Agroforest Syst (2022) 96:799–810
https://doi.org/10.1007/s10457-022-00740-z

Moderate shading did not affect barley yield in temperate silvoarable agroforestry systems

Christina Vaccaro · Johan Six · Christian Schöb

Received: 7 July 2021 / Accepted: 10 March 2022 / Published online: 18 April 2022

Abstract With climate change and an increasing global human population, the concept of agroforestry is gaining economic and environmental interest. The practice of growing trees and crops on the same land is mainly applied in (sub)tropical climate and rarer in temperate areas where farmers fear decreased understorey crop yields due to competition with trees. However, whether competition is stronger below- (soil moisture, nutrients) or aboveground (light) in a temperate silvoarable agroforestry system (AFS) is not clear. The effects of different treatments of light, water and nutrient availability on crop production in two temperate AFS in Central Switzerland were investigated, where summer barley (*Hordeum vulgare* L.) was grown as understorey crop under 90%, 40% and 0% shade nets, with and without irrigation and/or fertilisation in a fully factorial design. Yield was reduced by 26% under heavy shade; yield reductions under moderate shade were not significant. Fertilisation and irrigation increased crop yield by 13% and 6–9%, respectively, independent from shade. Individual seed mass was significantly increased by fertilisation from an average of 0.041 g (±0.008 SD) in unfertilised treatments to an average of 0.048 g (±0.010) in fertilised treatments. Fertilisation had the biggest impact on total seed number ($p < 0.001$) with on average 36 (±26) seeds per individual in unfertilised plots and 61 (±33) in fertilised plots. This study demonstrates that moderate shade (as can be expected in modern AFS) was not a major limiting factor for barley yield in these two AFS in Switzerland, indicating that AFS with appropriate management combined with suitable selection of understorey crops are an option for agricultural production in temperate regions without significant yield losses.

Keywords Temperate agroforestry · Silvoarable · Shade · Understorey growth · Yield · Barley

Introduction

As the human world population and greenhouse gas emissions are increasing, the concept of silvoarable agroforestry – the growth of trees and crops on the same land – is gaining more and more interest, also in Europe (Dagar and Tewari 2017). Agroforestry can be considered a more sustainable agricultural practice compared to conventional agriculture (Pardon et al. 2018) while remaining relative productive

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-022-00740-z.

C. Vaccaro (✉) · J. Six · C. Schöb
Department of Environmental Systems Science, Institute of Agricultural Sciences, ETH Zurich, Zurich, Switzerland
e-mail: christina.vaccaro@usys.ethz.ch

C. Schöb
Department of Biology, Geology, Physics and Inorganic Chemistry, University Rey Juan Carlos, Móstoles, Madrid, Spain

(Smith et al. 2013). Agroforestry systems (AFS) can deliver a range of ecosystem services such as biodiversity conservation, soil fertility and erosion control (Smith et al. 2012; Malézieux et al. 2009; Ong et al. 2015). Light competition between trees and the understorey crop is, however, regarded as a major limiting production factor in AFS and a main reason why farmers are reluctant to adopt this practice in temperate regions (Dupraz et al. 2018a).

Tree-crop competition for light may outweigh all positive effects, such as erosion control, a beneficial microclimate, improved water availability or soil fertility, leading to a substantial yield decrease of the understorey crop (Ong et al. 2015). According to Kho (2000), yield benefits in AFS exist mainly on nutrient-deficient soils with inadequate rainfall. However, increased land equivalent ratios (LER) of 1.3 up to 1.6 have been shown in Mediterranean AFS in Southern France (Lovell et al. 2017). In Switzerland, LER lay between 0.95 and 1.3 in 12 out of 14 representative AFS (Sereke et al. 2015). Even though light competition may be strong in the presence of trees, light use in AFS can be optimised through a suitable tree-crop-combination (Charbonnier et al. 2017; Dupraz et al. 2018b). Indeed, overyielding by multispecies cropping systems generally has often been attributed to an increased efficiency in light capture (Malèzieux et al. 2009); particularly in AFS with a complementarity in resource capture by trees and crops (Cannell et al. 1996).

Crop species differ in their metabolic pathways for carbon fixation in photosynthesis (C_3, C_4, CAM) and leaf properties (sun or shade leaves). Light-response curves of most leaves saturate between 500 and 1000 µmol m^{-2} s^{-1}, which is well below full sunlight (Taiz and Zeiger 2010). Tree canopy structure and timing of leaf emergence strongly influence understorey light conditions, as well as management practices (tree row arrangement and orientation, pruning). To increase light availability for the understorey crop, a North–South tree row orientation is recommend at high latitudes, an East–West orientation at low latitudes (Dupraz et al. 2018a). Jäger and Herzog (2017) recommend Swiss agroforestry farmers a distance of 18–26 m between tree rows and 10–12 m distance within tree rows, resulting in tree densities of 35–55 trees ha^{-1}. In Northern Europe, a survey indicated that farmers tend to envisage silvoarable AFS with an average tree density of 55 trees ha^{-1} (Graves et al. 2009). Young trees (little shade) and mature trees (high enough to permit an understorey light environment) allow more intensive crop production than intermediate systems with middle-aged trees where there is less light partitioning (Vandermeer 1989).

In general, results from past studies on light competition in AFS vary greatly with a common negative effect on crop productivity (Batish et al. 2008), though no effects (e.g. Gillespie et al. 2000) or positive effects (e.g. Kanzler et al. 2019; Pardon et al. 2018) on yield are possible. Yield reductions due to tree shading were found to range from minor decreases (Dupraz et al. 2018a) up to decreases of 50% (Dufour et al. 2013; Li et al. 2008; Reynolds et al. 2007) or more (e.g. 78% decrease in Mantino et al. 2020) compared to monocropping systems. Light as the primary limiting factor for understorey plant growth was found in different climatic zones, i.e. in tropical (Friday and Fownes 2002), subtropical (Zamora et al. 2009), semiarid (Yun et al. 2011) and temperate climates (Reynolds et al. 2007). Belowground competition for water near tree rows has also been pointed as a factor limiting agricultural production within different temperate silvoarable AFS (e.g. Jose et al. 2004). Nevertheless, whether light, water or nutrient availability is the main limiting factor for understorey crop growth in temperate silvoarable AFS is highly context dependent. Kho (2000) stated that light is the primary limiting factor in intensive systems in temperate regions. Ong et al. (2015) argue that in particular when water and nutrients are sufficiently available, crop growth in AFS is expected to be limited by light availability. Thus – apart from crop and tree species, management practices and the age of the system – the severity of yield and/or quality losses due to competition for light in the understorey depends on climate, soil water and nutrient availability.

In Switzerland (and other European countries), AFS farmers are advised to stimulate young trees to root into deep soil layers by ploughing very close to the tree row (farmers, pers. communication). With this practice, belowground competition with crops is expected to be reduced (Jose et al. 2004). Additionally, as average annual rainfall amounts to approximately 1200 mm (average from 2008 to 2018, BfS 2021) with 300 mm in summer and 250 mm in spring and autumn (MeteoSchweiz 2020), water competition is usually not the primary limiting factor for crop growth in Switzerland. As for nutrients, Swiss soils are regarded as one of the most fertile soils in the world (BAFU 2017; Gubler et al. 2019). Though remaining of substantial importance (particularly in the face of global warming and changed precipitation patterns), due to root education in tree management, sufficient rainfall and general good soil fertility, belowground competition is currently not in the focus. Yet, hardly any study assessed the relative importance of light, water and nutrient competition or their possible (interactive) effects in temperate AFS. In the present experimental study, possible yield limitations through light, water and nutrient competition are assessed in two AFS to test whether light competition is the primary limiting factor for understorey crop growth in a Central European climate and if light competition intensity is influenced by water and nutrient availability. We hypothesise that (1) shade is the primary limiting factor for barley grain yield under optimised water and nutrient management but that (2) shade may less negatively affect grain yield under less favourable conditions.

Materials and methods

Study area

Field experiments were carried out at two organically managed AFS in Switzerland where both climates are classified as Cfb (Köppen and Geiger classification), i.e. warm and temperate climate. The first AFS (10.2 ha) is located in Windlach in the Northern part of Kanton Zürich (47°32′16.4″N, 8°28′46.3″E), 410 m a.s.l. Apple trees (*Malus domestica*, cv. 'Heimenhofer', 'Schneiderapfel' and 'Spartan') were planted in a density of 37 trees ha^{-1} (10×28 m distance within and among tree rows, respectively) in West–East orientation in November 2015. Windlach has a mean annual temperature of 9.2 °C and a mean annual precipitation of 1038 mm with the summer months (June to August) receiving the highest amounts (111–123 mm per month) (https://de.climate-data.org/europa/schweiz-221 2018). The second AFS (1.9 ha) is located in Seegräben in the central part of Kanton Zürich (47°20′4 7.1″N, 8°45′42.0″E), 536 m a.s.l. Cherry trees (*Prunus avium*, cv. 'Avione', *Prunus cerasus*, cv. 'Königin Hortense' and 'Hallauer Aemli') were planted in a density of 62 trees ha^{-1} (8×20 m distance within and among tree rows, respectively) North–South orientation in 2011. Seegräben has a mean annual temperature of 8.7 °C and a mean annual precipitation of 1130 mm with the summer months (June to August) receiving the highest amounts (128–135 mm per month) (https://de.climate-data.org/europa/schweiz-221 2018). Both farms differ in their management: While tillage is reduced in Seegräben, it is intensive in Windlach due to weed control. Grown crops are diverse vegetables, summer crops (*Panicum* sp., *Triticum aestivum* subsp. *spelta*) and winter wheat in Seegräben and sunflower (*Helianthus annuus*), squash (*Cucurbita* sp.) and winter rye (*Secale cereale*) in Windlach. In Windlach, artificial pasture and fallow occupy several years in the crop rotation. Details can be found in the Supplementary Information.

On July 22, four random soil samples were taken with a cylindrical soil tube at each site and further divided in samples of 0–10 cm and 10–20 cm depth. Soil carbon and nitrogen were measured with the CHN628 Series Elemental Determinator at ETH Zurich. For total phosphorus determination, wet digestion with H_2SO_4 after Anderson and Ingram (1993) was used and samples where then analysed on the ICP. All soil nutrients differed significantly between sites. Soil carbon content was significantly higher in Seegräben (average 2.92% ± 0.28 SD) than in Windlach (average 1.59% ± 0.28). Likewise soil nitrogen content was significantly higher in Seegräben (average 0.29% ± 0.03) than in Windlach (average 0.14% ± 0.03), as was phosphorus (average 890 ± 111 mg P kg^{-1} in Seegräben and 636 ± 150 mg P kg^{-1} in Windlach). Soil nutrient levels in Seegräben correspond well to the average soil C, N and P levels present in agricultural soils in Switzerland (C: 3.13%, N: 0.29%, P: 932 mg kg^{-1}, source: NABO, pers. communication), but are rather low in Windlach.

Experimental design

In spring 2019, two shade intensities were implemented by means of artificial shade nets (R.G. Vertrieb, Austria) to achieve moderate and heavy shading. Shade net intensities were 40% (moderate) and 90% (heavy) of full sunlight (i.e. 60% and 10% of incident photosynthetically active radiation). However, the area beneath the shade nets received lateral sunrays during early and late hours of the day (as they would in a natural stand of trees). These degrees of opacity were chosen based on previous studies, where yield reduction was observed by a 30–50% relative irradiance (Dufour et al. 2013; Dupraz et al. 2018a) and model results suggest a 55–75% (17 m wide tree alleys) and 25–50% (35 m wide tree alleys) light capture by trees (Dupraz et al. 2018a). For a steeper contrast, severe shading was selected for the heavy shade treatment. Control treatments had no shade net. Nets measured 2×2 m and their height was adjusted throughout the season (0.3–1.2 m) to shade the central plot (0.7×0.7 m). Barley was sown on 2 April in Seegräben and 28 March in Windlach.

Shade (40%, 90%) and control (0% shade) treatments were examined in a full-factorial design with four treatments: (1) irrigation, (2) fertilisation, (3) fertilisation and irrigation and (4) control. The four environmental treatments with the three shade intensities built one replicate (12 plots per replicate). In Windlach there were four replicates (48 plots in total), in Seegräben there were three replicates due to limited space (36 plots in total).

Irrigation was conducted manually with watering cans. The amount of water was adapted to weather conditions and varied between 9 and 27 l per plot (i.e. 4.5–18.5 mm m^{-2}) once a week. Throughout the barley growing season in 2019 approximately 81 l per plot were irrigated in Seegräben and 90 l per plot in Windlach.

For fertilisation, the organic mineral NPK-fertiliser “Styria Fert Veggie Plus P+S” (Agro Power Düngemittel GmbH) was used in Windlach. It is manufactured out of residues from starch and glucose production, cocoa pods, Hyperphosphate, elemental potassium and sulphur and consists of 4% N, 5% P_2O_5 P and 2% K_2O with 7% CaO, 0.45% Mg, 5% S, 0.527% Fe and 0.0218% Zn. Styria Fert Veggie Plus has a C:N ratio of 10:1 and a pH of 6.5. Its dry matter has 65% organic substances. It is certified after the BIO AUSTRIA guideline and the Council Regulation (EC) No 834/2007 for organic agriculture. 520 kg ha^{-1} were applied on 22 April 2019. In Seegräben one half of the land used for the experiment received high nutrient input in the form of compost the autumn before. Due to a mistake during the sowing of the understorey crop, the area with the fertilisation treatment was initially sown with spelt and then ploughed again to remove the spelt before sowing of barley. However, the ploughing could not completely eliminate the germinating spelt. Therefore, the factor fertilisation is confounded with the unwanted spelt growth. This was accounted for during data analysis (see “Data analyses” section).

Sampling

The gross plot area was 2×2 m, however only the central area of 0.7×0.7 m (0.49 m^2) was manually harvested when plants reached maturity stage (end of July in Windlach, beginning of August in Seegräben 2019). Where the central plot area was damaged by accumulated water at heavy rainfall events on the surface of the shade nets and subsequent centralised trickling or by lodging, another area within the gross plot was sampled. The sampling position was documented as either “central” or “border” and taken into account during data analyses. The harvested material (ears with short stalks) were put in labelled paper bags and stored in a dry room for 21–28 days at the ETH Research Station for Plant Sciences in Eschikon (Lindau) where they were threshed with the threshing machine “Saatmeister Allesdrescher K35” (rotational frequency: tumbler: 9, fan: 6). Grains were weighed and stored in small paper bags in a dry room. For trait measurements, four individuals within the area designated for harvest were randomly selected at harvest time. The whole aboveground plant was manually harvested and put in labelled bags made out of baking paper which were left open to ensure drying. Internode length between nodes were measured separately and noted down and the number of stalks counted (tillering). Plant height, a common indicator for growth under shade, was obtained by adding all internode lengths, measured from four individuals per plot at harvest. Total grain yield was weighed, the total number of seeds counted and the seed mass calculated by randomly weighing 10 seeds and dividing the weight by 10. Straw (air-dried aboveground stalks) was weighed at the end.

Data analyses

Statistical analyses were carried out with R version 3.6.1. The data was tested for normality and homogeneity of variance by the Shapiro–Wilk test, the Fligner–Killeen test and a visual inspection of residuals. On the plot level, a logarithmic transformation was carried out for yield in the general model and the Windlach-model. On the individual level, a logarithmic transformation was applied for total seed number. In the plot-data one outlier (strong lodging occurrence) and in the individual-data one outlier (extremely high yield) was removed. Differences in group means among groups was analysed by multifactorial ANOVA (type I, sequential sum of squares). Significances of each factor were assessed by means of the F-test. Statistical modelling was performed with three linear models on the plot level – one model for each experimental site and a general model for both locations. The formula of the Seegräben-model is lm(yield ~ spelt + sampling position * plant density * shade * irrigation) where "yield" combines barley and spelt yield, "spelt" is the presence (1) or absence (0) of spelt in the experimental plots, "sampling position" is the sampling position (central/border) of the harvested area (70 × 70 cm) within the shaded area (2 × 2 m), "plant density" is the number of plants within the harvested area, "shade" is the applied shade treatment (0, 40%, 90% shade) and "irrigation" refers to the received irrigation treatment (yes/no). The factor "fertilisation" (yes/no) is not included in the Seegräben-model as it is inseparable with the presence of spelt. Similarly, the Windlach-model is lm(log(barley yield) ~ sampling position * plant density * shade * fertilisation * irrigation) with barley yield being log transformed. The general model at plot level was lm(log(yield) ~ site + sampling position * plant density * shade * fertilisation2 * irrigation) with "site" being the experimental site (Seegräben/Windlach). Again, the response variable "yield" includes barley and spelt yield and is log-transformed. As the factors fertilisation and presence of spelt are confounded in Seegräben, a second fertilisation factor ("fertilisation2") was created with "yes", "no" and "X" where "X" compiles those plots in Seegräben which were fertilised and where spelt was present. Models on the individual level followed the same structure, accounting additionally for dependency of individual samples within the same plots in linear mixed effects models of the structure lme(plant trait ~ spelt + site + sampling position + plant density + shade * fertilisation * irrigation, random = ~ 1|plot). Models on the individual level (Windlach data only) followed the same structure, accounting additionally for dependency of individual samples within the same plots in linear mixed effects models: lme(plant trait ~ sampling position + plant density + shade * fertilisation * irrigation, random = ~ 1|plot). Multiple coefficients of determination for the general model and the Seegräben- and Windlach-model were 0.91, 0.82 and 0.89, respectively, and lower for the models on seed mass, total seed number and height on the individual level (0.41, 0.57 and 0.46). For post-hoc analysis a Tukey test was used to compare the means of treatment groups with the HSD.test()-function within the R agricolae package (de Mendiburu 2020) with a significance threshold of $\alpha = 0.05$. Partial effects of each factor were extracted by means of the effect()-function within the R effects package (Fox and Weisberg 2019) for analysing main and interaction effects.

Results

Plot level

Site ($p < 0.01$), shade ($p < 0.001$), fertilisation ($p < 0.001$), irrigation ($p < 0.01$) and two interactions (shade and fertilisation ($p < 0.01$), fertilisation and irrigation ($p < 0.01$)) significantly affected understorey crop yield. Higher average yields were found in Seegräben with 2.75 ± 0.86 SD Mg ha^{-1} (in spelt-free plots 3.28 ± 0.56 Mg ha^{-1}) compared to 2.43 ± 0.67 Mg ha^{-1} in Windlach. Average yields in spelt-free control treatments with no shade amounted to 3.64 ± 0.59 Mg ha^{-1} in Seegräben and to 2.77 (± 0.64) Mg ha^{-1} in Windlach.

Crop yield was significantly reduced by shade ($p < 0.001$). Compared to yield in control treatments (mean 2.96 ± 0.68 Mg ha^{-1} for both sites), yield amounted to 2.54 (± 0.64) Mg ha^{-1} (86%) under moderate shade treatments and to 2.20 (± 0.81) Mg ha^{-1} (74%) under heavy shade treatments. The Tukey test for the general model indicated that yield decrease was significant between shade treatments. Looking at each site individually, yield in heavy shade treatments was significantly lower than yield in controls at both sites (Fig. 1). Yield in moderate shade treatments was not significantly lower than yield in controls or higher than yield in heavy shade treatments at Seegräben; at Windlach yield in moderate shade treatments was significantly higher than yield in heavy shade treatments (Table 1).

An effects overview of the environmental factors shade, fertilisation and irrigation at Windlach is given in Fig. 2. Yield under heavy shade and in the unfertilised, non-irrigated treatment had similar low yields

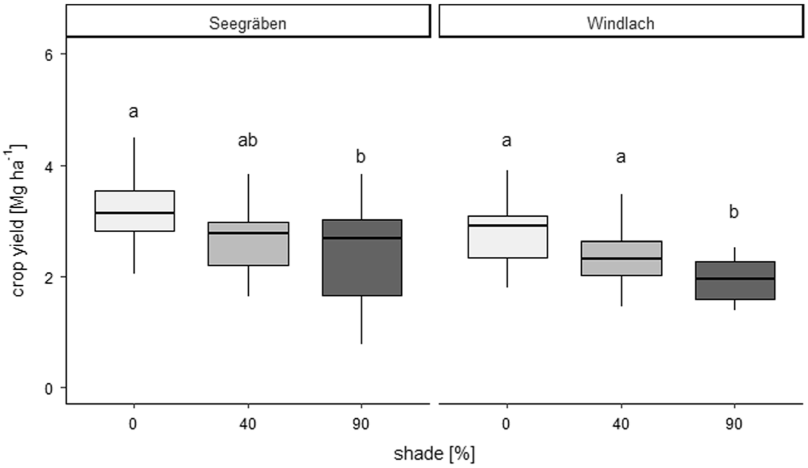

Fig. 1 Understorey crop yield under different shade treatments (no shade net, 40% and 90% shade nets) at two agroforestry systems in Switzerland (Seegräben, Windlach). Different lowercase letters indicate significant differences in mean crop yield at $p < 0.05$ probability level. Heavy shade (90%) reduced understorey crop yield significantly whereas yield reduction under moderate shade (40%) was not significant at both sites. The box plots range from the first to the third quartile where the horizontal line shows the median. The vertical lines go from each quartile to the minimum or maximum, respectively

Table 1 Comparison of crop yield in Mg ha^{-1} among different treatments. Small letters indicate significant differences ($p < 0.05$) within one treatment group (shade, fertilisation, irrigation) for one site

Site	Shade			Fertilisation		Irrigation	
	Control	40% shade n	90% shade n	Fertilised	Unfertilised	Irrigated	Non-irrigated
Seegräben	3.20 ± 0.69a	2.65 ± 0.67ab	2.41 ± 1.03b	–	–	2.84 ± 0.88a	2.66 ± 0.85a
Windlach	2.77 ± 0.64a	2.46 ± 0.63a	2.03 ± 0.57b	2.60 ± 0.64a	2.26 ± 0.68b	2.55 ± 0.67a	2.32 ± 0.67b

(2.03 ± 0.57 and 1.95 ± 0.45 Mg ha^{-1}, respectively). Throughout all shade treatments, yield in fertilised (non-irrigated) plots averaged 2.69 ± 0.66 Mg ha^{-1}, almost reaching the mean yield under no shade net over all fertilisation and irrigation treatments (with a mean of 2.77 ± 0.64 Mg ha^{-1}). Yield under moderate shade with fertilisation was higher than yield under no shade without fertilisation (2.64 ± 0.67 Mg ha^{-1} and 2.60 ± 0.60 Mg ha^{-1}, respectively). As for the fertilisation-irrigation-interaction, yield increased due to fertilisation and irrigation by 28% and 24%, respectively, with no mutual benefit in fertilised and irrigated treatments where yield was increased by 22% (Fig. 3).

For the individual models, the effects of shade ($p = 0.025$), fertilisation ($p = 0.019$) and the interaction of fertilisation and irrigation ($p = 0.005$) were significant while irrigation was not ($p = 0.085$) in Windlach. In Seegräben, the factor shade was significant ($p = 0.004$). Fertilisation was not included due its confounding with spelt. Irrigation was not significant ($p = 0.371$).

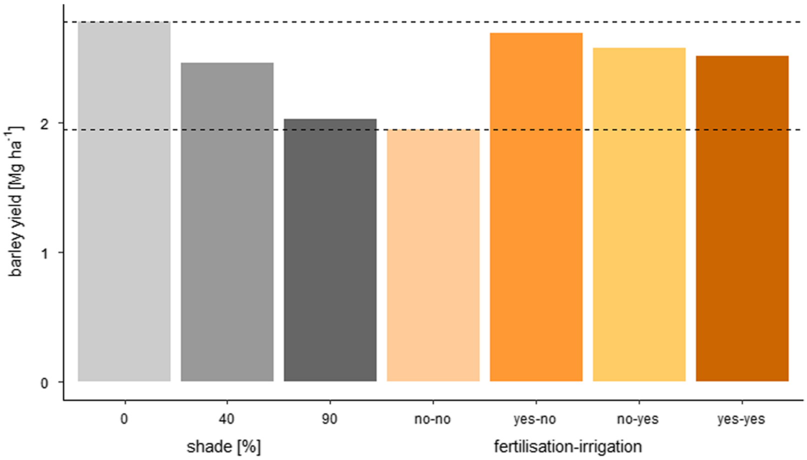

Fig. 2 Effect of environmental factors on understorey barley yield at Windlach. Left side: shade treatments (bright grey: 0%, grey: 40%, dark grey: 90% shade), right side: fertilisation-irrigation treatments (from left to right: no fertilisation + no irrigation, fertilisation + no irrigation, no fertilisation + irrigation, fertilisation + irrigation). Heavy shade treatment and non-fertilised, non-irrigated treatments both decreased understorey crop yield in the same range

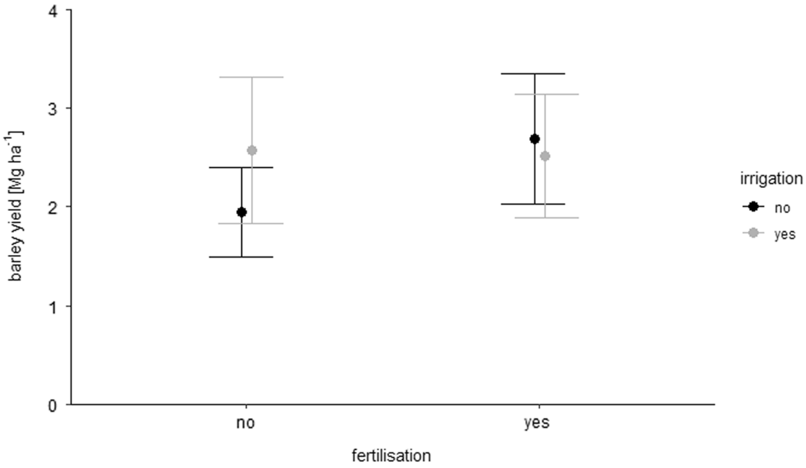

Fig. 3 Interaction plot of the factors fertilisation and irrigation in Windlach. Each of the two factors alone increased barley yield, however, there was no mutual benefit. Error bars indicate the standard error

Individual level

Seed mass

Average seed mass amounted to 0.045 g (±0.01) and ranged from 0.014 to 0.073 g, where the lower seed mass was found in plots where spelt was present ($p < 0.001$). In spelt-overgrown plots, barley seed mass amounted on average to 0.035 g compared to 0.045 g in spelt-free plots. Seed mass differed significantly between sites ($p = 0.001$) and was higher in Seegräben (0.047 g) than in Windlach (0.043 g). Seed mass was significantly increased by fertilisation ($p < 0.001$) from an average of 0.041 g (±0.008) in unfertilised treatments to an average of 0.048 g (±0.010) in fertilised treatments (Fig. 4). Shade reduced seed mass, but the reduction was not significant ($p = 0.2433$). The interactions of plant density and shade ($p = 0.044$), plant density and fertilisation ($p < 0.001$) and plant density and irrigation were significant ($p = 0.002$). Partial analyses showed a decrease in seed mass for heavily shaded plots with high plant density (−10%) but an increase in seed mass for unshaded (+118%) and moderately shaded (+29%) plots with a high plant density, respectively. The interaction effect between plant density and fertilisation was retested for Windlach only (due to the

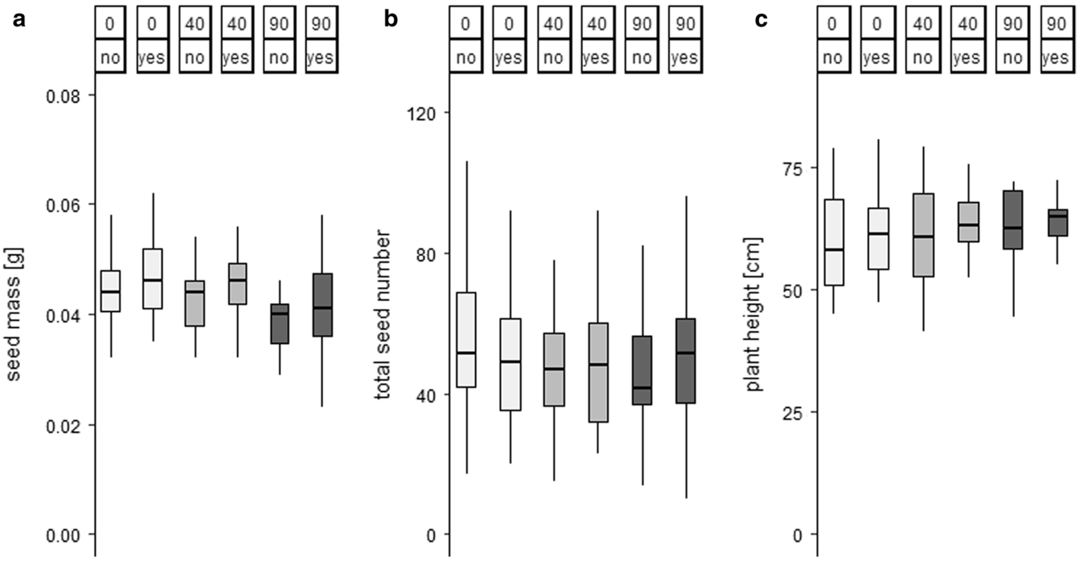

Fig. 4 Effects of shade (0%, 40% and 90%) and fertilisation (yes/no) on seed mass, total seed number and plant height of individual barley plants at Windlach

ambiguity with presence of spelt in Seegräben) and could not be verified. Partial analyses of the plant density and irrigation interaction, however, illustrated that a decrease in seed mass with increasing plant density in non-irrigated plots while seed mass increased with increasing plant density in irrigated plots.

Total seed number

On average, an individual barley plant had 50 seeds (±32). The number of tillers and seeds were correlated (r = 0.82). In spelt-overgrown plots, barley total seed number was low (on average 12 ± 4 seeds). At Windlach, where all plots where spelt-free, barley plants counted on average 52 (±22) compared to 47 (±42) seeds at Seegräben; this difference was significant ($p = 0.005$). Fertilisation had the biggest impact on total seed number, increasing it significantly ($p < 0.001$). Unfertilised plots averaged 36 (±26) barley seeds per individual, whereas fertilised plots averaged 61 (±33) seeds (Fig. 4). The number of barley plants within the harvested area significantly influenced total seed number ($p = 0.006$). Total seed number was lower when sampled in the central plot (47 seeds) compared to samples taken from the border (55 seeds). Regarding shade effects on total seed number, a tendency could be seen towards a reduction of total seed number (53, 49 and 48, on average, for 0%, 40% and 90% shade, respectively), however, this was not significant.

Plant height

Plant height averaged 60 (±13) cm for control treatments and increased slightly with increasing shade (62 cm in 40% shade treatments, 63 cm in 90% shade treatments) but this was not significant. In Windlach, the interaction between fertilisation and irrigation was significant ($p < 0.014$) (Fig. 4), with lowest barley plants in unfertilised, non-irrigated treatments and statistically equal plant heights in all other treatment combinations.

Harvest index

The ratio of seed yield to total shoot biomass, the harvest index, across all treatments averaged 0.48 (±0.07) and was slightly higher in fertilised, unshaded and moderately shaded plots (0.49).

Discussion

In this study, heavy shade reduced yield considerably but moderate shade had no significant effect on yield. This finding is in alignment with previous results. For example, in a Midwestern USA AFS where maize was grown in alleys between either black walnut (*Juglans nigra* L.) or red oak (*Quercus rubra* L.), shade did not have a major influence on crop yield (Gillespie et al. 2000). In Missouri, USA, water and not light competition was central in a silver maple-maize AFS system (Miller and Pallardy 2001). In presence of a root barrier between trees and crops, no differences in soil water content and net photosynthesis of maize adjacent to the tree row were found whereas they were reduced in absence of a barrier. Pardon et al. (2018) assessed yields of (silage) maize, potato, winter wheat and winter barley during three consecutive years (2015–2017) on 16 arable agroforestry fields in Belgium with young (2–7 years old) trees in alley cropping fields and moderate to older (15–48 years old) trees in an adjacent field. Relative yields for young trees ranged from 79 to 84%, for mid-aged trees from 76 to 99% and for older trees from 57 to 91%. Above all, maize (a C4 plant) and potato yields were substantially reduced, while yields for winter wheat and winter barley were hardly affected, which may indicate the importance of species-dependent light-limitation in this study.

However, there are some opposing findings. For example, in Ontario, Canada, hybrid poplar and silver maple trees significantly reduced photosynthetic radiation, soil moisture, net assimilation, growth and yield of maize and soybean in two subsequent study years (Reynolds et al. 2007). The authors concluded that water competition was of lesser importance than light competition in their study.

In Switzerland, AFS are still a relatively new agricultural practice and understorey crop yield is expected to decrease due to shade in the years to follow (Jäger and Herzog 2017). As stated by Pardon et al. (2018), experimental research addressing crop yield limitations in temperate AFS are rare, particularly for mature trees. This study used artificial shading in young temperate AFS to simulate higher shade intensities of mature trees. While there was a linear trend in yield reduction with shade, yield in the moderate shade treatment was not significantly lower than the control treatment at both sites. Yield reductions of 90% shade and non-fertilised treatments were in the same range (−26% and −24%, respectively). However, while 90% opacity in AFS may be an interesting research question, in practice such a high shading level is a rather unrealistic scenario. Light transmittance was never lower than 80% at a distance of half the tree height in six tree-based intercropping systems in southern Quebec, Canada (Carrier et al. 2019). Though trees in five of these systems were young (3–7 years old), in one system they were twenty years old. Dupraz et al. (2018a) investigated light availability in alley-cropping agroforestry at different latitudes by means of a 3D model and found that light availability never dropped below 50% with 41 trees ha^{-1} tree density, even at high latitudes. The 40% shade treatment is likely to better approximate real light conditions in modern agroforestry systems with wide between-row spacing and a North–East-orientation.

As yield in moderate shade treatments was significantly higher than yield in non-fertilised treatments, our results suggest that fertilisation might play a more important role in understorey crop yield than light availability in temperate AFS. Fertilisation caused a yield increase through a 17% higher seed mass, reaching a rather high barley seed mass (compared to e.g. Žáková and Benková 2006; Hoyle et al. 2020). Though there was a trend towards reduced seed mass with increasing shade, this reduction was not significant, strengthening the greater influence of nutrient limitation than shade on understorey crop growth. Fertilisation also increased total seed number and plant height, whereas the increase among the shade treatments was minor and not significant. In particular in Windlach, yield increased strongly with either fertilisation or irrigation. It should be born in mind, however, that Windlach has a relatively nutrient-poor soil with significantly lower soil carbon, nitrogen and phosphorous contents than average agricultural soils in Switzerland.

The in general relatively low barley yield in control treatments (3.20 and 2.77 Mg ha^{-1}) is not uncommon for organic farms in Switzerland: Mean organic summer barley yields in Switzerland amounted to 3.59 Mg ha^{-1} (2003–2019, source: Agristat 2020, pers. communication). This corresponds well to yields in unshaded, fertilised plots (3.25 Mg ha^{-1} for both sites). A harvest index of 0.49 for unshaded and moderate shaded plots is slightly higher than average harvest indices of cereals (0.45 in Fan et al. 2017).

Carrier et al. (2019) claimed that net photosynthesis rate of C3 plants remains constant at approximately 25%-50% of full sunlight, a level of light availability which is achievable in AFS even at high latitudes (Dupraz et al. 2018a). A 50% reduction in light availability allows often an 80–100% relative yield for shade tolerant species (such as barley) (Dupraz et al. 2018a; Reynolds et al. 2007). Bommarco et al. (2013) argue that efforts to minimize the yield gap, i.e. the potential yield of a locally adapted cultivar which depends ultimately on available light, typically become non-economical when yields reach 80% of the yield potential. As the yield gap is widened by water scarcity, low nutrient levels, weeds, pests and a lack of pollination (Bommarco et al. 2013), it could be argued that minor shade-induced yield reductions in temperate silvoarable AFS may be tolerable and further alleviated through optimisations in water and soil nutrient management.

As discussed in this paper, whether light or water availability lead to yield reductions may be site- and climate-dependent. Switzerland and other countries in temperate regions are receiving abundant precipitation and possess healthy fertile soils; in this environment moderate shade—as has been shown with barley—does not necessarily affect yield gravely.

Conclusion

This study addressed the ongoing scientific discussion of whether below- or aboveground competition is limiting understorey crop growth in temperate silvoarable AFS. Yield limitations through restricted light, water or nutrient availability were assessed across two AFS in Switzerland. Though 40% and 90% shade treatments reduced barley yield by 14% and 26%, respectively, yield under moderate shade was significantly higher than yield in non-fertilised treatments. On the individual plant level, fertilisation significantly increased seed mass, total seed number and plant height, whereas the converse trend due to shade was not significant. The presented results suggest that fertilisation might play a more important role in understorey crop yield in our AFS than light availability and that light must not necessarily be the primary limiting factor in temperate AFS. Given that trees also yield agricultural products, AFS hold the potential to remain economically feasible.

Acknowledgements We thank Felix Herzog (Agroscope) and Mareike Jäger (formerly Agridea, now ZHAW) for providing access to AFS farmers and Adrian Meierhofer, Christian Guyer and Pius and Doris Strickler for their permission and help to grow barley on their fields. We also thank Austen Lynn, Matthieu Sparr, Ahmed Abuyousef-Gmeiner, Dalil Yusef, Anita Vaccaro, Tobias Werner, Gitte Nenning, Lisa Kohler, Pawel Strzelczyk, Helga Palli and Kennedy Aigbe for their help during field work.

Funding Open access funding provided by Swiss Federal Institute of Technology Zurich.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

References

Anderson JM and Ingram JSI (1993) Tropical soil biology and fertility. A handbook of methods. CAB International, Wallingford, Oxon, UK. 221 p

BAFU (ed) (2017) Boden in der Schweiz. Zustand und Entwicklung. Stand 2017. Bundesamt für Umwelt, Bern. Umwelt-Zustand Nr. 1721: 86 p.

Batish DR, Kohli RK, Jose S, Singh HP (2008) Ecological basis of agroforestry. 1st edition. CRC Press, 400 p

Bommarco R, Kleijn D, Potts SG (2013) Ecological intensification: harnessing ecosystem services for food security. Trends Ecol Evol 28(4):230–238. https://doi.org/10.1016/j.tree.2012.10.012

Bundesamt für Statistik (BfS) (ed) (2021) Klimadaten: Sonnenscheindauer, Niederschlag, Temperatur und Neuschnee. BFS-Nummer je-d-02.03.03.02

Cannell MGR, van Noordwijk M, Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agroforest Syst 34(1):27–31. https://doi.org/10.1007/BF00129630

Carrier M, Gonzalez FAR, Cogliastro A, Olivier A, Vanasse A, Rivest D (2019) Light availability, weed cover and crop yields in second generation of temperate tree-based intercropping systems. Field Crop Res 239:30–37. https://doi.org/10.1016/j.fcr.2019.05.004

Charbonnier F, Roupsard O, le Maire G, Guillemot J, Casanoves F et al (2017) Increased light-use efficiency sustains net primary productivity of shaded coffee plants in agroforestry system. Plant, Cell Environ 40:1592–1608. https://doi.org/10.1111/pce.12964

Dagar JC, Tewari VP (eds) (2017) Agroforestry. Springer, Anecdotal to Modern Science

de Mendiburu F (2020) agricolae: Statistical procedures for agricultural research. https://cran.r-project.org/web/packages/agricolae/index.html.

Dufour L, Metay A, Talbot G, Dupraz C (2013) Assessing light competition for cereal production in temperate agroforestry systems using experimentation and crop modelling. J Agro Crop Sci 199(3):217–227. https://doi.org/10.1111/jac.12008

Dupraz C, Blitz-Frayret C, Lecomte I, Molto Q, Reyes F, Gosme M (2018a) Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system. Agrofor Syst 54(2–3):245. https://doi.org/10.1007/s10457-018-0214-x

Dupraz C, Lawson GJ, Lamersdorf N, Papanastasis VP, Rosati A, Ruiz-Mirazo J (2018b) Temperate agrorestry: the European way, 2nd edition. In: Gordon A, Newman SM, Coleman B (eds) Temperate agroforestry systems, 2nd edn. CAB International, Wallingford, p 368

Fan J, McConkey B, Janzen H, Townley-Smith L, Wang H (2017) Harvest index–yield relationship for estimating crop residue in cold continental climates. Field Crop Res 204:153–157. https://doi.org/10.1016/j.fcr.2017.01.014

Fox J, Weisberg S (2019) An R Companion to Applied Regression, 3rd edition. Sage, Thousand Oaks CA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/index.html.

Friday J, Fownes J (2002) Competition for light between hedgerows and maize in an alley cropping system in Hawaii, USA. Agrofor Syst 55:125–137. https://doi.org/10.1023/A:1020598110484

Gillespie AR, Jose S, Mengel DB, Hoover WL, Pope PE, Seifert JR et al (2000) Defining competition vectors in a temperate alley cropping system in the midwestern USA: 1 production physiology. Agrofor Syst 48:25–40. https://doi.org/10.1023/A:1006285205553

Graves AR et al (2009) Farmer Perceptions of Silvoarable Systems in Seven European Countries. In: Rigueiro-Rodróguez A, McAdam J, Mosquera-Losada MR (eds) Agroforestry in Europe: Advances in Agroforestry, vol 6. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8272-6_4

Gubler A, Wächter D, Schwab P, Müller M, Keller A (2019) Twenty-five years of observations of soil organic carbon in Swiss croplands showing stability overall but with some divergent trends. Environ Monit Assess 191(5):277. https://doi.org/10.1007/s10661-019-7435-y

Hoyle A, Brennan M, Pitts N, Jackson GE, Hoad S (2020) Relationship between specific weight of spring barley and malt quality. J Cereal Sci. https://doi.org/10.1016/j.jcs.2020.103006

Jäger M, Herzog F (2017) Agroforestry with standard fruit trees in Switzerland. Improving production and enhancing biodiversity. https://www.agforward.eu/index.php/en/Innovation-leaflets.html. Accessed 30 June 2021

Jose S, Gillespie AR, Pallardy SG (2004) Interspecific interactions in temperate agroforestry. Agrofor Syst 61–62(1–3):237–255. https://doi.org/10.1023/B:AGFO.0000029002.85273.9b

Kanzler M, Böhm C, Mirck J, Schmitt D, Veste M (2019) Microclimate effects on evaporation and winter wheat (*Triticum aestivum* L.) yield within a temperate agroforestry system. Agroforest Syst 93(5):1821–1841. https://doi.org/10.1007/s10457-018-0289-4

Kho RM (2000) A general tree-environment-crop interaction equation for predictive understanding of agroforestry systems. Agr Ecosyst Environ 80(1–2):87–100. https://doi.org/10.1016/S0167-8809(00)00136-5

Li F, Meng P, Fu D, Wang B (2008) Light distribution, photosynthetic rate and yield in a Paulownia-wheat intercropping system in China. Agrofor Syst 74(2):163–172. https://doi.org/10.1007/s10457-008-9122-9

Lovell ST, Dupraz C, Gold M, Jose S, Revord SE, Wolz KJ (2017) Temperate agroforestry research: considering multifunctional woody polycultures and the design of long-term field trials. Agrofor Syst 263:151. https://doi.org/10.1007/s10457-017-0087-4

Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H et al (2009) Mixing plant species in cropping systems: concepts, tools and models. A review. Agron Sustain Dev 29(1):43–62. https://doi.org/10.1051/agro:2007057

Mantino A, Volpi I, Micci M, Pecchioni G, Bosco S, Dragoni F et al (2020) Effect of tree presence and soil characteristics on soybean yield and quality in an innovative alley-cropping system. Agronomy 10(1):52. https://doi.org/10.3390/agronomy10010052

MeteoSchweiz (2020) Klimareport 2019. Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Zürich. 96 p

Miller AW, Pallardy SG (2001) Resource competition across the crop-tree interface in a maize-silver maple temperate alley cropping stand in Missouri. Agrofor Syst 53:247–259. https://doi.org/10.1023/A:1013327510748

Ong CK, Black CR, Wilson J (2015) Tree-crop-interactions-agroforestry-in-a-changing-climate. Agroforestry in a Changing Climate. CAB International.

Pardon P, Reubens B, Mertens J, Verheyen K, de Frenne P, de Smet G et al (2018) Effects of temperate agroforestry on yield and quality of different arable intercrops. Agric Syst 166:135–151. https://doi.org/10.1016/j.agsy.2018.08.008

Reynolds PE, Simpson JA, Thevathasan NV, Gordon AM (2007) Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario. Can Ecol Eng 29(4):362–371. https://doi.org/10.1016/j.ecoleng.2006.09.024

Sereke F, Graves AR, Dux D, Palma JHN, Herzog F (2015) Innovative agroecosystem goods and services: key profitability drivers in Swiss agroforestry. Agron Sustain Dev 35(2):759–770. https://doi.org/10.1007/s13593-014-0261-2

Smith J, Pearce BD, Wolfe MS (2012) A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renew Agric Food Syst 27(04):323–332. https://doi.org/10.1017/S1742170511000597

Smith J, Pearce BD, Wolfe MS (2013) Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renew Agric Food Syst 28(1):80–92. https://doi.org/10.1017/S1742170511000585

Taiz L, Zeiger E (eds) (2010) Plant physiology, 5th edn. Sinauer Associates Inc, Sunderland, p 782

Vandermeer J (1989) The ecology of intercropping. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511623523

Yun L, Bi H, Tian X, Cui Z, Zhou H et al (2011) Main interspecific competition and land productivity of fruit-crop intercropping in Loess Region of West Shanxi. Chin J Appl Ecol 22:1225–1232

Žáková M, Benková M (2006) Characterization of spring barley accessions based on multivariate analysis. Commun Biometry Crop Sci 1(2):124–134

Zamora DS, Jose S, Jones JW et al (2009) Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO. Agrofor Syst 76:423–435. https://doi.org/10.1007/s10457-008-9166-x