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Review

The Influence of Trees on Crop Yields in Temperate Zone Alley Cropping Systems: A Review

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Abstract: Agroforestry is a multifunctional land use system that represents a promising approach to mitigate the environmental impact of agriculture while enhancing the resilience of agricultural systems and ensuring sustainable food production. However, the tree rows in agroforestry systems, particularly in alley cropping systems (ACS), can affect crop productivity on adjacent agricultural fields through various mechanisms. Hence, concerns about declining yields and reduced farm profitability persist and explain the reluctance of farmers to implement ACS on their land. In this review, we examine the available literature on the effects of temperate ACS on yields of various agricultural crops to evaluate if and to what extent crop yields in ACS are affected by tree presence. We identified that ACS crop yields often vary substantially across different species, geographical locations, weather conditions and ACS designs. Our analysis also revealed that several parameters are modified in ACS by the presence of tree rows affecting crop yields positively or negatively and that ACS design aspects play a crucial role in determining crop productivity.

Keywords: agroforestry; tree-based intercropping; crop productivity; microclimate; soil moisture

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1. Introduction

Modern agriculture is facing tremendous current and future challenges. With an ever-increasing world population, which will have reached 9.1 billion people by 2050—34% more than today [1]—agricultural production is under a lot of pressure to feed all these people. As a consequence, agricultural production will have to increase and some sources suggest that this increase will have to amount to at least 70% to satisfy the global demand for agricultural products [1]. The majority of this growth will have to emanate from an increase in crop production rather than an expanse in agricultural land, as most of the land suitable for agricultural production is already occupied. Simultaneously, agriculture is also heavily affected by climate change and its consequences. Increasing temperatures and infrequent rainfalls are anticipated to result in declining global crop yields [2]. Model simulations suggest that for every °C increase in temperature, global wheat (*Triticum aestivum* L.) yields will drop by 6% [3]. Apart from these rather gradual changes, climate change will also lead to an increase in the frequency and intensity of extreme weather events, e.g., floods and droughts. Such events are, in most cases, unpredictable and are thus a major threat to local agricultural production and yield stability, particularly in the poorest regions.

The agricultural sector is also one of the main contributors to global climate change. Approximately 12% of the total global greenhouse gas emissions emanate from agricultural production and another 9% from land use conversions related to agriculture (e.g., forest clearings for the purpose of cropland or pastureland establishment [4]). But despite these prospects current global aspirations to alleviate greenhouse gas emissions in agriculture and to make agriculture more sustainable and resilient are low [4]. Therefore, clear policy signals, as well as effective mitigation and adaptation strategies, are necessary to foster low-emission, sustainable and productive agricultural systems.

Agroforestry is a multifunctional land use system where trees or shrubs and agricultural crops and/or livestock are intentionally combined on the same land [5] and is increasingly considered by researchers and practitioners alike as being one of the solutions to the challenges related to future climate change [6]. Often, agroforestry is referred to as being a new name for an old practice because the concept itself is not new [5]. Trees, shrubs and hedgerows were key parts of the agricultural landscape for centuries until they were removed in the course of the industrialization and modernization of agriculture and as part of land consolidation schemes in the middle of the 20th century [7].

In recent decades, the societal and political awareness of the negative consequences of modern agricultural practices for species, habitats and the environment fueled renewed interest in the concept of agroforestry [8]. The total area of agroforestry in the EU 27 has been estimated to encompass approximately 15.4 million ha, about 8.8% of the total utilized agricultural area, the majority of which is located in southern Europe [9]. Commonly, agroforestry systems (AFS) are classified according to their structure either into silvoarable (a combination of trees and crops), silvopastoral (a combination of trees and livestock) or agrosilvopastoral (a combination of all three) systems [10].

There are various types of traditional AFS in Europe; an overview can be found in [8]. In traditional systems, trees are often scattered on farmland, which limits their potential to be adapted to modern farming practices [8,11]. Modern AFS, on the other hand, often feature trees or hedges that are arranged in several linear rows with defined distances between them. In these so-called alley cropping systems (ACS), the crop alleys between the tree rows have a multiple of the width of agricultural machinery, which enables easy access for mechanized farming and the cultivation of annual crops or pastures [11].

In temperate ACS, the tree component often consists of fast-growing tree species such as poplar (*Populus* spec. L.), black locust (*Robinia pseudoacacia* L.) or willow (*Salix* spec. L.), which are regularly coppiced to use their woody biomass (short-rotation alley cropping systems, SRACS). The tree component can also be composed of mature trees, e.g., fruit trees or hardwood trees, producing high-quality timber.

Tree rows in ACS act as windbreaks and inhibit wind-related mechanical damages to crops, reduce wind and water erosion, positively influence microclimatic processes and affect above- and below-ground fluxes of water and nutrients [12,13]. ACS or AFS also improve pest and disease control and increase biodiversity and C-sequestration. The combined cultivation of trees and crops on the same land can also increase the productivity and profitability per unit of land in a more sustainable way than the single cultivation of either of those two components [7]. Moreover, a diversification of production through ACS can be beneficial, especially in years when yields of the crop component are compromised due to, e.g., droughts or other natural hazards [14].

The effect of temperate ACS on the microclimate and water balance is well documented [15]. Yet, the effect of tree rows on overall site productivity is less known. In ACS, site productivity is defined as the combined yield of the trees and the crops. Initially, the site productivity of the ACS will be lower compared to that of a crop monoculture as part of the land will now be occupied by trees and will no longer be available for crop cultivation. Additionally, in SRACS, the first harvest of the tree component will only occur after several years once a sufficient growth of woody biomass has accrued.

Once the system is established, a widely used indicator to measure overall site productivity is the land equivalent ratio (LER). Established by Mead and Willey in 1980 [16], the LER is defined as the amount of land needed for a monocropping system to obtain the same yield as an intercropping system with two or more plants growing together under the same management level and for the same period of time [13]. A LER ≥ 1 epitomizes a positive or at least indifferent effect of ACS on-site productivity. For temperate conditions, LERs of between 0.94 and 1.35 have been determined for ACS with various planting patterns of black locust and triticale (x *Triticosecale* Wittmack) in Hungary [17]; of 1.41 for ACS with willow and spring wheat, potato (*Solanum tuberosum* L.) and squash (*Cucurbita* spec. L.) in the UK [18]; and of 0.98 for ACS with black locust, poplar and alfalfa (*Medicago sativa* L.) in a post-mining landscape in Brandenburg [19]. Thus, the positive effects of ACS on overall site productivity predominate, which is vital given the scarcity of (agricultural) land. The use of the LER has several limitations; for instance, it is often only determined for a single point in time and not for the whole lifespan of a system. Additionally, it relies on the assumption that agricultural production is always reliable and constant [20].

The focus of this review is, however, not on overall site productivity but rather on the effect of ACS on the productivity of the arable intercrop. Once they have reached a certain height, the tree rows in ACS can affect crop productivity on the crop alleys adjacent to them through various direct and indirect mechanisms. The intensity of this effect can vary depending on the design of the ACS as well as site and growth conditions [21]. Understanding the effects of tree rows in ACS on crop productivity is thus not trivial.

Moreover, impacts on crop productivity are an essential aspect in farmers' decisions of whether or not to adopt ACS on their land. Concerns about declining yields and reduced farm profitability are one of the main reasons for the reluctance of farmers to implement ACS in the Mediterranean [21].

Thus, for ACS to become a viable climate change mitigation and adaptation tool, the influence of tree rows in ACS on yields of different arable intercrops has to be fully understood. In this review, we examine the available literature on the effects of temperate ACS on yields of various agricultural crops to evaluate if and to what extent crop yields in ACS are affected by tree presence. We also use the available literature to identify factors that are responsible for crop yield changes in ACS in order to be able to derive conclusions on (i.) which crops are most suited for cultivation in ACS and which are less suitable, (ii.) which parameters and design decisions affect crop yields in ACS and (iii.) research gaps and recommendations for future research.

2. Materials and Methods

A literature search was performed in Web of Knowledge and Google Scholar for studies in German or English that addressed yield effects in ACS in the temperate zone. In Europe, many traditional AFS are located in the Mediterranean, and significant contributions to ACS research were made in southern France in particular. Our focus in this review was on ACS from the temperate middle latitudes, and we thus did not include studies from the Mediterranean. However, reviews on crop yields in Mediterranean ACS are available (e.g., [22]).

The focus of this review was on silvoarable ACS, but we excluded grasses and forage crops. We also included studies that featured structures similar to ACS, such as hedgerows, linear installations simulating tree rows via shade cloths or tree-based intercropping (TBI) systems.

Studies examining yield effects in temperate ACS are not abundant, which was also observed in a recent meta-analysis on crop yields in European ACS [23]. In total, 32 studies were included in this review, including original research articles, one dissertation, final project reports and conference contributions (Table A1).

3. Study Locations and Investigated Crops

The studies considered in this review are listed in Table A1. The majority of studies addressing yield effects in temperate ACS were carried out in Germany (n = 9), followed by Canada and the United States (each n = 6), Belgium (n = 4) and China (n = 3). Austria, Croatia, Switzerland and the United Kingdom each produced one study. The crop most commonly examined was wheat (n = 15), followed by maize (*Zea mays* L., n = 12) and soybean (*Glycine max* (L.) Merr., n = 7). Crops such as lucerne (*Medicago sativa* L.), potato, black bean (*Phaseolus vulgaris* L.), field bean (*Vicia faba* L.), triticale, pea (*Pisum sativum* L.) or mustard (*Brassica alba* L.) were only featured in one study each. To evaluate the effects of tree presence in ACS on crop yields, it is crucial to identify whether and how crop yields will be quantitatively and spatially affected in the first step, i.e., whether and in which parts of the crop alley they increase, decrease or remain constant as a result of tree presence. In the second step, it is also beneficial to understand why crop yields are affected, i.e., which design aspects or parameters are altered in ACS as a consequence of tree presence, which may affect crop productivity.

In the following paragraphs, we will first elaborate on the *how* of crop yield patterns in ACS, i.e., the general yield effects that can be observed in ACS as a result of tree row presence. We will then proceed to identify the *why* of crop yield effects in ACS or, more specifically, the parameters that have been identified in the literature that affect agricultural yields on adjacent crop alleys and are responsible for the formation of the typical yield pattern in ACS.

4. General Yield Effects in ACS

Early reviews on the topic concluded that crops cultivated in temperate climates generally benefit from shelter [24] and can yield between 6% and 44% more when grown next to windbreaks or shelterbelts [25]. It is not clear, though, whether these numbers take into account the area that is occupied by the trees, which diminishes overall crop yields (see Section 5).

Positive yield effects in ACS are often attributed to the shelter provided by the tree rows, which affect crop growth and yields through direct (e.g., protection against wind-related mechanical damages) and indirect (e.g., improvement of microclimatic conditions) mechanisms [26]. However, not all crops profit from the shelter provided by ACS. Positive effects were found to be more pronounced for yields of vegetables, specialty crops and in orchards and vineyards, but less so for field and forage crops, where yield responses to shelter varied [26]. Crops are also affected differently depending on their position in the crop alley as microclimate and soil water effects also vary with distance to the tree rows.

The zone directly next to the tree rows between 1 and 2 H (with H = height of the tree row, Figure 1) is often referred to as the competition zone because here, trees and crops may compete for nutrients, water and light. Crop yields in this zone can be reduced because of the reduced availability of nutrients and soil moisture, allelopathy, shading and the reduction of ambient temperatures that result from shading [24]. In the adjoining zone between 3 and 10 H, the shelter zone, crop yields increase, and maximum yield gains can be obtained, which can even exceed the yields of crops that are cultivated without trees [24]. In the shelter zone, competition for light and soil moisture is negligible, and crop yields benefit from the positive effects of microclimatic modifications (see Section 6.1) and their influence on soil moisture dynamics (see Section 6.2).

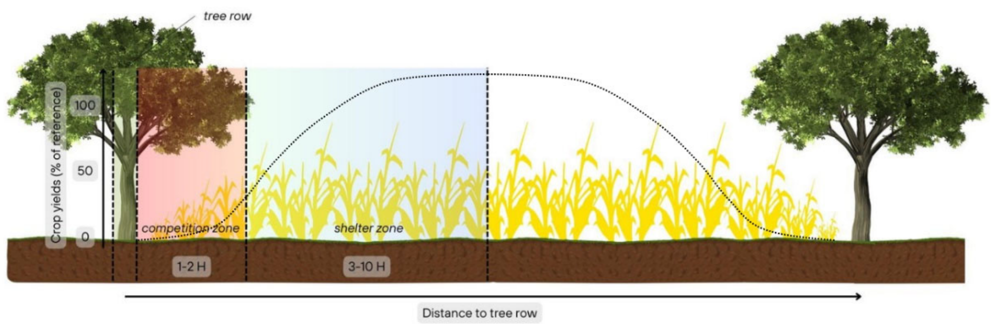
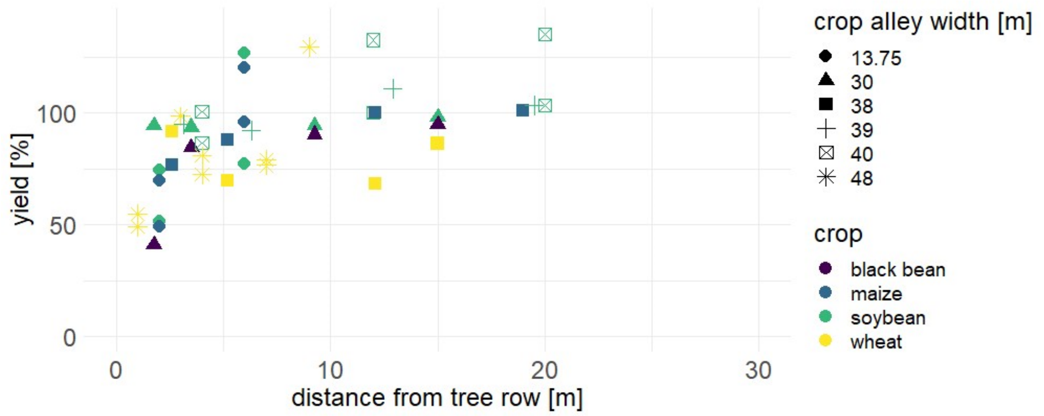


Figure 1. Bell-shaped crop yield pattern between tree rows in ACS. Schematic representation (not to scale).

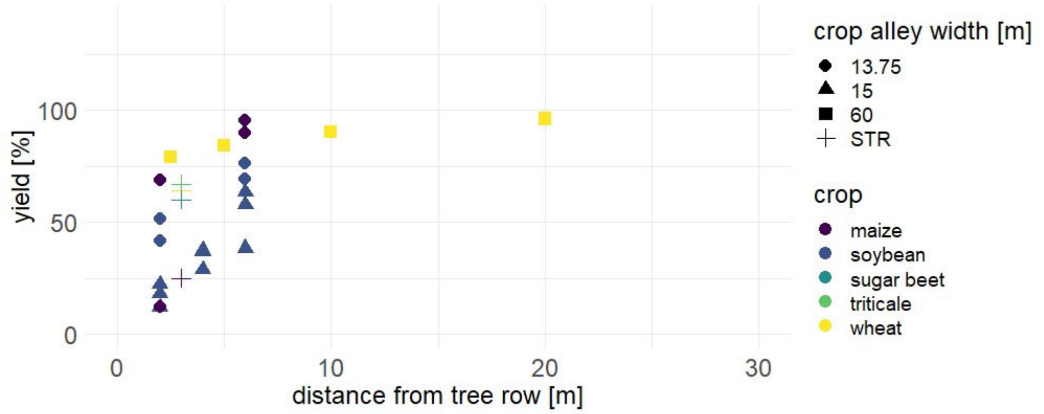
Compared to a single windbreak or hedgerow, which is either located solitary in the landscape or where other windbreaks follow at greater distances, the distinctive feature of ACS is that here, several windbreaks are installed comparatively close to each other. As a result of this characteristic design, competition and synergistic zones will constantly alternate in ACS, whereas, next to single windbreaks or hedgerows, positive synergistic effects will eventually phase out at some distance.

5. Specific Yield Effects in ACS

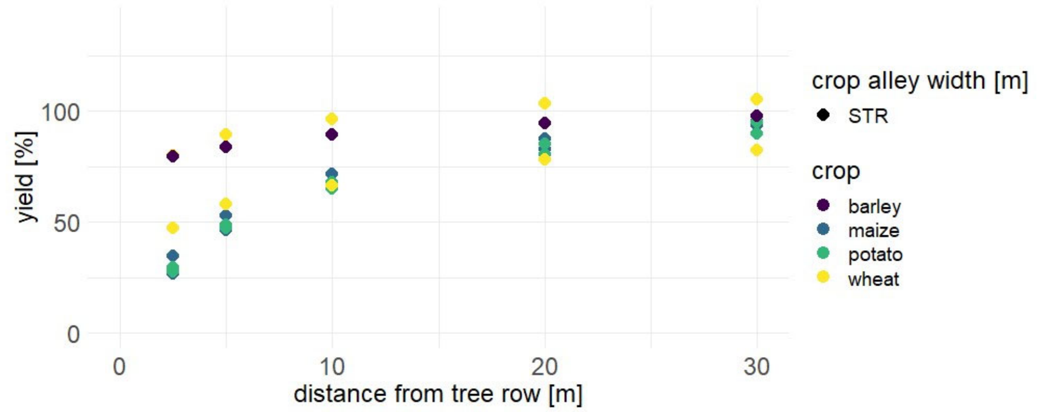
Crop yields in ACS thus vary at different distances to the tree rows as a result of competitive and synergistic effects. We checked whether these theoretical findings could be supported (Table A2, Appendix A) and calculated yields at different distances to the tree rows as a percentage of reference yields, separated by crop alley width and for systems where tree row height was between 0 and 10 m (Figure 2a), between 10 and 20 m (Figure 2b) and above 20 m (Figure 2c).



(a)



(b)



(c)

Figure 2. Crop yields in ACS at different distances from the tree row as percentage of crop yields on reference site for systems with tree row heights (**a**) between 0 and 10 m, (**b**) between 10 and 20 m and (**c**) above 20 m, all based on results from field studies. Different shapes indicate different crop alley widths; STR: single tree row.

Black bean, maize, wheat and soybean were found to yield low in close proximity to the trees in systems with tree row heights between 0 and 10 m, but all crops also showed a tendency to yield higher with increasing distance to the tree rows (Figure 2a). In systems with tree row heights between 0 and 10 m, the competition zone can extend up to a 20 m distance from the tree row (i.e., when the tree row height is 10 m). Yet, in some studies, reference crop yields were reached or exceeded already in the competition zone (e.g., wheat at a 9 m distance, maize at a 6 m distance, soybean at a 1.75 m distance to the tree rows). Soybean reached or exceeded reference crop yields in some studies already relatively close to the tree rows (e.g., at 1.75 m, 3.15 m), while maize and black bean reached reference yields at 6 m and 15 m distances to the tree rows, respectively. The results fluctuate for wheat as reference yields were approached in some studies already at a 3 m distance to the tree row [27]; in others, only at a 24 m distance to the tree rows [28]. Maize, soybean and wheat crop yields also tended to increase with increasing distance to the tree rows in systems with tree row heights between 10 m and 20 m (Figure 2b). Reference yield levels were approached at approximately 6 m (maize) and 20 m (wheat) distances to the tree row. Lastly, in systems with tree row heights above 20 m (Figure 2c), there was a distinct trend for increasing yields with increasing distance to the tree rows for all crops and reference yield levels were reached at approximately 20 m (barley (*Hordeum vulgare* L.), wheat) and 30 m (potato, maize) distances to the tree row.

It is noticeable, though, that there are comparatively more results reported for crop yields in close proximity to the trees where competitive effects between trees and crops often resulted in lower crop yields than further away from the trees beyond 10 m distance where increased crop yields can be anticipated. As a result, the focus was more on crop yield reductions due to tree–crop competition, while beneficial effects on crop yields occurring in the shelter zone were underrepresented. In some studies, e.g., [29], very narrow crop alleys were combined with very tall trees so that, ultimately, the entire crop alley became a competition zone. Interestingly, even in these cases of rather unfavorable ACS designs, reference yields were achieved or even exceeded.

Despite the great variety of experimental and ACS designs and methods of yield sampling and data analysis, the majority of studies confirmed the theoretical assumption that crop yields are reduced in close proximity to tree rows and increase with increasing distance to them. General statements that are based on quantitative comparisons between studies are nonetheless difficult to make because the number of studies that provided sufficient information to be included in such calculations was very limited, and as such, the actual yield effects in ACS can be distorted.

The design of the ACS significantly affects crop yields (see Section 6.4). Consequently, in systems where tall trees are combined with narrow crop alleys, the positive yield effects in ACS could be underrepresented. This is because such systems are dominated by the competition zone, resulting in crop yields that are lower than their potential.

Crop yields in ACS are often compared to crop yields on reference sites based on the area of arable land (e.g., yields per ha). In ACS, a certain percentage of the area is occupied by trees and is thus not available for crop production. Therefore, when comparing ACS productivity with the productivity of a treeless reference, the area occupied by trees must be added to the total crop yield of the ACS; otherwise, the ACS crop yield will be underestimated.

ACS have numerous positive effects on the environment, which extend beyond their impact on crop productivity. In times where increasing political and societal pressure on conventional agricultural systems calls for more sustainable land use options, a mere focus on ACS productivity could potentially discourage farmers from implementing ACS on their land. Moreover, a financial return after ACS implementation can also be generated by marketing yields of the woody component, which must then be added to the overall (economic) productivity of the system. In Europe, the planting of trees on agricultural land has been financially supported since the early 1990s through various measures within the Common Agricultural Policy (CAP) [30], yet AFS implementation by farmers has been low as not all member states have integrated the relevant measures into their regional development programs [31]. However, there is potential to improve current regulations in the course of the next CAP revision. If this is performed in a way that provides a true incentive for AFS and ACS implementation, CAP funding can also constitute a further source of income for farmers.

6. Parameters Affecting Crop Yields in ACS

Parameters that can affect crop yields in ACS include microclimatic conditions with wind speed, air temperature, relative humidity, precipitation and solar radiation; soil moisture; distance to the tree rows; ACS design with height of the tree row, orientation of the tree row, tree species, tree or ACS age, width of the crop alley and tree row and crop species; and management aspects. In the following paragraphs, these parameters and their effect on ACS crop yields based on the findings from the literature will be elaborated further.

6.1. Microclimatic Conditions

In ACS, the presence of tree rows will lead to a modification of the microclimate on adjacent crop alleys. Microclimatic parameters that can be altered as a result of tree row presence are wind speed, air temperature, relative humidity, precipitation, global radiation and photosynthetically active radiation (PAR). A general positive impact of microclimatic modifications for crop yields in ACS was reported in studies from Belgium and Germany (Table A1, [32–34]). In Belgium, yields of several crop species were assessed in ACS with trees of varying ages [34]. The authors contend that increased wheat yields in systems with middle-aged poplar trees were potentially the result of improved microclimatic conditions. Similarly, crop yields of lucerne profited from improved microclimatic conditions in an ACS with black locust on a post-mining reclamation site in Germany [32]. On another site in Germany, yields of summer barley exhibited the typical bell-shaped pattern (see Section 4) with lower yields on the field margins and increasing yields towards the crop alley center, which were also attributed to the enhanced microclimate between the poplar tree rows [33].

The relevance of individual microclimate parameters for crop yield modifications in ACS based on the results from the literature will be discussed in the following paragraphs.

6.1.1. Wind Speed

A typical feature of ACS is that the tree rows reduce wind speeds and thereby act as windbreaks, which can positively affect crop growth in neighboring crop alleys through several direct and indirect mechanisms [26]. First off, ACS are an effective measure to prevent wind erosion, the large-scale removal of the most fertile parts of the topsoil [35]. This is not trivial, as wind erosion is a significant threat to agricultural production throughout the European Union, where it affects more than 42 million ha of agricultural land [36]. The reduction of wind speeds in ACS also entails that wind-related morphological adaptations of crops and the frequency of wind-related mechanical damages to crops are reduced [37].

The distance to which wind speeds are reduced on adjacent crop alleys is influenced by the turbulence of the approaching wind [26] and the height of the tree rows [37]. On the leeward side of the windbreak, wind speed reductions can extend to a distance of four to 12 H [38] or even up to 30 H [26]. The magnitude of wind speed reductions, on the other hand, is determined by the porosity of the tree row [26] and their spatial orientation relative to the prevailing wind direction [37]. In the temperate zone where winds blow predominantly from the west, ACS with tree rows oriented in a north–south direction will thus reduce wind speeds most effectively.

Wind speed effects were mentioned in 7 of the 32 considered studies (Table A1, [27,28,32,33,39–42]). In southern Québec, Canada, wind speeds in a TBI system with several hardwood species were reduced by up to 70% in the direct vicinity of tree rows and by up to 28% in the middle of the 40 m wide crop alley [39]. In Germany, mean wind speeds were reduced by up to 54.6% in a 12 m distance to a 3.88 m high black locust row in the ACS on the post-mining reclamation site [32] and on a second site by up to 43% in close vicinity to poplar and black locust tree rows [40] and by up to 70% in close vicinity to poplar tree rows [27]. In the latter study, wind speeds were reduced at almost all positions in the 48 m wide crop alley. Several authors assumed that reduced wind speeds and, as a consequence thereof, less physical damage to crops combined with improved microclimatic conditions and a better water supply of crops led to an enhanced agricultural productivity [27,33,40]. Indeed, in the ACS with poplar, a yield gain of 16% could be measured for winter wheat [27]. However, according to the authors, the microclimate data were not sufficient to explain these surplus yields. In the two other studies [33,40], the positive influence of wind speed reductions on crop yields could also not be verified.

A bell-shaped yield pattern with increasing crop yields at a certain distance to woody structures was also found in studies from Canada and Belgium. In Canada, crop yields of wheat increased at a distance of 2 H to 4 H next to a 6 m high shelterbelt composed of caragana (*Caragana arborescens* Lam.), Manitoba maple (*Acer negundo* L.) and green ash (*Fraxinus pennsylvanica* Marshall) [41]. Similarly, in Belgium winter wheat yields at a distance of 20 m or further away from a single row of walnut (*Juglans regia* L.) trees exceeded the yields measured in the reference [42]. On the other hand, a positive windbreak effect could not be detected in an ACS with poplar, winter wheat and rapeseed (*Brassica napus* L.) in Germany, most likely because the climatic conditions were generally beneficial for crop growth with high precipitation rates and low wind speeds [28]. Positive yield effects in ACS or similar systems may thus be more pronounced under weather conditions that are less favorable for crop growth.

Wind speed reductions and their effect on crop growth and yields are the most common and popular features of ACS, and accordingly, they were mentioned in every fifth study of the considered literature. Yet, when wind speed reductions were addressed, they were often not tied to yield effects, potentially because wind speed reductions are tightly intertwined with modifications of other microclimate parameters and soil moisture, so it is challenging to isolate their individual effect on crop yields.

6.1.2. Air Temperature

Tree rows in ACS affect air temperature on adjacent crop alleys. In close proximity to the tree rows, the air temperature can be lower than in the open due to (i.) higher evapotranspiration rates induced by the trees, which cool the surrounding air volume, and (ii.) tree shading [37]. Tree shading was responsible for lower daytime temperature values close to poplar tree rows during the summer months in the ACS with winter wheat and poplar in Germany [27]. More specifically, shading led to lower air temperatures at the eastern tree row in the morning and the western tree row in the afternoon [27]. Similarly, the incidence of measurements over 30 °C close to the leeward side of poplar and black locust tree rows in the ACS in Germany was almost 40% lower than on the reference [40].

Up to a distance of 8 H from the tree row, the reduction of wind speeds diminishes turbulences, and as a consequence, less heat is removed, which results in a reduction of cooling during the day and warming during the night [24,26,43]. Near-surface temperatures in this zone can thus be higher by day and lower by night. Further away from the tree rows at a distance of between 8 H and 24 H, turbulences increase, and heat fluxes become more efficient, which leads to cooler temperatures by day and higher temperatures by night [26]. Overall, air temperatures can be higher in crop alleys of ACS compared to the open field [38], but lower temperatures have also been reported [37]. For instance, in ACS with narrow crop alleys and tall trees, the effect of shading is more relevant than wind speed reductions, and as a consequence, maximum temperatures are reduced on the crop alley. Reduced maximum temperatures were also reported in an ACS with summer barley in Germany and were associated with the observed bell-shaped yield pattern [33]. Given that higher air temperatures can accelerate developmental processes and lead to premature seed ripening [38], the reduction of maximum temperatures in ACS has a beneficial effect on crop productivity. A contrary effect on air temperatures, however, can occur in fully enclosed, basin-like plantings with very dense tree rows, where the limited exchange of air can lead to overheating of the crop alley and heat damage to crops [37].

In the studies that reported temperature effects in ACS, however, no effect of air temperatures on crop yields could be demonstrated, or this effect was assumed but not proven. Yet, even subtle temperature differences can have an effect on plant physiology [38] and may thus influence crop yields. Tree rows can thus have a significant impact on air temperature, which should not be underestimated, particularly in light of the increasing frequency of extreme temperature events during summer, which have been projected to occur due to climate change.

6.1.3. Relative Humidity

Wind speed reductions and air temperature modifications affect relative humidity on crop alleys in ACS. The more wind speeds are reduced, the less water vapor is removed close to the tree rows [37]. As a consequence, relative humidity is usually higher in the vicinity of the tree rows than in the open. With increasing distance to the tree rows and decreasing wind speed reductions, relative humidity on the crop alley can decrease and even fall below values measured on the open field [37]. An increase in relative humidity close to tree rows can also affect evapotranspiration and, ultimately, soil moisture and the availability of water for crops (see Section 6.2) but can also facilitate fungal infestations [37].

Three studies addressed modifications of relative humidity in ACS (Table A1, [33,40,44]). In the ACS with poplar in Germany, summer barley yield modifications were assumed to be a result of, among others, an increase in relative humidity, which resulted in higher soil moisture levels in the ACS and an improvement in the water supply of barley crops [33]. In another ACS in Germany, relative humidity was only slightly (<1%) higher in the middle of a 96 m wide crop alley compared to the reference but up to 13% higher on the leeward side of the black locust and poplar tree rows on hot summer days [40]. In the TBI with poplar, silver maple (*Acer saccharinum* L.) and walnut in Ontario, Canada, relative humidity was between 5.9% and 8.0% higher compared to the reference [44].

6.1.4. Precipitation

Tree rows in ACS can affect the amount of precipitation reaching the ground, which can be more or less than that in the open field, depending on the wind direction and the orientation of the tree rows relative to it [24]. When the tree rows are oriented against the prevailing wind direction, they will intercept a fraction of the rainfall, thereby creating a rain shadow on the leeward side [45]. The extent of rainfall interception varies with the degree of foliation. In Brittany, France, mean rainfall interception per rainfall event in up to 2 m distance of a hillslope oak (*Quercus robur* L.) hedgerow ranged from 12% when trees were defoliated to 28% when trees were foliated [46]. On the windward side of the crop alley, tree rows will act as a rainfall barrier; the amount of precipitation reaching the ground can be higher in this zone compared to the open field. In regions where precipitation is mainly found in the form of snow, ACS can influence its height and distribution via snowfall retention and entrapment and promote delayed thawing during spring, which increases early-season water availability for crops [25,37].

Precipitation effects were mentioned in three studies (Table A1, [40,47,48]). In a mature ACS with silver maple in Missouri, USA, maize and soybean yields were significantly reduced, particularly during years with drought stress, with exceptionally high precipitation and with low rainfall amounts during critical growing periods [48]. Temporal variations in precipitation patterns were also crucial for maize yields in several mature single-tree-row windbreak systems with white spruce (*Picea glauca* (Moench) Voss), green ash, Scots pine (*Pinus sylvestris* L.) and tamarack (*Larix laricina* (Du Roi) K. Koch) in eastern Canada [47]. Here, maize yields were significantly reduced at the tree crop interface but often significantly higher between 2 and 20 H than at 24 H; both effects were less pronounced in wetter years. In both studies, precipitation or the lack thereof was thus a limiting factor for crop productivity. In the ACS with black locust and poplar in Germany, precipitation was 4.6%

higher in the middle of a 96 m wide crop alley compared to the reference, whereas close to the leeward tree rows, precipitation was reduced by 3.4% [40].

6.1.5. Solar Radiation

Tree rows in ACS influence the amount of solar radiation that reaches the crops on adjacent agricultural fields. Depending on the spatial orientation and height of the tree rows, different parts of the crop alley will be shaded by the trees at different times throughout the day [37]. For instance, in the north–south-oriented ACS, the eastern and western crop alley margins will be shaded during the morning and afternoon, respectively, while in an east–west-oriented ACS, shading affects the area north of the tree rows. In the shaded parts of the crop alley, reduced intensities of solar radiation will also lead to a decrease in air temperature and an increase in relative humidity. As solar radiation is essential for plant growth and the key prerequisite for photosynthesis, shading in ACS can, depending on the crop species, cause a decrease in biomass and grain/seed yield of crops.

Effects on solar radiation in ACS were covered in 16 studies (Table A1, [29,39,40,44,49–59]). In the majority of these studies, the presence of tree rows or similar structural elements reduced solar radiation on the agricultural area in direct vicinity to them. In three studies [49,50,58], the reduction of solar radiation and its effect on crops was investigated using shade cloths, which were deliberately deployed to simulate the shade pattern generated by woody elements. In 12 studies [29,40,44,49–57,59], lower crop yields in close proximity to tree rows or other structural elements were associated with a reduction of solar radiation.

Reduced maize yields as a result of PAR reduction in close proximity to mimosa (*Albizia julibrissin* Durazz.) tree rows have been found in an ACS in Alabama, USA [53]. After pruning mimosa trees, light interception for maize plants increased, which also led to higher maize yields. Similarly, in an ACS in Germany, crop yields of rapeseed, winter wheat and winter barley were reduced adjacent to poplar tree rows, which was attributed to the delayed phenological development of seedlings as a result of tree shading [54]. In Missouri, USA, the maize yield of plants growing next to silver maple trees was reduced compared to that of maize plants, where a root barrier was installed next to the tree rows [56]. But even with a root barrier in place, the grain yield of maize plants next to the tree rows was not as high as the yield of maize plants growing in the alley center, suggesting that light availability was also a limiting factor for maize productivity. In the silvoarable experiment in the United Kingdom, the reduction of short-wave radiation in close proximity to poplar tree rows was sufficient to explain crop yield reductions at two of the three investigated sites [59].

In TBI systems with Paulownia (*Paulownia* Siebold and Zucc.) in China, wheat yields on adjacent crop alleys were reduced, which was attributed to differences in photon flux density [52] and variations in the amount of PAR intercepted [55]. In the latter study, mean wheat yields in the TBI system were reduced by 49% compared to a reference and by 30% in close proximity to the tree rows compared to the middle of the crop alley. PAR, as well as maize and soybean yields, were also significantly reduced in another TBI system in China close to plum (*Prunus salicina* Lindl.) and walnut tree rows [57]. Yield reductions were more severe under plum than under walnut and for maize than for soybean, but yields of both crops were highly correlated with PAR. In TBI systems in Canada, reduced light transmittance [51] and reduced PAR [29] were associated with yield reductions of maize, soybean and black bean in close vicinity to tree rows with various species. In another TBI system in Canada, maize yield was more adversely affected by poplar and silver maple shading than soybean yield [29]. In a follow-up study 15 years later, PAR reduction was three times higher under poplar trees and four times higher under silver maple trees [44]. In this study, soybean yield was reduced by between 28% and 42% under poplar and silver maple trees, respectively.

In Belgium, the growth and productivity of wheat [49] and sugar beet (*Beta vulgaris* L.) [50] were investigated using military shade cloths, which simulated the shade pattern created by late-flushing hybrid walnut trees. The shade treatments resulted in two shade conditions, one under which the crops were exposed to continuous shade and one where crops were exposed to periodic shade. Wheat yields were reduced by between 25% under periodic and 45% under continuous shade, whereas sugar beet showed an even stronger response with a maximum yield reduction of 74% under continuous shade. However, the authors contend that conditions such as under continuous shade only occur on 10% of the cropped area in real ACS and only in systems with east–west tree row orientation [49].

Contrary to these findings, summer barley grown under shade nets in two AFS with apple (*Malus domestica* Borkh.) trees in Switzerland did not show a significant yield reduction [58]. Although heavy shade reduced summer barley yields by 26%, no significant reduction was found in moderate shade (90% vs. 40% shade). Likewise, in a TBI system with poplar and various hardwood species in Canada, soybean yield at a 4 m distance to the tree rows was similar to that on the reference, although average daily PAR was reduced by 26% at the same distance [39]. Similarly, PAR was reduced close to black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) tree rows in an ACS in Indiana, USA [60]. Although it was highly correlated with net photosynthesis, PAR reduction did not have an influence on maize yields. Significant reductions of global radiation close to black locust and poplar tree rows were also measured in an ACS in Germany, but this did not affect wheat yields [27]. On the contrary, in some cases, wheat yields were significantly higher at a 3 to 5 m distance to the tree rows than in the reference.

The results from the literature illustrate that some crops are apparently better able to cope with shading from tree canopies than others. This ability is determined by the photosynthetic pathway a crop uses. Crops such as wheat, barley and soybean photosynthesize using the normal C3 pathway. Under temperate climatic conditions, the C3 photosynthetic pathway is advantageous as (i) the limiting factor for photosynthesis is CO_2 availability and not light and as a result, (ii) light saturation is already reached at 50% of full sunlight [29]. Crops with a C3 photosynthetic pathway produce more biomass under temperate conditions but close their stomata when it is hot and dry to prevent excessive transpiration; this, however, also limits photosynthetic performance. Species with a C4 photosynthetic pathway, such as maize, on the other hand, have adapted to hot and dry conditions and developed the ability to circumvent excessive photorespiration through an additional, extremely effective CO_2 fixing mechanism [61]. As a consequence, C4 plants are light-saturated at almost full sunlight and have a high CO_2 affinity, which allows them to boost their biomass production under increasing temperatures. However, this also implies that C4 plants are more susceptible to yield losses under conditions of reduced light availability, as is the case under shading in ACS [29,42].

6.2. Soil Moisture

There is consensus amongst researchers that the establishment of AFS and ACS has many beneficial effects on water cycling processes and hydrological ecosystem services (ES, [62]). These include the improvement of soil water storage, recharge and retention, enhanced water infiltration, improved water quality, reductions in the amount of nutrient leaching to the groundwater body, as well as the reduction of runoff and water erosion [13,63,64]. However, when it comes to the distribution of soil water reserves, the spatial proximity of trees and crops can also have adverse effects. Particularly in a scenario of water scarcity, both components may compete for soil water reserves.

This is reflected in the concept of spatial competition, which assumes that the root distribution of crops and trees overlaps in the upper soil layers, and as a result, the same resource pools are utilized [65]. As a consequence, soil water content can be lower in close proximity to woody elements, which can concur with lower crop yields in this zone. The existence of spatial competition between trees and crops is well documented (Table A1, [34,41,47,48,58,60,66,67]). Similarly, lower soil moisture was often associated with lower crop yields, either in close vicinity to tree rows or in the whole ACS (Table A1, [29,33,39,41,44,56,64]).

For instance, competition for water between trees and crops was found to be one of the reasons for reduced yields of soybean and maize in the ACS with silver maple in Missouri, USA [48]; of sugar beet yields in close proximity to black locust and poplar tree rows in Germany [67]; of maize next to ACS and single tree rows (STR) of varying age in Belgium [34]; and in close vicinity to windbreaks with white spruce, green ash, Scots pine and tamarack on several sites in southern Quebec, Canada [47]. Further away from the tree rows, improved microclimatic conditions and less below-ground competition for water may lead to higher soil moisture levels, which can result in enhanced crop yields. This was found, for instance, in ACS with sugar beet [67] and summer barley [33] in Germany and for maize close to windbreaks in southern Quebec, Canada [47].

In the ACS with summer barley and rapeseed in Germany, soil moisture was 4% lower up to a distance of 4 m to the poplar tree rows but 3% higher at a distance of 4 m to 8 m, both compared to a reference [33]. Crop yields of spring barley were also lowest directly next to the tree rows but highest at an 8 m distance from the tree rows, where they were also higher than average crop yields in the ACS. For rapeseed, no such trend was observable. In the ACS with black locust and poplar, sugar beet yields increased at a distance of 12 m to the tree rows [67]. Both authors argue that improved microclimatic conditions, such as the reduction of wind speeds and maximum air temperatures combined with lower evapotranspiration, resulted in higher air and soil moisture contents, which enhanced the moisture availability for crops and, thus, crop productivity.

In southern Quebec, Canada, maize yields increased at a distance of 2 H to 20 H next to the windbreaks with white spruce, green ash, Scots pine and tamarack and were often significantly higher there than at the reference [47]. In wetter years, both effects, i.e., reduced yields in close vicinity to windbreaks and increased yields at a greater distance to them, were less pronounced, which made the authors contend that positive windbreak effects are much more likely under drier weather conditions when soil water is scarce. A similar effect was found in the province of Saskatchewan in Canada, where soil water content decreased with increasing distance from a 6 m high shelterbelt in one year [41]. This effect was absent when overall soil water content dropped in the following year. In years where water supply was limited, wheat yields were reduced up to a distance of 2 H and increased at a distance of between 2 H and 4 H. In contrast, in years when the water supply was sufficient, there was no zone of reduced yields, and the zone of higher yields was less pronounced.

Spatial competition between trees and crops was also found in the ACS in Indiana, USA, where maize yields next to black walnut and red oak tree rows declined by up to 50% in the course of 10 years [60]. After the installation of root barriers that separated crop and tree roots, maize yields close to the tree rows were equal to those in the middle of the crop alley, indicating that the interaction between maize and tree roots and the resulting below-ground competition for soil water was more decisive for maize productivity than the above-ground competition for light. A root barrier also increased soil water content in the ACS with silver maple and maize in Missouri, USA, which was significantly reduced close to the tree rows before barrier installation [56]. The grain yield of maize plants growing adjacent to maple tree rows was also lower compared to that of maize plants where a root barrier was installed.

Lower soil moisture values next to tree rows have also been observed in TBI systems with soybean [39] and maize and soybean [29,44]. Compared to the reference, soil moisture was generally lower at 4 m and 12 m distance to the tree rows with poplar and several hardwood species in Québec, Canada [39]. After the installation of rainfall interception appliances, soil moisture further declined, and soybean yield was also reduced by 14%. In the TBI with maize and soybean cultivated next to silver maple and poplar tree rows in Ontario, Canada, soil moisture was significantly correlated with soybean yield but not with maize yield [29]. Soybean yields were also slightly more correlated with soil moisture than with PAR, but the authors contend that overall, competition for water was of lesser importance for crop productivity than competition for light. In the follow-up study, soil water content in the ACS was also reduced next to poplar, silver maple and walnut rows and was in total 1.2% lower than 15 years earlier [44].

The soil water content in ACS can also differ depending on the timing during the growing period and the developmental stage of crops. This was shown in a study from Croatia, where maize productivity was assessed in a 14-year-old walnut orchard [64]. It was found that the intercropped system conserved more water in late spring during the early stages of maize development but had much lower soil water content later in the growing period during the dry summer months. The authors note that this was probably a result of the combined effects of high temperatures, low precipitation and walnut water uptake.

In contrast to spatial competition, the concept of spatial complementarity acknowledges that trees and crops have different root distribution patterns and, therefore, penetrate different resource pools [62]. Shallow-rooted crops take up water mostly from upper soil layers, while deeper-rooted trees can take up water from upper wet soil layers at the beginning of the growing period and switch to deeper soil layers later in the season when the upper soil layer has dried out [68]. The adaptability of tree roots in ACS was also demonstrated in a study from France [69]. Initially, fine roots predominated in the upper soil layers during the first four years following ACS installation. Subsequently, from years four to six, they primarily grew vertically and, thereafter, began to extend laterally into deeper soil layers [69].

Apart from their direct influence on precipitation and snowfall patterns, tree rows in ACS can also indirectly affect soil moisture through modifications of the microclimate. For instance, the reduction in wind speeds on crop alleys can result in less water vapor, which is transported away from the soil [38]. As a consequence, relative humidity increases, which leads to (i.) a reduction of the vapor pressure deficit between leaf and air and, thereby, plant transpiration [38] and (ii.) a reduction in the amount of evaporation from the soil [24].

The observation that transpiration and evaporation are reduced in ACS led to the establishment of the water-saving hypothesis [70]. It postulates that due to lower evapotranspiration rates in ACS soil moisture is conserved, which is then available for the crop for later use in the growing season. Reduced evapotranspiration and higher soil moisture contents in ACS can potentially enhance the water availability for crops, which may result in increased crop productivity per unit of water and a higher overall productivity of the system [37,45].

Higher soil moisture contents in ACS have been found next to black locust tree rows in the ACS on the reclamation site in Germany [32], in four to eight meter distances to poplar tree rows in the ACS with summer barley and rapeseed in Germany [33], at the beginning of the growing period in the orchard with walnut and maize in Croatia [64] and adjacent to an eight meter high hedgerow in Austria [71]. Here, soil moisture values and crop yields of lucerne were higher close to the hedgerow and decreased with increasing distance to it, which, according to the authors, signifies an interrelation between those two parameters. In Germany, a similar lucerne yield pattern was observed, which was also assumed to be related to soil moisture conditions in the ACS [32]. In another ACS in Germany, soil moisture content was 3% higher in four to eight meter distances to poplar tree rows, and summer barley yields were also highest at 8 m distance to the tree rows [33].

No effect of tree rows on soil moisture was observed in the TBI systems with maize, soybean, wheat and black bean in Québec, Canada, and in the Paulownia–wheat TBI system in China [52]. In both studies, soil moisture did not significantly change at different distances to the tree rows. In the Canadian ACS, no relationship between crop yield and soil moisture was found, and the authors argue that soil moisture was only of marginal relevance for crop productivity in their systems [51]. However, rainfalls were relatively frequent in the study region, and soil moisture was, therefore, not a significant limiting factor for crop productivity. Given these conditions, the impacts of soil moisture on crop yields are unlikely.

6.3. Distance to Tree Rows

Crop yields in ACS often vary with distance to the tree row or windbreak (see Section 4, Figure 1). The effect of distance to the tree row was investigated in 26 of the 32 considered studies; 24 reported lower crop yields close to tree rows (Table A1, [27–29,33,34,39–42,44,47,48,51,52,54–57,60,67,71–73]), 5 studies reported higher crop yields close to tree rows [32,40,71,72,74] and 1 study reported no distance effect [39].

Due to below- and above-ground competition for nutrients, water and light, crop yields in direct vicinity to tree rows can often be reduced, which was shown for barley [33,34,54,72], black bean [51], maize [29,34,42,47,48,51,56,57], potato [34], rapeseed [51], soybean [29,39,44,48,51,57], sugar beet [42,67], triticale [42] and wheat [27,28,34,40–42,52,54,55,72]. In an ACS in Germany, summer barley yields were lowest in close vicinity to poplar tree rows, increased up to a distance of 8 m to the tree rows and decreased again at 16 m distance, resulting in a bell-shaped yield pattern (see Section 4, [33]). Similar results were obtained in Québec, Canada, where maize yields were substantially reduced close to a windbreak with white spruce, green ash, Scots pine and tamarack but were significantly higher between 2 H and 20 H compared to 24 H [47].

Typically, lower crop yields are observed adjacent to tree rows in ACS, although there have been instances where higher crop yields were observed within the competition zone. For lucerne, this seems to be common, as higher crop yields have been found close to black locust tree rows in three consecutive years in an ACS on a reclamation site in Germany [32] and also next to a 6 m high hedgerow in Austria [71]. In both cases, the authors claim that higher soil moisture contents close to the woody elements due to either reduced wind speeds and resultant lower evapotranspiration [32] or during dry summer months [71] are responsible for the observed yield pattern. In other studies from Germany, higher yields close to tree rows were found for wheat in an ACS with black locust and poplar [40] and for rapeseed in an ACS with poplar [72]. For maize, higher yields adjacent to red alder (*Alnus rubra* Bong.) and black locust tree rows in an ACS in Oregon, USA, were observed, but only in the first year of the study [74].

In a TBI with sugar maple (*Acer saccharum* Marshall), black walnut, different oak species, shagbark hickory and poplar, soybean performed differently depending on the weather conditions (Table A1, [39]). In the first year, when weather conditions were unusually dry and warm, yields were lower close to the tree rows and increased with increasing distance to them, but in the second year, under normal temperature and rainfall conditions, yields did not differ at different distances to the tree rows. This result corroborates early allegations that the response of crops to shelter is often unpredictable and may vary strongly depending on the crop species, geographical location, weather conditions, soil type and windbreak design [38].

6.4. ACS Design Aspects

Apart from the distance to the tree rows, crop yields in ACS can also be affected by other design aspects, including the height of the tree rows, the tree row or ACS orientation, tree species, tree or ACS age, crop alley or tree row width, crop species and the porosity of the tree row. Although the latter is usually regarded as being relevant for microclimatic alterations, e.g., the magnitude of wind speed reductions [26], it was not addressed by any of the studies considered in this review.

6.4.1. Height of the Tree Row

Tree row height can be of importance for crop productivity because higher trees will usually cast longer shadows, which will, in turn, affect other microclimatic parameters, soil moisture (see Sections 6.1 and 6.2) and, ultimately, crop yields. Taller trees typically also tend to have a larger leaf area, which in turn leads to a higher water consumption by trees.

Tree row height was addressed by only one study from Alabama, USA (Table A1, [53]), which investigated the importance of hedgerow pruning for crop productivity. In this study, pruning of mimosa hedgerows to a height of 5 cm reduced competition for light and water between the hedgerow and maize plants and increased light interception by maize, which resulted in higher maize yields. Pruning ACS tree rows to such a low height should not be standard practice, as this could potentially diminish the positive effects the tree rows have on aspects such as the microclimate.

6.4.2. Orientation of the Tree Row

The orientation of the ACS in the landscape determines how effective the tree rows are in reducing wind speeds (see Section 6.1.1) and the intensity with which other microclimatic parameters and soil moisture dynamics are affected. For instance, the spatial extent of shading by tree rows will be different when tree rows are oriented in north–south direction compared to an east–west direction (see Section 6.1.5). Tree row orientation was addressed in three studies (Table A1, [49,50,52]).

Under an east–west orientation, crops close to the tree rows experience continuous shade conditions on the northern side of the tree row, which can significantly reduce final yields, as has been shown in Belgium for the wheat [49] and sugar beet [50]. When tree rows are oriented in north–south direction, the impact of shade on crop yields on the western and eastern sides of the tree rows can be similar. For instance, in a TBI with Paulownia and wheat in China, no difference in wheat yields between the eastern and western sides of tree rows could be detected [52].

Given the limited number of studies focusing on tree row orientation, it is challenging to determine the most beneficial orientation for enhancing crop productivity. However, if the aim of ACS implementation is to reduce wind speeds and provide a more favorable microclimate on adjacent crop alleys, a north–south tree row orientation is more beneficial, especially in temperate climates where the prevailing wind direction is west. Additionally, permanent shading on one side of the tree row and intense solar radiation on the other side of the tree row implies high competition and unfavorable growing conditions in east–west-oriented systems, which are not beneficial for crop cultivation.

6.4.3. Tree Species

The tree species of the ACS can affect crop productivity in various ways. Crops and trees can overlap in the timing of phenological processes, which can be disadvantageous for crop productivity [34,42]. For instance, the leaf emergence of trees and germination of summer crops in spring, as well as the leaf senescence and germination of winter crops in autumn, can coincide, which may lead to less seeds germinating in the competition zone adjacent to trees. Tree species can also differ in their height, crown diameter and crown permeability, rooting depths and other morphological characteristics, which may affect crop growth and productivity through their impact on light and water availability. Certain species, such as walnut, release allelopathic compounds through their leaf litter, which are known to inhibit the growth of neighboring plants. The selection of appropriate tree species can thus be vital for successful crop germination, growth and productivity.

Six studies included in this review addressed the impact of the tree species on crop productivity (Table A1, [29,42,44,57,60,64]). In an ACS in Indiana, USA, maize yields were lower next to black walnut tree rows compared to red oak tree rows [60]. Crop yield declines near a single walnut tree row in Belgium were attributed to both the release of allelochemicals and the overlapping growing seasons between the walnut trees and the crops [42]. Juglone release was also assumed to be responsible for low germination rates, lower maize plant density and reduced yields in a walnut orchard in Eastern Croatia [64]. In contrast, in a TBI with soybean and maize in China, crop yield reductions were higher under plum tree rows than under walnuts, which was attributed to the greater reduction of PAR under plum trees [57]. In a TBI in Ontario, Canada, poplar tree rows had a greater shading effect on understory maize and soybean than silver maple tree rows, which was attributed to the taller poplar crown, which casts longer shadows than silver maple [29]. In the follow-up study in the same system, shading was found to be greater under poplar and silver maple compared to walnut tree rows [44].

6.4.4. Tree or ACS Age

The age of the ACS or the tree rows can also impact crop productivity, which was reported in five of the 32 studies (Table A1, [33,34,44,48,59]). Older trees normally have a larger crown, which casts broader and longer shadows [53], and a larger rooting system, which can extract more soil moisture and nutrients from the crop alley than that of younger trees [33,34]. Long-term soybean yields were also reduced in a TBI in Ontario, Canada [29,44] and in an ACS in Missouri, USA [48]. The yield reduction of various crops was higher seven years after planting of poplar trees in a silvoarable experiment in the United Kingdom compared to the first three years following planting [59].

As mature trees exert greater influence on crop productivity compared to younger trees, systems with shorter rotations should be preferred, or trees should be harvested in time to minimize competition between trees and crops, particularly when crop production is the primary focus. Alternatively, if the emphasis is on hardwood production and ES provision, longer rotations or older trees may be more suitable, but potential impacts on crop productivity must be anticipated [34]. It should be noted, however, that also, in systems with short rotations, the below-ground rhizome expands as the trees age despite regular above-ground biomass harvesting. The expanding rhizome can also affect crop growth on adjacent crop alleys, for instance, by affecting soil water dynamics. Tree root pruning can address this issue without compromising arable crop yields [75], although negative impacts of tree root pruning on crop yields have also been reported [39].

6.4.5. Width of the Crop Alley and Tree Row

Crop alley width can impact crop productivity in ACS as the competition zone is comparatively larger and the shelter zone comparatively smaller in narrow crop alleys compared to wider crop alleys [28]. Overall, crop yields in ACS with narrow crop alleys can thus be lower than in systems with wider crop alleys. Crop alley width was addressed in four of the 32 considered studies (Table A1, [28,40,44,54]).

In an ACS with poplar in Germany, winter wheat and rapeseed yields were lower in a 48 m wide crop alley compared to yields in a 96 m wide crop alley [28]. The authors suggest that the comparatively larger competition zone in the narrow crop alley likely contributed to this outcome, particularly during dry years when competition for water was most intense between crops and trees. Similarly, other authors argue that in their TBI with poplar, silver maple and walnut, the narrowly spaced 15 m wide crop alley should be widened to reduce competition for water and light [44]. However, in an ACS with winter wheat cultivated on crop alleys of varying widths between black locust and poplar tree rows, overall crop yields were 2% higher on a narrow 24 m wide crop alley compared to the reference [40]. In a similar ACS with poplar in Germany, crop alley width did not affect overall crop yields of rapeseed, winter wheat and winter barley [54].

Tree row width can affect crop yields, as wider tree rows often feature an increased tree density, which in turn may affect the ability of the tree rows to effectively reduce wind speeds [24]. However, only one study addressed tree row width (Table A1, [66]). Here, data from fields with and without windbreaks across Kansas and Nebraska, USA, were analyzed using a GIS approach to assess the effect of windbreaks on soybean and wheat productivity. It was found that narrow windbreaks with an average width of 13 m resulted more often in yield increases of soybean and wheat than wider windbreaks.

The role of tree row width for crop productivity in ACS has not been thoroughly investigated. The width of the crop alley, on the other hand, can indeed affect crop productivity, although conflicting results have been reported in the literature regarding its specific effect. Nevertheless, it is advisable to design ACS in a manner that ensures the width of the crop alley is a multiple of the width of agricultural machinery to facilitate mechanical management of the site. Additionally, crop productivity benefits from an ACS design that minimizes the competition zone and maximizes the zone of positive synergistic effects, meaning that the width of the crop alley should be comparatively larger than the height of tree rows.

6.4.6. Crop Species

Crop productivity in ACS is significantly influenced by the ability of the crop to tolerate tree shading, particularly in the competition zone close to the trees. In addition to light availability, the competition for nutrients and soil moisture at the tree–crop interface further challenges ACS crop selection. The shade tolerance of a crop is primarily determined by the photosynthetic pathway the crop employs (see Section 6.1.5). Approximately one-third of the studies considered investigated more than one crop (n = 12, Table A1), and out of these, nine studies reported differences in the magnitude of yield effects for different species (Table A1, [29,33,34,42,48,51,57,59,72]).

In Belgium, yield reductions were lowest for winter wheat, barley and triticale compared to maize and sugar beet next to a STR with walnut [42] and compared to maize and potato in ACS and STR of varying age [34]. Similarly, in ACS with poplar in Germany, wheat was least affected by tree presence compared to spring barley and rapeseed [72] and showed a bell-shaped yield pattern with lower yields close to the tree rows and increasing yields towards the crop alley center, which could not be detected for rapeseed [33]. In the United Kingdom, crop yield response in the silvoarable experiment with poplar varied depending on the species and across different sites and years [59]. As a consequence of the difference in photosynthetic pathways, maize, a C4 species, was found to be more affected by shading from tree rows than soybean in ACS and TBI in China [57], Canada [29,51] and the USA [48]. In temperate ACS and particularly in systems with mature trees [29], crop species with a C3 photosynthetic pathway should thus be preferred over species that are sensitive towards shading, such as those with a C4 photosynthetic pathway. Further, the selection of winter cereals is beneficial in temperate ACS as they show less overlap in growing seasons with deciduous tree species [42].

6.5. Management Aspects

Crop yields in ACS are also affected by management practices, such as weed and leaf litter cover, fertilization or soil tillage (Table A1, [28,34,39,51,54,58,60,67,73]). Yield reductions close to the tree rows were associated with increased weed cover in a TBI in Québec, Canada [51] and in an ACS in Germany [67], where the lack of soil tillage close to the tree rows was also associated with lower crop yields in this zone.

For winter cereals, leaf litter coverage during autumn can be disadvantageous as it may coincide with seed germination. When fewer seeds germinate, the number of ears per area is most likely reduced, which will eventually lead to lower crop yields. Leaf litter coverage was found to be one of the reasons for lower yields in close vicinity to tree rows in ACS in Germany [28,54]. In the apple and cherry (*Prunus avium* L., *Prunus cerasus* L.) tree orchard in Switzerland, it was assumed that fertilization might be more important for understory crop yields than other factors [58], and the same was also assumed as being one of the reasons for crop yield declines next to STR and in ACS in Belgium [34].

Another possible explanation for lower yields close to tree rows is that farmers do not apply chemical inputs such as fertilizers, plant protection and plant promoters in similar amounts to those in the middle of the crop alley [73]. In Germany, for instance, the application of chemical inputs at field edges is restricted by law [73]. However, AFS and ACS are considered a part of the agricultural area according to CAP regulations, and as such, the restrictions that apply for the input of chemicals are the same as those that apply for treeless agricultural areas. Tree rows in ACS are thus not treated as natural landscape elements under protection; likewise, the transition zone to the tree rows is not regarded as a true field margin, and therefore, chemical inputs are allowed here.

To limit below-ground competition for water and nutrients between trees and crops, some studies have also investigated whether tree root pruning or root isolation through barriers had an impact on crop yields. Interestingly, this strategy can have different outcomes. In an ACS in Indiana, USA, root isolation of black walnut and red oak tree rows resulted in uniform maize yields across the whole crop alley as compared to a situation where no barriers were in place, and maize yields close to tree rows were reduced [60]. Here, the availability of soil moisture was apparently of greater importance for maize yields than above-ground competition for light. The opposite was found in a TBI with sugar maple and various other tree species, where root pruning in two years negatively affected soybean yields [39]. The authors argue that tree root pruning might have reduced biochemical compounds within the soil, which negatively affected soybean yields. Lower crop yields close to tree rows can thus not only be the result of competition for water and light at the tree–crop interface but also of differences in site management. Therefore, when planning and conducting field studies that aim to compare crop yields within ACS or between an ACS and a reference, differences in site management between the ACS and the reference or between different points in the ACS crop alley should be taken into consideration.

6.6. Crop Yield Modeling in ACS

Data on long-term crop yields in ACS, e.g., over the lifespan of a system, are difficult to obtain. This is, among other reasons, due to the fact that field experiments in ACS often have restricted time spans because of their reliance on limited external funding [76]. However, it is crucial to be able to predict the long-term productivity and environmental impact of ACS in advance because empirical field studies are not feasible for every location, ACS design, combination of tree and crop species and time horizon [77]. Modeling has thus emerged as a promising approach, not only for the projection of crop yields in ACS but also for predicting general biophysical interactions within ACS and between ACS and their environment [78]. A number of biophysical and economic models have been developed during the last decades, and a comprehensive overview of their characteristics, possible fields of application, benefits and shortcomings can be found in [77].

7. Conclusions

The aim of this review was to examine the available literature in order to evaluate the effect of tree rows on crop productivity in temperate AFS, with a particular focus on ACS. We identified that ACS crop yields often varied substantially depending on the species, the geographical location of the site, the effects on the microclimate, as well as ACS design. The observed pattern of lower yields near tree rows and increasing yields at greater distances emphasizes the importance of understanding the principles behind the spatial dynamics of crop productivity within ACS.

Our analysis revealed that in temperate ACS, the presence of tree rows affects several parameters, which impact crop productivity in both positive and negative ways. These parameters can be broadly classified as microclimate parameters, soil moisture, distance to the tree rows, ACS design and management aspects. Among these, solar radiation, management aspects, crop species and soil moisture were most frequently addressed in relation to crop productivity.

Particularly when close to the tree rows, competition between trees and crops becomes more pronounced, and less sunlight, less soil moisture and differences in how the area is managed often result in lower crop yields. However, when further from the trees, many studies reported that crops yielded more, though the specific reasons for this increase are not fully understood yet. Synergies between trees and crops exist, and crops clearly benefit from tree presence, but further research is needed to understand the specific mechanisms driving these effects. However, the lack of recent research on the productivity of crops in temperate ACS challenges the formulation of broad recommendations for ACS design. The wide variation in study approaches, ACS configuration and methods of collecting, analyzing and interpreting data complicates the comprehensive evaluation of results from different studies. Viable general recommendations on effective ACS design must be grounded on a substantial body of field research.

It is evident that ACS and the interactions within and between them and their environment are highly complex as well as spatially and temporally variable. This variability and complexity should be taken into consideration in data collection and analysis, for instance, through long-term monitoring of microclimate parameters, crop yields, soil moisture dynamics and evolving ACS design aspects (such as tree height) and multivariate methods of data analysis, which are able to identify and analyze complex interactions. Such data are also invaluable for robust simulations of future yield development in ACS modeling and for the development of regional planning tools. Concerning the reduced crop yield in close proximity to trees, future research could focus on identifying alternative crops suitable for cultivation in this area, which might cope more effectively with the prevailing competition for water and light in this zone.

Additional research is thus essential to further advance our understanding of the dynamics of crop productivity in ACS, to establish guidelines for effective ACS design and management and to promote the adoption of ACS as a resilient and productive agricultural land use system.

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Appendix A

Table A1. Studies addressing yield effects in temperate ACS, their location, geographical coordinates of the study site and considered crop(s). ACS: alley-cropping system; STR: single tree row; TBI: tree-based intercropping system; SB/WB/H: shelterbelt/windbreak/hedgerow; n.s.: not specified. * For studies with several study sites, geographical midpoints were calculated.

No	Author	Refs. No.	Site	State/Province and Country	Latitude	Longitude	System	Crop Species	Tree Species
1.	Artru et al. (2017)	[49]	Hesbaye	Hesbaye, Belgium	50.564051	4.696963	-	Winter wheat	-
2.	Artru et al. (2018)	[50]	Hesbaye	Hesbaye, Belgium	50.564051	4.696963	-	Sugar beet	-
3.	Böhm (2012)	[32]	Welzow	Brandenburg, Germany	51.575493	14.257508	ACS	Lucerne	Black locust
4.	Burgess et al. (2005)	[59]	several sites *	England, United Kingdom	52.541722	52.541722	n.s.	Wheat, barley, field beans, peas, mustard	Poplar
5.	Carrier et al. (2019)	[51]	several sites *	Québec, Canada	45.906829	−73.103097	TBI	Maize, soybean, wheat, black bean	American ash (*Fraxinus americana* L.), red oak, bur oak (*Quercus macrocarpa* Michx.), poplar
6.	Chirko et al. (1996)	[52]	Zhengzou	Henan, China	34.760277	113.641944	TBI	Wheat	Paulownia
7.	Gagné et al. (2022)	[39]	Baie-du-Febvre	Québec, Canada	46.13374	−72.666709	TBI	Soybean	Sugar maple, black walnut, red oak, swamp white oak (*Quercus bicolor* Willd.), bur oak, shagbark hickory (*Carya ovata* (Mill.) K. Koch), poplar
8.	Gillespie et al. (2000)	[60]	near Butlerville	Indiana, USA	39.050183	−85.499967	ACS	Maize	Black walnut, red oak
9.	Grünewald et al. (2009)	[33]	Dornburg	Thuringia, Germany	51.006389	11.666111	ACS	Summer barley, rapeseed	Poplar
10.	Jung et al. (2014)	[72]	Dornburg	Thuringia, Germany	51.006389	11.666111	ACS	Spring barley, rapeseed, wheat	Poplar
11.	Kang et al. (2008)	[53]	Shorter	Alabama, USA	32.442228	−85.897486	ACS	Maize	Mimosa
12.	Kanzler & Böhm (2016)	[40]	Forst	Brandenburg, Germany	51.744146	14.647491	ACS	Winter wheat	Black locust, poplar
13.	Kanzler et al. (2019)	[27]	Forst	Brandenburg, Germany	51.744146	14.647491	ACS	Winter wheat	Poplar
14.	Kowalchuk & Jong (1995)	[41]	Conquest	Saskatchewan, Canada	51.530091	−107.242507	SB	Wheat	Caragana, Manitoba maple, green ash
15.	Lamerre et al. (2016)	[54]	Braunschweig	Lower Saxony, Germany	52.266666	10.516667	ACS	Rapeseed, winter wheat, winter barley	Poplar
16.	Li et al. (2008)	[55]	Jiangcun Forest Farm	Henan, China	34.3	114.433333	TBI	Wheat	Paulownia
17.	Miller & Pallardy (2001)	[56]	Shelbyville	Missouri, USA	39.948180	−92.060751	ACS	Maize	Silver maple

Table A1. *Cont.*

No	Author	Refs. No.	Site	State/Province and Country	Latitude	Longitude	System	Crop Species	Tree Species
18.	Mirck et al. (2016)	[67]	Forst	Brandenburg, Germany	51.744146	14.647491	ACS	Sugar beet	Black locust, poplar
19.	Osorio et al. (2019)	[66]	several sites *	Kansas and Nebraska, USA	39.281396	−98.063876	WB	Soybean, wheat	Not specified
20.	Pardon et al. (2018)	[34]	several sites *	Flemish-Brabant and Flanders, Belgium	50.810178	4.032707	ACS and STR	Winter wheat, grain maize, winter barley, forage maize, potato	Poplar, wild cherry, walnut, wild service tree (*Sorbus torminalis* (L.) Crantz)
21.	Pardon et al. (2019)	[42]	Tielt-Winge	Flemish-Brabant, Belgium	50.917370	4.900013	STR	Winter wheat, winter barley, winter triticale, grain maize, sugar beet	Walnut
22.	Peng et al. (2009)	[57]	Nanshetou, Yongyao *	Shaanxi, China	34.328489	107.63276	TBI	Soybean, maize	Walnut, plum
23.	Peng et al. (2015)	[44]	Guelph	Ontario, Canada	43.541886	−80.208819	TBI	Soybean	Poplar, silver maple, walnut
24.	Raatz et al. (2019)	[73]	Göttingen, Dedelow *	Lower Saxony, Germany	52.488406	11.844473	H	Wheat	Not specified
25.	Reynolds et al. (2007)	[29]	Guelph	Ontario, Canada	43.541886	−80.208819	TBI	Maize, soybean	Poplar, silver maple
26.	Rivest & Vézina (2015)	[47]	near Montréal, Saint-Félicien *	Québec, Canada	46.134189	−73.922155	WB	Maize	white spruce, green ash, scots pine, tamarack
27.	Seiter et al. (1999)	[74]	near Corvallis	Oregon, USA	44.574479	−123.241390	ACS	Maize	Red alder, black locust
28.	Surböck et al. (2005)	[71]	near Wien	Wien, Austria	48.237172	16.337664	H	Lucerne	Not specified
29.	Swieter et al. (2018)	[28]	Braunschweig	Lower Saxony, Germany	52.266666	10.516667	ACS	Winter wheat, rapeseed	Poplar
30.	Udawatta et al. (2014)	[48]	Shelbyville	Missouri, USA	39.948180	−92.060751	ACS	Maize, soybean	Silver maple
31.	Vaccaro et al. (2022)	[58]	Windlach, Seegräben *	Zürich, Switzerland	47.442262	8.622859	AFS/TBI *	Summer barley	Apple, cherry
32.	Žalac et al. (2023)	[64]	near Đakovo	Slavonia, Croatia	45.306842	18.438995	AFS/TBI	Maize	Walnut

Table A2. Literature results for crop yield in ACS at different distances to the tree row as percentage of crop yields on reference. Distances were either provided in studies or have been calculated based on the information given in the study. Tree height class: 1: between 0 and 10 m; 2: between 10 and 20 m; 3: above 20 m. STR: single tree row.

References	Author	Crop	Percent Crop Yield at Distance to Tree Row [%]													
			1 m	1.75 m	2 m	2.5 m	2.6 m	3 m	3.15 m	3.5 m	4 m	5 m	5.2 m	6 m	6.3 m	7 m
[51]	Carrier et al., 2019	soybean							94.89						92.19	
		soybean		94.36						93.60						
		maize					76.57						87.82			
		maize														
		wheat					91.66						69.69			
		black bean		40.96						84.58						
[52]	Chirko et al., 1996	wheat				79.07						84.30				
[39]	Gagne et al., 2022	soybean									100.71					
		soybean									86.41					
[27]	Kanzler et al., 2019	wheat						98.59								
[34]	Pardon et al., 2018	maize				34.61						53.08				
		maize				26.80						46.46				
		potato				29.41						48.55				
		potato				27.73						47.18				
		wheat				80						89.15				
		wheat				47.14						57.97				
		barley				79.34						83.87				
[42]	Pardon et al., 2019	wheat						64								
		triticale						67								
		sugar beet						60								
		maize						25								
[44]	Peng et al., 2015	soybean			18.05						28.70			38.42		
		soybean			12.03						37.03			57.87		
		soybean			22.22						37.5			63.42		
[29]	Reynolds et al., 2007	soybean			41.43									76.06		
		soybean			51.39									77.22		
		soybean			51.33									69.19		
		soybean			74.22									126.66		
		maize			68.64									95.44		
		maize			49.16									96.06		
		maize			12.10									89.96		
		maize			69.64									120.23		
[28]	Swieter et al., 2018	wheat	49.20								72.46					79.22
		wheat	54.68								80.82					76.54

Table A2. *Cont.*

References	Author	Percent Crop Yield at Distance to Tree Row [%]												Alley Width [m]	Tree Height Class
		9 m	9.25 m	10 m	12 m	12.1 m	12.9 m	15 m	19 m	19.5 m	20 m	24 m	30 m		
[51]	Carrier et al., 2019						110.81			103.30				39	1
			94.36					98.12						30	
						100.20			101.13					38	
														39	
						68.18		86.36						38	
			90.30					94.71						30	
[52]	Chirko et al., 1996			90.34							96.17			60	2
[39]	Gagne et al., 2022				132.61						135.12			40	1
					100						103.39			40	
[27]	Kanzler et al., 2019	129.57												48	1
[34]	Pardon et al., 2018			71.42							87.35		95.50	STR	3
				65.68							82.85		93.39	STR	
				67.62							85.10		95.07	STR	
				64.86							80.51		89.80	STR	
				96.55							103.29		105.31	STR	
				66.66							77.94		82.35	STR	
				89.24							94.62		97.84	STR	
[42]	Pardon et al., 2019													STR	2
														STR	
														STR	
														STR	
[44]	Peng et al., 2015													15	2
														15	
														15	
[29]	Reynolds et al., 2007													13.75 *	2
														13.75 *	1
														13.75 *	2
														13.75 *	1
														13.75 *	2
														13.75 *	1
														13.75 *	2
														13.75 *	1
[28]	Swieter et al., 2018											86.66		48	1
												110.14		48	

* mean value; alley width was 12.5 m or 15 m [29].

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