.10	5.58	6.21	7.63	7.38	7.53	7.90
SM 2019	SRACS	16.04	14.27	11.81	0.66	0.34	7.67	9.79	16.69
SM 2019	C	16.02	15.16	13.67	12.84	15.21	13.62	14.74	14.97

TABLE 2 Mean row woody biomass production (t/ha^{-year}) in the different rotation cycles (Mean of all rows ±standard error, different letters indicate statistically different biomass production [$p < .05$]) (Lamerre et al., 2015)

	Leeward rows	Middle rows	Windward rows
3-year rotation cycle	16 ± 2.89 a	8 ± 0.58 b	15.7 ± 1.61 a
6-year rotation cycle	16.1 ± 1.09 A	8.6 ± 0.38 B	12.8 ± 1.43 AB

That we found a lower horizontal poplar fine root distribution compared with other studies is probably due to the fact that our trees were harvested after 6 years, resulting in a severe reduction in the rooting system due to the strong relationship between shoot and root biomass production (Van Noordvijk et al., 1996). In general, results of root distribution, achieved in different studies, are hard to compare, due to different varieties/species under investigation and large differences in sampling methods, soil characteristics and cultivation methods (e.g., harvesting/pruning of the trees, ploughing at the crop fields).

4.2 | Competition for nitrogen and nutrient input by trees

Decomposition of leaf and fine root litter is a very complex process that depends on various abiotic (e.g., temperature, humidity) and biotic factors (e.g., soil food web, chemical composition of litter) (Krishna & Mohan, 2017; Neumann et al., 2018). There are two potential end-points of decomposition: mineralization, entailing the conversion of organic substances into inorganic, plant available nutrients and humification, which results in the formation of stable humic substances and the immobilization of certain nutrients and C. Thus, the nutrient content of the litter determines the potential of mineralization and the potential amount of nutrients that enter the soil via tree litter. A part of it can be converted into inorganic forms via the process of mineralization, which is influenced by the C/N ratio, soil moisture, temperature or the microbial community (e.g., Wang & D'Odorico, 2013).

Corresponding to the leaf litter and fine root distribution of the poplars, the potential nutrient input via leaf and root litter also decreased with increasing distance from the tree strip (leaf litter and fine roots) and soil depth (fine roots). 70%–97% of potentially releasable nutrients from leaf litter, and 88% of potentially releasable nutrients from poplar fine roots were concentrated in the area between the tree strip and 1 m distance from the zero line. Thus, for the majority of the fertilized crop field, the additional nutrient input through the leaf litter and fine roots is negligible. Our soil analyses revealed even lower mineral nitrogen contents in the soil at the zero line compared with the soil at 7 m distance from the zero line (cf., section 3.2), indicating a nutrient removal from the first metres of the crop field by the trees. Since we use a boom spreader for fertilizing, fertilizer can be applied precisely to the edge of the field. Thus, the reduction in nitrogen fertilization in AFS, suggested by some authors (e.g., Pardon et al., 2017; Thevathasan & Gordon, 2004), does not seem to be advisable for the special case of our SRACS, possibly due to a greater nutrient removal from the crop field by the roots of the very dense planted trees (plant density around 10,000 trees ha^{-1}). However, since tree strips are not fertilized, decomposed poplar leaf litter and fine roots can be an important nutrient source and part of the nutrient cycle within the tree strip. Fertilization of poplar trees in short rotation coppices is not common (Rutz & Dimitriou, 2015). Poplar trees use nutrients (re)cycled from leaf and root litter/mineralization, atmospheric N deposition and benefit from better uptake of nutrients through mycorrhization (Bärwolff et al., 2012). At our study site, potential nutrient input from annual poplar litterfall deposited at 1 m distance from the zero line averaged 55 kg Ca ha$^{-1\text{-year}}$, 7 kg K/ha^{-year}, 1 kg Mg/ha^{-year}, 6 kg N/ha^{-year} and 2 kg P ha$^{-1\text{-year}}$, potential nitrogen input through poplar fine roots at 1 m distance was 154 kg Ca ha^{-1}, 52 kg K/ha, 18 kg Mg/ha, 48 kg N/ha and 12 kg P ha^{-1}. Thus, quantitatively, fine roots appear to be more significant for nutrient input than leaf litter. However, more long-term research is necessary on decomposition, humification and mineralization processes of poplar root and leaf litter in SRACSs. Moreover, the amount of nutrients entering the soil from poplar fine roots also depends on the times fine root biomass is replaced each year (i.e., turnover rate) (Lukac, 2012). Lifespan of poplar fine roots depends on various factors, such as tree species and clone type, tree age, season in which a root is produced, root diameter and soil environmental conditions. It varies between 30 and 150 days, whereas turnover rates vary between 1 and 2 years (Block et al., 2006; Lukac, 2012). Moreover, recently Pardon et al. (2017) showed that an increase in soil nutrient concentrations (i.e., N, P, K, Mg and Na) through leaf litter is quantifiable only in older (>15 years) AFSs without coppice. This is a reminder of the need for long-term experimental field studies to quantify complex issues such as nutrient enrichment in soils of agroforestry systems.

All in all, at the age of our SRACS during the study (i.e., 12 years) for the annual crop plants in the transition zone, the negative effects of poplar leaf litter (light reduction for winter crop seedlings, allelopathic effects) and poplar fine roots (nutrient uptake from the crop field) seem to outweigh their possible positive effects (i.e., additional nutrient input through leaf and root litter, build-up of organic substance). This might result in stress due to deteriorated growth conditions (e.g., reduced space, light and nutrient supply) and reduced crop yields, which is in accordance with our yield results (cf., section 3.5). However, the trees in the transition zone at the edge of the crop field, apparently benefit from the availability of more space and light as well as from nutrient uptake from the fertilized crop field, being possible reasons for increased biomass production of the outer tree rows compared with the middle tree rows (cf., section 3.5).

4.3 | Competition for water between trees and crops

A SWT increase can be an indication for the presence of plant roots. Within the tree strip, the SWT pattern showed that the soil dried out homogenously at each investigated soil depth, indicating a rooting depth of 5-year-old poplars of at least 90 cm. This is in accordance with our data on poplar fine root distribution, where the presence of fine roots of 10-year-old poplar trees was proven up to a depth of 160 cm (cf., section 3.1) as well as with literature (e.g., Jha, 2017). In the transition zone at 1.5 m from the zero line in 15 cm soil depth, SWT was relatively low. In this part of the crop field, the barley plant density was observed to be very low, possibly due to competition for resources and/or seedlings being covered by poplar litter in autumn. This matches with the low yields of maize, winter wheat and oilseed rape in the crop field at 1.0 m from the zero line (cf., section 3.5). Due to the reduced number of barley plants at 1.5 m from the zero line, a low barley root density is expected in the surface soil at 1.5 m. Higher SWTs in 30 and 60 cm soil depth that we measured in the transition zone are an indication for the presence of poplar roots at 1.5 m into the crop field. This might be another reason for the low yields in crop plants observed in this part of the transition zone. Fine roots of 10-year-old poplar trees have been found in soil samples up to 3 m from the zero line (cf., section 3.1). The investigation of poplar root distribution in a Canadian agroforestry system showed a high concentration of roots at 2 m from the tree line in deeper soil horizons (i.e., 60 cm) (Gray, 2000 in Link et al., 2015; Thevathasan & Gordon, 2004). Using stable isotopes, Link et al. (2015) found a shift of the dominant soil water uptake zone of poplar trees from 20 cm in the early season (pre-crop) to 40–70 cm in the late season (with crop).

In the middle of the crop field, 24 m from the zero line, the increase in water tension with time at 15 and at 30 cm soil depth is expected to be a consequence of the barley crop drawing water from these depths, as no poplar roots are present at this position (cf. section 3.1).

4.4 | Impacts of tree strips on light, temperature and relative humidity

Solar radiation has a strong influence on the microclimate in transition zones of alley cropping agroforestry systems. Shading lowers the air temperature and thus also alters relative humidity. The effect of shading on plant growth is complex and might vary with crop species and varieties (Schmidt et al., 2019). Because of the north-south orientation of tree strips at our agroforestry site, the windward side of the crop fields is shaded in the morning, the leeward side in the afternoon, and at noon, there is almost no shade on the crop fields. In addition, solar radiation changes with the season. Large reductions in solar radiation in comparison with full sun conditions were shown in the first three metres of the crop fields on both the leeward and windward side of the tree strips, with an average tree height between 5.8 and 9.4 m. However, due to our mathematical approach and the simplified input parameters used, the solar radiation reduction on the crop field is overestimated. No temporal differentiation, for example concerning the effect of solar radiation reduction on different developmental stages of crops is possible. Nevertheless, supported by literature, for example on recent studies of light interception by trees (Van Noordwijk et al., 2021), our results can provide some indications to explain our observations of crop yield and development in the transition zone. In the present study, a slight delay in the phenological development of winter wheat and barley in the transition zone was observed, and plants remained small and developed grains with lower thousand grain and hectoliter weights compared with the control (data not shown, Lamerre, 2017). Several recent studies showed that tree shading can cause delayed maturity, negatively affect yield components and finally lead to reduced yields in field crops (e.g., Arenas-Corraliza et al., 2020; Blanchet et al., 2021; Inurreta-Aguirre et al., 2018; Qiao et al., 2020; Schmidt, Nendel, et al., 2019; Surki et al., 2020). For field-to-forest transition zones, simulations of Schmidt, Nendel, et al. (2019) showed a reduction in wheat yield up to a distance of 15 m, which is 0.75 times the tree height. The temporal differences in the developmental stages of crop and tree are important. For example, the impact on crop yield is small, if crops have reached important developmental stages before trees are fully foliated; this is the case for late leafing trees such as walnut (Reyes et al., 2021). Past research found indications for morphological and/or physiological adaptation strategies of field crops to shade conditions. To increase their photosynthetically active surface, winter wheat cultivars have been shown to increase their leaf area under shade conditions (Arenas-Corraliza et al., 2019; Li et al., 2010), whereas barley showed rather physiological adaptation mechanisms (Arenas-Corraliza et al., 2019). Thus, planting shade-tolerant cultivars might be a solution to increase yield in transition zones. In climate change with rising temperatures, tree shading can lower extreme temperatures and reduce heat stress of crop plants in agroforestry systems (Arenas-Corraliza et al., 2019; Sida et al., 2018).

If the entire measurement period is considered as well as cloudy days, there was almost no effect of the tree strips on air temperature in the crop field transition zone. On hot and sunny days, however, air temperature in the shaded zones close to the tree strips (i.e., 1.5 m into the crop field) was similar to that measured in the tree strip, whereas in the sun-exposed zones, air temperature was higher in the crop field than in the control field from noon to sunset. Kanzler et al. (2019) report similar results from a comparable agroforestry system in the northeast of Germany. Reduced air temperatures in close proximity to the tree strips were explained by sun position or shading.

Higher air temperature in the afternoon hours in the agroforestry crop field compared with the control crop field is a consequence of reduced wind speed due to the windbreak effect of the tree strips. In the leeward (i.e., wind-protected) zone of a hedge, the air temperature can be increased up to a distance of eight times the height of the hedge (Brandle et al., 2004; Cleugh, 1998; Grace, 1988; McNaughton, 1988). Measurements of wind speed that took place during the same period as the recordings of temperature and relative humidity (RH) showed the lowest wind speeds on the leeward side directly behind the 5.8 m high tree strips. These increased with distance from the tree strip and reached 50% of the control field wind speed between 11 and 25 m; the control field wind speed was not reached at all (data not shown).

Just as for air temperature, effects on RH were most pronounced on hot and sunny days. The changes in RH were opposite to those in air temperature; because cool air has a lower capacity to hold water than warmer air, with constant moisture content, the RH increases. Thus, on hot days, lower air temperatures in the shaded zones of the crop field can help to retain humidity (Brandle et al., 2004; Kanzler et al., 2019). However, high humidity in sheltered zones behind tree strips may increase the risk of diseases (Brandle et al., 2004). Overall, the influence of air temperature and RH on crop performance in the transition zone is estimated to be low. Measureable effects on both parameters were just detectable on hot and sunny days, which were relatively rare.

4.5 | Yield

In all years and for all arable crops, decrease in crop yield from the middle of the crop field (i.e., 24 m from the zero line/field edge) to 1 m distance from the zero line/field edge was greater in the SRACS than in the control field, indicating negative effects of the tree strips on crop growth in the transition zone. Tree height was approximately between 4.8 and 7.5 m (2016–2019, that is 2–5 years after last wood harvest), and we observed reduced crop yields up to 7 m from the zero line, which is in line with earlier studies (Akbar et al., 1990; Chirko et al., 1996; Kowalchuk & de Jong, 1995) that found yield reductions up to a maximum distance from the tree strip/hedge of two times its height.

Regarding our results of leaf litter and fine root distribution, nutrient contents in leaf litter, fine roots and the soil, soil water tension and shading, the observed crop yield reduction in the transition zone was apparently caused by a combination of competition between trees and crops for space, nutrients, water and light. A thick leaf litter coverage may hampered the development of the winter crop seedlings close to the tree strip (Batish et al., 2008; Singh et al., 2001). The presence of poplar (fine) roots up to 3 m from the zero line was obviously associated with root competition for nutrients and water, which was confirmed by lower mineral nitrogen contents in the soil and greater soil water tensions in deeper soil layers close to the tree strip compared with larger distances from the tree strip and the control field (cf., section 3.2 and 3.3). Earlier research by Van Noordwijk et al. (1996), Gillespie et al. (2000) and José et al. (2004) corroborates our results. The reduced solar radiation next to the tree strip, both at the leeward and at the windward side (cf., section 3.4), will probably also have contributed to the observed yield reduction in the transition zone, especially in close vicinity to the tree strip (e.g., Yang et al., 2019). In our study, yield deficit in the SRACS at 1 m from the zero line compared with the middle of the crop field was due to phenological and physiological differences between the crop plants greater for silage maize than for winter wheat and oilseed rape. Stronger shading effects of poplar trees in Canadian and Belgium AFSs on the productivity of C4 plants (maize) than on the productivity of C3 plants (e.g., winter wheat) were observed by Thevathasan and Gordon (2004) and Pardon et al. (2017). Moreover, in Germany, summer crops like maize are not seeded before the end of April. Early phases of development overlap with sprouting and leaf unfolding of the trees, resulting in competition for light and water (Pardon et al., 2017).

In poplar short rotation coppice strips in SRACSs, yield of outer tree rows was higher than that of middle rows (Lamerre et al., 2015). Thus, after the establishment phase, poplars, because of their size, are inevitably superior to arable crops in competition for resources such as space, nutrients, water and light in the transition zone.

5 | CONCLUSION

The transition zone is a challenging area in a short rotation alley cropping agroforestry system. Because of the direct proximity of the systems (annual arable crops – perennial trees), a variety of effects on microclimate and growth characteristics of plants can be observed. At the below-ground level, analyses of horizontal and vertical tree root distribution proved the presence of tree roots in the transition zone up to several metres into the crop field, where they caused changes in the soil mineral nitrogen content and the soil water tension. At the above-ground level, the crop yield is reduced next to the trees; the leaf litter coverage of seedlings in autumn and the reduced solar radiation during the growing season seem to be the main stressors. Yield and growth studies showed that trees are competitive with arable crops in this area. However, this has no effect on the average long-term yield of arable crops on our agroforestry site.

For an optimal management of short rotation agroforestry systems, it is important to find a compromise between choice of arable crops, tree and crop strip widths or rotation periods. Our results give important hints that are needed for possible improvements for the establishment of temperate alley cropping agroforestry systems. For example, yield in the shaded zone of the crop field might be enhanced by planting shade-tolerant cultivars or plant species in that area. As shade increases with tree height, tree harvest intervals should be adjusted to avoid excessive height.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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