Agriculture, Ecosystems and Environment 361 (2024) 108814

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Phenology and radial growth of poplars in wide alley agroforestry systems and the effect on yield of annual intercrops in the first four years of tree age

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A R T I C L E I N F O

Keywords:
common wheat
dendrometers
diameter at breast height
"high environmental sustainability" clones
silvoarable systems
soybean

A B S T R A C T

Silvoarable agroforestry systems have the potential to combat the negative effects of climate change while also enhancing productivity per unit land. Although the growth rate of large-spaced trees remains poorly investigated and the yield of annual intercrops uncertain, silvoarable agroforestry systems with poplar are receiving an ever-growing interest. This study assessed the growth of the new HES (High Environmental Sustainability) poplar clone, Moncalvo, arranged in 40-m spaced parallel alleys with a density of 35 trees ha^{-1} (SA, silvoarable). Their growth was compared to those cultivated in a specialized poplar plantation (C, control) with 277 trees ha^{-1}, and the agronomic impact on wheat and soybean as intercrops was explored. Measurements took place between 2018 and 2021 during the first 4 years, which represents the midpoint of the expected poplar rotation. Here it was demonstrated that at the end of the investigated period, diameter at breast height was significantly greater (23.8 vs. 20.5 cm, +16%) and the plant height lower (14.3 vs. 15.5 m, −8%) in poplar grown in SA as compared to those in C, likely due to reduced intraspecific competition for environmental resources. In SA, seasonal tree phenology was delayed by approximately two weeks in spring, possibly due to the high sensitivity of poplar to low soil water content and cooler night air temperatures in springtime. The grain yield of wheat was not impaired by tree shading but instead occasionally improved when neighboring the poplar alley (e.g., year 2021: +28% at 12 m from the tree row vs. full sun conditions), while soybean yield was generally reduced (maximum −38% at 6 m from the tree row). This study innovatively studied the growth response of HES poplar clones in silvoarable systems by providing valuable insights into the growth dynamics of trees grown in combination with field crops. It is concluded that poplars in wide spaced alleys of silvoarable systems in temperate climates grow faster than poplars in plantations of high population density due to enhanced access to resources, while future investigations will allow for the identification of clone-specific rotation durations. In the arable tree interrow, winter crops more readily benefit from such agroforestry system than summer crops due to reduced cycle overlap and light competition with the tree canopy.

1. Introduction

Silvoarable systems consist of widely spaced trees intercropped with annual or polyannual crops and have been applied for centuries as traditional land use systems in temperate climates (Eichhorn et al., 2006; Smith, 2010). Among them, alley-cropping systems consist of trees planted along parallel rows regularly alternated with arable fields, representing the most common design in high productive agricultural areas. The relatively recent shift to intensive agriculture in industrialized countries accelerated in the 1960 s when trees were removed from agricultural lands at great rates to facilitate agricultural mechanization. This has had a negative impact on both biodiversity and ecosystem services delivery, while also reducing the carbon storage potential of agro-systems (Paris et al., 2019; Pantera et al., 2021). With the

Abbreviations: C, Control poplar plantation; DBH, Diameter at breast height; FS, Full sun conditions; H, Tree height; ½ H, Half of the tree height; HDR, Height-to-diameter ratio; HES, High Environmental Sustainability poplar clones; MDS, Maximum daily shrinkage; TKW, Thousand kernel weight; VPD, Vapor pressure deficit.

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https://doi.org/10.1016/j.agee.2023.108814
Received 6 February 2023; Received in revised form 5 November 2023; Accepted 10 November 2023
Available online 29 November 2023

awareness of such problems, global policies are currently trying to address the environmental issues associated with intensive agricultural systems, highlighting the need for more sustainable agricultural practices such as agroforestry (FAO, 2013; Santiago-Freijanes et al., 2018; Kumar & Singh, 2020). Agroforestry can provide both wood products and food from the same land while simultaneously improving the use-efficiency and allowing for the conservation of natural resources (Nerlich et al., 2013; Smith et al., 2012; FAO, 2013; Lawson et al., 2019; Propopulus, 2021). Despite many environmental benefits, farmers are currently still reluctant to adopt these farming systems (Sollen-Norlin et al., 2020). According to the most recent survey involving a large panel of >180 European farmers by Rois-Dìaz et al., (2017), concern among farmers arises from intra-species competition and the concurrent potential reduction in intercrop yields, the lack of sufficient knowledge on the optimal design and management strategies to adopt for the woody component of the system, and the marketability and profitability of the derived timber.

To efficiently introduce trees into agroforestry systems and minimize their impact on intercrop yields, investigations on tree growth and their interaction with environmental resources, particularly solar radiation, is necessary (Reisner et al., 2007; Eichhorn et al., 2006). As such, appropriate tree-crop combination, design (i.e., row orientation and spacing), and management (pruning) should be carefully planned. North-south oriented tree rows are less competitive in terms of solar radiation, than east-west rows in temperate regions (Dufur et al., 2013), and pruning lower branches from the second year onwards allows for a knot-free timber production while contemporaneously increasing light availability for the intercrops (Chauhan et al., 2011). Choosing deciduous trees with a phenology compatible with the intercrops' seasonability is also a key factor in maximizing radiation use. For instance, Chauhan et al. (2011) suggest that poplar-based agroforestry systems allow the understory winter cereals to complete their vegetative growth and enter the reproductive phase before complete tree foliation, thus minimizing competition for solar radiation.

Poplar is a relatively common tree species in Europe, and silvoarable systems based on poplar are expected to have the largest potential cultivation area (FAO, 2016). Indeed, it has a high capacity to mitigate nitrate leaching and eventually reduce soil erosion, both of which are issues that are currently relevant in large parts of the European arable land (Reisner et al., 2007). Poplar also exhibits a fast growth rate, which allows for accumulation of high carbon stocks in the short term, up to 25 t CO_2 ha^{-1} y^{-1} (Chiarabaglio et al., 2014a; 2014b; Corona et al., 2018; Propopulus, 2021). In addition, poplar wood is appreciated for being light, easy to work, and having excellent mechanical properties, and is therefore highly demanded by numerous industries.

In recent years, innovation in this sector has mainly focused on the release of several poplar clones, of the High Environmental Sustainability (HES) type, which possess high resistance to crown diseases and parasites. These clones therefore exhibit a great potential to drastically reduce chemical treatments, thus minimizing management costs and environmental impacts (Coaloa et al., 2016). Their adaptation to low water availability, a growing issue in Europe, remains poorly explored, however (Paris et al., 2022).

Poplar is currently a good candidate for agroforestry systems of temperate regions, but little information is currently available on the impact of the alley design on the growth of this species as compared to trees cultivated in conventional high-population plantations. Furthermore, knowledge on the effect on the yield of arable crops cultivated in the intercropping areas of poplar also remains limited. In this framework, we assessed these still poorly understood variables in a new HES poplar clone grown in an agroforestry system and compared it to the findings of polar individuals grown in conventional monoculture plantations with high tree density. The investigations took place in Ceregnano (Rovigo, NE Italy) between 2018 and 2021 in the first 4 years of the tree's age. This timespan roughly corresponds to the midway point in the trees expected full cycle (commonly 10 years) when the optimal commercial stem diameter in a conventional poplar plantation under the pedoclimatic conditions of NE Italy is reached. As such, the objectives of the study were to: *(i)* assess and compare the dynamics of tree growth (height and diameter at breast height) of large-spaced poplars in agroforestry to those of trees in a neighboring poplar plantation grown in a high density setting; *(ii)* study poplar leaf phenology and radial growth, which included assessment of water sensitivity at the 4th year through maximum daily shrinkage analysis; and *(iii)* quantify yield and quality response of annual intercrops, in particular winter wheat and soybean, at different distances from the tree row.

2. Materials and methods

2.1. Site description

The trial was carried out between 2018 and 2021 at the “Sasse Rami” pilot farm of Veneto Agricoltura Agency, located in Ceregnano (Rovigo, NE Italy, 45° 05’06” N, 11° 87’ 66” W; 1 m a.s.l.). In February 2018, 14 poplar clones (*Populus* × *canadensis* Moench) of the HES (High Environmental Sustainability) type, selected by the CREA Forest and Wood Research Centre of Casale Monferrato (Alessandria, Italy), were planted as rods, both in a specialized poplar plantation (3 blocks of 9 trees per clone) and in a nearby alley-cropping system (one clone per row). Poplar rods were approximately 5–6 m long and 7–8 cm in diameter in both systems. HES clones are highly resistant to several crown diseases, i.e., Marssonina leaf spot, spring leaf and shoot blight, woolly poplar aphids, leaf rusts, cortical necrosis, brown spots, and leaf mosaic. Among the available clones, only Moncalvo, which is early sprouting, was considered in this study. The tree row of the agroforestry system was very close to the poplar plantation (~200 m to the east).

The soil at the site was very similar between the poplar plantation and the silvoarable system and was characterized as alluvial with clay loam texture (sand 22%; silt 47%, clay 31%) and with a pH of 8.0. The water table varied within a 1.5–2 m depth interval throughout the year. The local climate is temperate humid subtropical (*Cfa*) according to the Köppen classification, with high air humidity, an average yearly temperature of 13.7 °C, and a mean annual precipitation of 727 mm (1994–2022 period). The growing season is around 254 days, from 10 March to 19 November (arpa.veneto.it, weatherspark.com).

2.2. Experimental design

The specialized poplar plantation had a 6×6 m block design, translating into 277 trees ha^{-1}, and was assumed as the control (C). The soil was never fertilized, neither prior plantation nor annually post plantation. The ground was covered by natural grasses which were mowed once a year in the springtime and left on the soil surface as natural mulch. The alley-cropping silvoarable system (SA) had north-south oriented tree rows 40-m apart which were placed along 140-m long agricultural drainage ditches. The poplar trees had an intra-row of 6 m, resulting in a population density of 35 trees ha^{-1}. The arable zones between tree rows were cultivated with a wheat-soybean rotation. As regards tree management, to obtain a log suitable for rotary cut veneering, pruning was carried out once a year during winter in the poplar plantation, and twice a year during winter and summer in the SA to reduce tree vigor. Chemical treatments with deltamethrin against xylophages were applied in the first year to ensure appropriate plant protection and establishment.

The allometric parameters were monitored on 14 individual poplar trees per treatment (C and SA) and radial growth on 3 trees per treatment.

In the SA system, poplar trees were intercropped with winter common wheat (Triticum aestivum L.) and soybean [Glycine max (L.) Merr.] according to the selected year (Table 1; Figure SI.1).

For the initial wheat cultivation, the soil of the SA system was ploughed to a depth of 25 cm in October 2018, burying the crop residues

Table 1
Variety, sowing date and density, and harvest time of crops cultivated in the silvoarable treatment (SA) from 2018 to 2021.

Season	Crop	Variety	Sowing time	Sowing density	Harvest time
2018–2019	Winter common wheat	Arkeos (*CGS Sementi, IT*)	22 October 2018	250 kg ha^{-1}	28 June 2019
2020	Soybean	P21T45 (*Corteva, IT*)	27 May 2020	44 seeds m^{-2}	3 October 2020
2020–2021	Winter common wheat	Arkeos (*CGS Sementi, IT*)	30 October 2020	240 kg ha^{-1}	26 June 2021

of the previous maize crop. It was harrowed twice before sowing the biscuit-making variety Arkeos of common wheat in rows 10 cm apart. During the wheat cycle, N was supplied as ammonium nitrate (beginning of March) and urea (mid-April), for a total amount of 146 kg N ha^{-1}. Wheat was protected against weeds with application of a post-emergence herbicide (a.i. Clodinafop-propargyl + Cloquintocet-mexyl + Florasulam + Pinoxaden) at the end of March, and against insects (a.i. lambda-Cyhalothrin) and fungal pathogens (a.i. Prothioconazole + Tebuconazole) in mid-May, following local recommendations.

After the first cycle of wheat, the soil was grubbed twice (November 2019, March 2020) to a depth of 30 cm, and harrowed in May 2020 prior to soybean sowing. The fertilizers applied to wheat consisted of 28, 84 and 84 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, which were incorporated into the soil by harrowing. Soybean var. P21T45 was sown at the end of May, at a density of 44 plants m^{-2} through precision sowing. The crop was protected against weeds by pre-emergence (a.i. clomazone + pendimethalin + metribuzin) and post-emergence herbicides (a.i. cycloxydim), the latter at mid-June 2020.

To sow wheat in 2020 (rows 15-cm apart), the soil was grubbed, harrowed, and fertilized with 24, 72 and 72 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. Nitrogen was also dress applied with ammonium nitrate at the beginning of March and with urea in mid-April, for a total amount of 170 kg N ha^{-1}.

Upon reaching maturity, each intercrop was sampled (1 m^2 area) along transects orthogonal to the poplar rows in both the eastern and western direction. Sampling took place at three different distances from the trees, referred to as ½H, H and FS, where H was equal to the poplar height (12 m in 2021) and FS ("full sun" conditions) referred to the middle of the arable zone, namely 20 m away from the rows of poplar (Fig. 1). FS sampling points were considered controls as they were minimally subjected to tree shading and not subjected to interspecific water or nutrient competition. The transects were replicated 3 times for each intercrop at both the eastern and western side of the tree rows, with a total of 18 sampling points. The conditions of each point are comparable, since they have been accurately identified to avoid confounding factors (i.e., tire tracks, and overlapped fertilization zones).

2.3. Climatic and microclimatic parameters

Climatic data were available from the weather station in Villadose (Rovigo, Italy) located approximately 3 km from the test site. In 2021, air temperature (°C) and relative humidity were also recorded by sensors installed in the SA system at a height of 2 m on the north-facing side of a poplar stem among the monitored ones and used to calculate the vapor pressure deficit (VPD, kPa). Soil water content (%) in the top 30-cm soil layer was also measured in both the C and SA systems every 15 min between March and November 2021 using a time domain reflectometer (TDR Campbell Sci. Ltd.). These sensors were placed at the central position between two neighboring trees along the poplar row in both C and SA systems. Two data acquisition systems (CR1000, Campbell Scientific, Inc., Logan, UT, USA), one for the C and one for the SA, were used for data recording. All sensors were connected to dataloggers via buried cables.

2.4. Poplar growth and phenology

2.4.1. DBH, height and volume

Diameter at breast height (DBH) and tree height were monitored yearly at the end of the growing season on 14 trees from 2018 to 2021. DBH was measured with a tree caliper as the average of two orthogonal measurements, and tree height with a Suunto clinometer (PM-5/360 PC). This allowed the competition index Height-to-Diameter ratio to be calculated (Opio et al., 2000). The cumulated volume of the wood stem biomass at the 4th year was estimated using the following equation (Cannell, 1984):

$$V = \frac{D^2}{4} \times \pi \times H \times f$$

where D is the DBH, H the tree height, and f the timber form factor. An f value of 0.40 was chosen as an intermediate value between 0.38 (beginning of the cycle) and 0.42 (end of the cycle).

2.4.2. Phenology

Both vegetative and reproductive phases of poplars were monitored through field surveys and photos from the end of February to the end of July 2021 in both the C and SA systems. Data were collected according to the sequential phenological scale GFI provided by Malossini (1993) (Table SI.1). The scale describes the course of the vegetative phase from 0 (buds closed) to 14 (leafless tree) and the reproductive phase ranging from 0 (buds or catkins present but underdeveloped) to 12 (few residual fruits remained). A phenological stage was assigned when clues of a certain stage were visible in over 50% of the crown.

2.4.3. Radial growth and maximum daily shrinkage

Radial growth of the poplars was monitored with point dendrometers (Linear Motion Potentiometers, Bourns-3048) during the 2021 growing

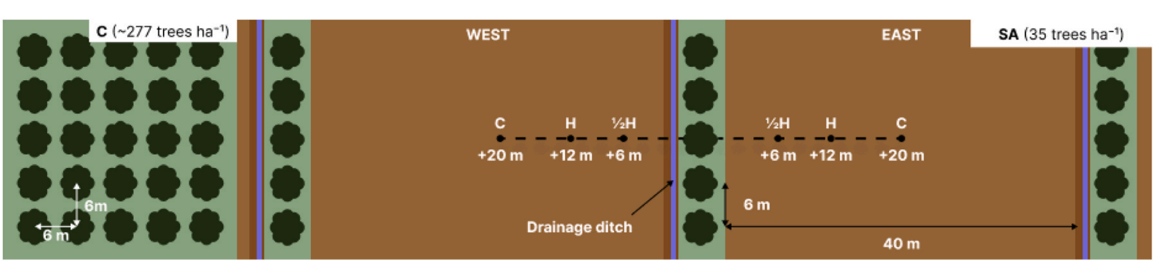

Fig. 1. Layout of the study area comparing poplar trees in a specialized poplar plantation (C, left) and an alley-cropping system (SA, right), with the sampling positions in the intercrops along a transect orthogonal to the poplar row at ½H, H and FS, where H is tree height (12 m) and FS ("full sun") is the center of the arable zone at 20 m of distance, towards both the eastern and western side. The distance between the tree base and the arable zone was 1 m to the east, and around 2 m to the west (including the width of the drainage ditch).

season, from March 12 to November 11, on 3 trees in both growing systems. The dendrometers were installed at a height of about 1.3 m on the north-facing side of the stem, and subsequently covered with a plastic sheet to protect against precipitation. Each dendrometer consisted of a stainless-steel plate with a linear motion potentiometer positioned perpendicularly to the stem. Potentiometers had a 5-kΩ resistance, 10.16 mm electrical travel, ±5% independent linearity, infinite resolution, 1000 ppm $^{\circ}C^{-1}$ temperature coefficient and a long mechanical life. Since poplar is a fast-growing species, dendrometers were reset on June 9 as the maximum reading capacity was approaching. Stem growth data were collected at 15-minute interval by means of two data acquisition systems (CR1000 Datalogger, Campbell Scientific, Inc., Logan, UT, USA).

The data of stem growth were fit into daily radial growth curves for each tree. The Gompertz model was used to describe the growth processes, allowing for high determination coefficients, as follows:

$$y = A\exp\left(-e^{\beta-\kappa t}\right)$$

where *y* is the stem diameter increment (mm); *t*, time expressed as day of the year (DOY); *A*, maximum y value (asymptote); β, placement parameter for x-axis; κ, growth rate at the flex point (Rossi et al., 2005). The inflection point corresponds to the maximum growth rate at time T_p, which is related to the placement parameter β as follows:

$$\beta = T_p \quad \kappa$$

Onset and cessation of growth were estimated based on the Gompertz function when 5% and 95%, of annual growth were reached, respectively (Van der Maaten et al., 2016; Cruz-Garcìa et al., 2019). As such, growth duration can be calculated as the difference between onset and cessation.

Besides the radial increment, dendrometers can also detect fluctuations in the stem diameter driven by soil hydration and dehydration cycles and by evapotranspiration dynamics that lead to stem swelling and shrinkage. To detect such swelling and shrinkage, the linear stem growth trend was subtracted from the seasonal stem growth curve. Thus, the Maximum Daily Shrinkage (MDS) was calculated as the difference between the maximum and minimum daily stem diameter (Ortuño et al., 2006). The greater the MDS, the greater the stem fluctuation.

To detect the correlation between daily stem fluctuations and soil water content, the net mean daily stem growth (after deduction of the seasonal growth trend) was calculated. Thereby, the impact of precipitation events on trees, i.e., the water absorption capacity in both the C and SA system could be analyzed.

2.5. Vegetative growth and grain yield of annual intercrops

2.5.1. Leaf vegetational index NDVI of wheat crop in 2021

From April 20 to June 16 of 2021, the normalized difference vegetation index (NDVI) was measured every ten days on the wheat canopy in the SA system at the ½H, H, and FS sampling points by means of an active handheld Greenseeker spectrometer (Ntech Industries, Ukiah, CA, USA). The sensor measures the canopy reflectance at wavelengths 590 nm (refRED) and 880 nm (refNIR) and provides a ratio as follows:

$$NDVI = \frac{refNIR - refRED}{refNIR + refRED}$$

NDVI provides an accurate indication of leaf chlorophyll abundance, which correlates with plant health and soil coverage by green vegetation. The index ranges from 0 to 1.

2.5.2. Grain yield and quality

The grain yield of annual intercrops grown in the SA system was measured at each sampling point (1 m^{-2} area; n = 3) upon reaching maturity. The yield was quantified by manually collecting all the plants and then threshing them by means of a stationary thresher. For each treatment/replicate, three samples of 1000 grains were weighed for determining the thousand kernel weight (TKW). The straw biomass at harvest (dry weight) was determined after oven drying (48 h at 105 °C). Nitrogen concentration in the grains of wheat was determined according to the *Kjeldahl* method. The grain protein content was derived by multiplying the % of N by 5.7 and 6.25 for wheat and soybean, respectively (FAO, 2003).

2.6. Statistical analysis

To compare the growth, diameter, and height of poplars in the two treatments, a two-sample *t*-test ($p \leq 0.05$) was used, while for crop analysis ANOVA ($p \leq 0.05$) together with the Tukey-HSD test were used for multiple comparisons of means.

3. Results

3.1. Climatic conditions during the trial

During the first year of trial (2018), the annual mean air temperature was at least 0.9 °C higher than the historical mean 1994–2022 (Table 2, Fig. SI.2), while rainfall was more abundant in the intervals February-March (209 mm vs. 99 mm) and September-October (205 mm vs. 142 mm) (Table 2, Fig. SI.3). The growing season of the first wheat was characterized by an initial dry period from November 2018 to March 2019 (−121 mm: 163 mm vs. 284 mm), followed by a cold and rainy spring (April-May).

The effects of climate change have been acutely evident from the summer of 2019 to February 2020, with the average monthly temperature being ~1.5 °C higher than the historical mean and high heterogeneity in the rainfall pattern.

The first half of 2020 was characterized by low rainfall (110 mm vs. 278 mm), while large parts of the growing season of soybean, that is from June to October 2020, witness precipitation slightly exceeding historical values. The temperature in this period was comparable to those of the recent past.

During the second growing season of wheat, from November 2020 to June 2021, the average monthly temperature was again ~2 °C higher than the historical mean in December, February and June, and lower from March to May, with the highest observed in April (−1.9°C).

The year 2021 was characterized by extreme dryness, with 427 mm precipitation, much below the 727 mm average. Indeed, all of North Italy experienced significant water scarcity during the springtime of 2021.

3.2. Poplar tree growth

Poplar diameter at breast height (DBH) in the C system increased by 13.96 cm, from 6.51 cm (±0.16 S.E.) in end-2018 to20.47 cm (±0.25) in end-2021, while in the SA system it increased by 15.52 cm, from 8.28 cm (±0.16) to 23.80 cm (±0.40). Overall, poplar DBH in SA was significantly greater compared with C at the end of all the four seasons ($p \leq 0.001$). The only exception was given by 2019 when a slightly lower value was measured in the SA system, although not significant (Fig. 2). However, it appears that the relative difference between the growing systems reduced with tree age: in 2018 the DBH was 27% greater in SA than in C ($p \leq 0.05$), while at the end of the 2021 growing season, this value had fallen to 16% ($p \leq 0.05$). The average annual DBH increment was in both cases high; +4.65 cm in C and +5.17 cm in SA, confirming that poplar is a fast-growing species. A rapid expansion in DBH occurred earlier in C, i.e., between 2018 and 2019 (+5.79 cm), than in SA, which witnessed its greatest DBH growth between 2019 and 2020 of +8.26 cm.

The dynamics of tree height was also different between SA and C. The height of trees in the C system increased from 7.64 m in end-2018 to 15.53 m in end-2021 (+7.89 m). At the beginning, the height of the poplars in SA was comparable to that of C, while in 2021 it was

Table 2
Monthly and annual temperature and precipitation in the experimental period 2018–2021 compared with the historical mean 1994–2022.

	Monhtly precipitation (mm)					Average monthly temperature (°C)				
month	2018	2019	2020	2021	1994–2022	2018	2019	2020	2021	1994–2022
Jan	12	19	25	45	40	5.4	2.3	3.7	2.9	3.0
Feb	96	28	7	11	49	3.7	5.9	7.4	6.9	4.9
Mar	113	15	52	8	51	7.3	9.8	9.3	8.4	8.8
Apr	15	107	8	64	63	15.9	13.2	14.0	11.3	13.2
May	59	162	17	87	76	19.8	15.0	18.6	16.6	18.3
Jun	68	4	85	15	63	22.8	25.2	21.9	24.0	22.4
Jul	48	93	56	35	45	24.9	25.2	24.2	24.6	24.2
Aug	55	18	77	22	55	24.9	24.6	24.2	23.2	23.6
Sep	112	61	31	27	69	20.3	19.5	20.1	19.8	19.0
Oct	93	44	95	7	73	15.8	15.9	13.5	13.3	14.3
Nov	80	160	14	63	88	11.2	10.7	8.6	9.6	8.9
Dec	22	96	106	44	57	3.3	5.7	6.0	4.2	4.0
	Annual precipitation (mm)					Annual mean temperature (°C)				
	772	807	573	427	727	14.6	14.4	14.3	13.7	13.7

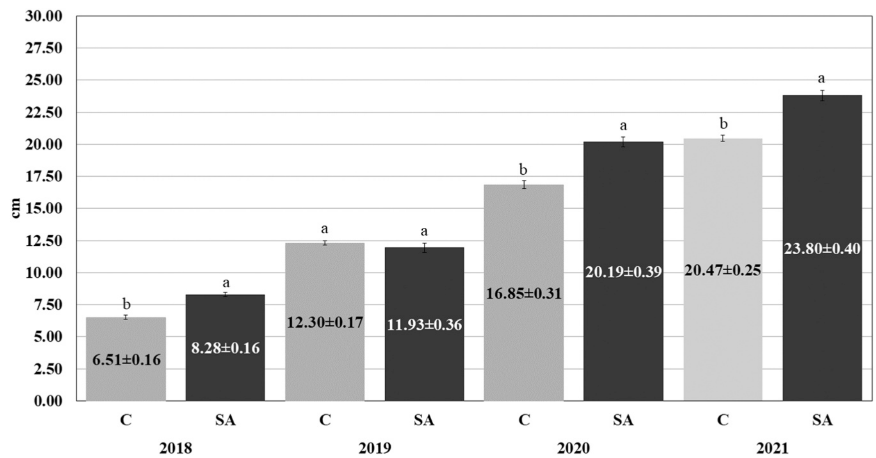

Fig. 2. Diameter at breast height (DBH; mean ± S.E.; n=14) of poplar trees clone Moncalvo in the specialized plantation (C) and the silvoarable system (SA) at the end of each growing season from 2018 to 2021. For each year, different letters above histograms indicate significant difference between treatments according to the Welch two sample t-test ($p < 0.05$), while numbers inside histograms represent the mean ± standard error.

significantly ($p \leq 0.05$) lower in SA than in C (14.25 m vs. 15.53 m; −8%) (Fig. 3). This led to a significantly greater height-to-diameter ratio (HDR) in the poplars grown in C as compared to SA (0.76 vs. 0.60; $p \leq 0.05$). In both cases, a rapid increase in tree height was observed between 2019 and 2020, with +4.07 m in C and +4.30 m in SA.

In 2021, at the end of the 4th vegetative season, the stem volume of poplars was significantly higher in SA as compared with C (0.26 m^3 $tree^{-1}$ vs. 0.20 m^3 $tree^{-1}$, $p \leq 0.05$), although per hectare C had much

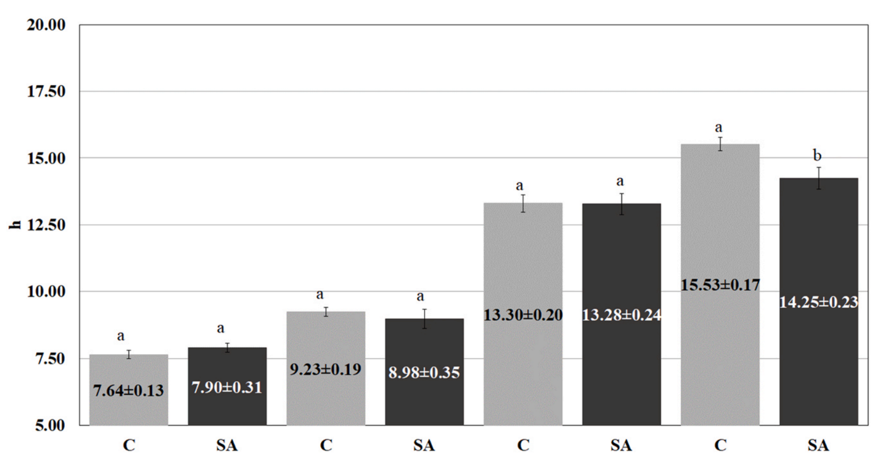

Fig. 3. Height of poplar trees clone Moncalvo (mean ± S.E.; n=14) in the specialized poplar plantation (C) and the silvoarable system (SA) at the end of each growing season from 2018 to 2021. For each year, different letters above histograms indicate significant difference between treatments within the same year according to the Welch two sample t-test ($p < 0.05$).

larger values than SA (9.09 m^3 ha^{-1} vs. 55.15 m^3 ha^{-1}) (Fig. 4) as is to be expected with the greater population density.

3.3. Yield and quality of annual intercrops

The overall aboveground biomass (straw + grain) and grain yield of wheat cultivated in 2018–19 revealed slightly higher values at the H sampling point as compared to the FS sampling point. In fact, the biomass and grain yield were up to 10% and 4% greater, respectively ($p > 0.05$, n.s.), depending on the side of the tree row considered. Significant improvements for wheat in position H occurred in 2021, when the grain yield was enhanced by 28% on average, and the aboveground plant biomass by 21%, though significance occurred on the east side only ($p \leq 0.05$) (Table 3).

At ½H, the sampling position closer to the trees, plant biomass and grain yield showed similar results to FS in both years of wheat cultivation, with slight but not significant negative differences at the east side of the tree rows (−13% plant biomass, and −8% grain yield vs. FS; $p > 0.05$).

Unlike wheat, both aboveground plant biomass and seed yield of soybean were negatively affected by tree proximity, with significant reductions at the closest position ½H: plant biomass was reduced by 28% at the eastern side (n.s.), and by 48% at the western side of the tree line ($p \leq 0.05$), respectively. Similarly, seed yield was significantly reduced by 24% (East) (n.s.) and 43% (West) ($p \leq 0.05$). At distance H, a different response was revealed according to the side of the tree row, with slight decrease on the western side, and improved plant biomass (+8%) and seed yield (+16%) at the eastern side, but again not significantly vs. FS. As regards grain protein content of soybean, there were small, yet not significant positive variations in both H and ½H positions.

The thousand grain weight (TGW) in wheat showed lower values at position H in 2019 (−8% on East; $p \leq 0.05$), but significantly higher values in the interaction zone with trees in soybean (up to +16% vs. FS; $p > 0.05$) especially at ½H, showing an opposite trend compared to seed yield.

As regards the quality of wheat, small variations of grain protein content were observed in 2019 across different positions in the field, while in 2021, a large positive impact of the trees was evident. Values of grain protein in 2020–21 were considerably low, but a significant increase in protein accumulation rate was recorded in wheat growing near the tree row, i.e. at position H and ½H, particularly on the eastern side ($p \leq 0.05$).

3.4. Mid-term (4th growing season) assessment of poplars

3.4.1. Microclimate parameters

Precipitation of 328 mm were recorded from March to November 2021 in the 4th year age of poplars, mainly distributed in spring and autumn with daily peaks of 25–30 mm (Table 2, Fig. SI.3), a value approximately half of the mean recorded between 1994 and 2022 (583 mm).

In 2021, the highest maximum daily temperature occurred on August 15, while the lowest minimum value was measured March 21 (Figure SI.4). The daily mean vapor pressure deficit (VPD) ranged between 0.05 kPa and 2.04 kPa, with the highest values occurring at the end of June (2.04 kPa, 25.8 °C, 45.5% RH), mid-July (1.74 kPa, 26.9 °C, 57.2% RH), and mid-August (1.63 kPa, 28.6 °C, 68.2% RH). The soil water content in the top-30 cm layer along the tree row was higher in C than in the SA system during the whole season (Fig. 5). Soil water content ranged between 30% and 47% v/v in C, and between 20% and 43% in SA. Because both the C and SA systems are purely rain fed, peaks in soil water content corresponded to rainfall events, as follows: April 10 (26 mm) May 12 (16 mm), May 23 (30 mm), June 8 (12 mm), July 2 (15 mm) and August 30 (22 mm) (Fig. 5).

3.4.2. Leaf phenology of poplar

In 2021, the V02 stage, i.e., *buds swollen close to sprouting*, was achieved at the same time in both C and SA, namely on March 26. From the beginning of April onwards, a delay in the phenological development, ranging from one to two weeks of poplar trees in SA became evident (Fig. 6). The largest gap between C and SA was found in April (Fig. 7). During this month, the V05 phase (i.e., *young leaves with foliar limb extended*) was reached on April 9 in C, and two weeks later in SA. The V07 phase (i.e., *adult leaves - complete leaf expansion*) was instead reached one week later in SA as compared with C. The delay in the phenological development became less evident after April 23 and had disappeared completely by May 27 at V07.

3.4.3. Poplar radial stem growth and intercrop NDVI

The Gompertz function allowed accurate description of the dynamics of the stem radial growth during the 4th vegetative season (2021) of the poplars, and to derive key phases in both the C and SA system (Fig. 8). The time of radial growth onset was synchronized in the two systems, it being estimated to occur on April 14 and 15 in SA and C, respectively. On the contrary, the end of radial growth occurred 10 days earlier in SA, i.e. October 1 vs. October 10 in C. During the whole growing season, radial growth reached 20.45 mm in SA and 18.89 mm in C, allowing SA to exhibit a diametric annual increment of 40.90 mm, compared to 37.78 mm in C. In this way, SA had a diametric increment 3.12 mm greater than that of C, though not significant ($p > 0.05$), which mirrors the 3.33 mm difference in DBH (Fig. 2) measured by means of a less precise tool compared to the dendrometers. Data variability was much larger in C vs. SA (Fig. 8).

In 2020–21, poplars were intercropped with common wheat, whose NDVI dynamics were opposite compared to poplar radial growth. Indeed, a decline of leaf greenness associated with the initiation of

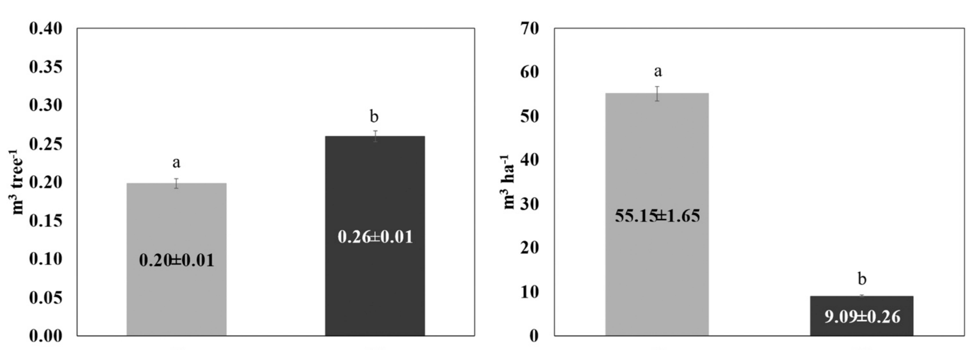

Fig. 4. Stem volume per tree (left) and per hectare (right) (mean ± S.E. n=14) in the specialized poplar plantation (C) and the silvoarable system (SA) of poplars clone Moncalvo at the end the 4th vegetative growth (2021). For each parameter, different letters indicate significant differences between treatments according to the Welch two sample t-test ($p < 0.05$).

Table 3
Aboveground dry biomass (straw + grain), grain yield and quality parameters (mean ± S.E.; n=3) of wheat (var. Arkeos) and soybean (var. P21T45) cultivated in the eastern and western arable zones of poplar rows in the silvoarable system (SA) from 2018 to 2021, at different distances from the N-S oriented tree row. DW: dry weight; TGW: Thousand Grain Weight. For each parameter and within each crop, different letters indicate significant difference among distances according to Tukey-HSD test (p < 0.05; highlighted in bold). For each parameter and intercrop, percentage of variation in comparison to crops growing in full sun (% var./FS) are provided for both the western and eastern arable zones.

Side	Distance	Aboveground plant biomass		Grain yield		TGW		Grain proteins	
		Mg ha^{-1}	% var./FS	Mg ha^{-1}	% var./FS	g	% var./FS	% DW	% var./FS
Common wheat (2018–19)									
East	½H	22.1 (±0.47) a	-8%	9.66 (±0.28) a	=	**36.3 (±0.82) a**	+4%	**13.1 (±0.33) ab**	-9%
	H	24.8 (±1.97) a	+3%	10.1 (±0.61) a	+4%	**32.3 (±0.54) b**	-8%	**14.2 (±0.34) a**	-1%
	FS	24.1 (±2.61) a	Ref.	9.66 (±1.38) a	Ref.	**35.0 (±2.23) ab**	Ref.	**14.4 (±0.44) a**	Ref.
West	½H	21.4 (±0.73) a	-4%	10.1 (±1.18) a	-1%	**36.1 (±0.50) a**	-1%	**12.4 (±0.90) b**	-2%
	H	24.6 (±1.94) a	+10%	10.4 (±1.13) a	+2%	**34.7 (±1.02) ab**	-4%	**13.5 (±0.11) ab**	+6%
	FS	22.3 (±2.35) a	Ref.	10.2 (±0.91) a	Ref.	**36.3 (±0.81) a**	Ref.	**12.7 (±0.90) ab**	Ref.
Soybean (2020)									
East	½H	**8.25 (±2.30) ab**	-28%	**3.52 (±0.83) ab**	-24%	165 (±4.30) a	+16%	43.6 (±0.33) a	+6.3%
	H	**12.3 (±2.13) a**	+8%	**5.40 (±0.75) a**	+16%	163 (±7.23) a	+15%	41.2 (±0.53) a	+0.5%
	FS	**11.4 (±1.61) a**	Ref.	**4.65 (±1.29) ab**	Ref.	142 (±11.82) a	Ref.	41.0 (±1.11) a	Ref.
West	½H	**6.02 (±1.44) b**	-48%	**2.65 (±0.80) b**	-43%	162 (±15.81) a	+14%	41.9 (±0.30) a	+1%
	H	**10.8 (±0.68) ab**	-6%	**4.49 (±0.63) ab**	-4%	145 (±8.10) a	+2%	42.1 (±0.50) a	+1.4%
	FS	**11.6 (±0.72) a**	Ref.	**4.68 (±0.70) ab**	Ref.	142 (±8.71) a	Ref.	41.6 (±1.74) a	Ref.
Common wheat (2020–21)									
East	½H	**15.8 (±0.95) bc**	-13%	**7.46 (±0.46) bc**	-8%	36.4 (±0.71) a	=	**10.2 (±0.43) ab**	+11%
	H	**22.6 (±1.28) a**	+23%	**10.6 (±0.65) a**	+27%	36.3 (±1.03) a	-0.3%	**11.1 (±0.63) a**	+21%
	FS	**18.3 (±1.88) b**	Ref.	**8.12 (±0.82) b**	Ref.	36.4 (±0.83) a	Ref.	**9.20 (±1.34) abc**	Ref.
West	½H	**13.0 (±0.59) c**	-2%	**6.13 (±0.31) bc**	+8%	37.0 (±0.40) a	=	**9.53 (±0.11) abc**	+26%
	H	**15.8 (±1.96) bc**	+19%	**7.36 (±0.99) bc**	+29%	35.2 (±0.70) a	-4.9%	**8.50 (±0.63) bc**	+13%
	FS	**13.3 (±0.89) c**	Ref.	**5.69 (±0.48) c**	Ref.	37.0 (±0.82) a	Ref.	**7.51 (±0.60) c**	Ref.

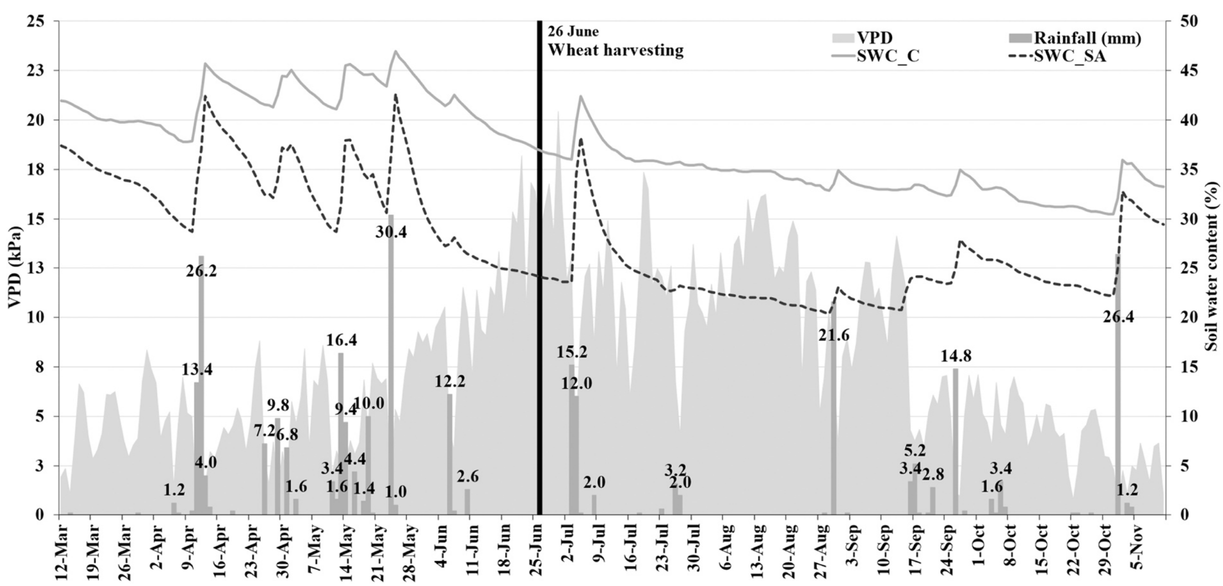

Fig. 5. Soil water content (SWC % v/v, top 0–30 cm layer) measured in the specialized poplar plantation (C) and in the silvoarable system (SA) along poplar rows during the 4th vegetative growth season of poplar from March 11 to November 10, 2021 (right y axis). Variations of vapor pressure deficit (VPD; kPa) within the SA system are shown as grey background (left y axis). Rainfall events are highlighted with grey bars. The black vertical bar indicates wheat harvest.

wheat leaf senescence was observed from end-May at all distances from the tree row, while concurrently, the maximum daily increment of poplar radial growth in both the C and SA system occurred (June 5; Fig. 8). As regards the effect of the distance from the poplar row on wheat, a longer maintenance of NDVI, i.e., leaf greenness, was recorded in the interaction zone with trees in positions H and ½H, as compared to FS. Indeed, during grain filling between end-May and mid-June, NDVI was significantly higher in the two shaded positions, with an average NDVI between H and ½H of 0.45 vs. 0.33 in the FS position ($p \leq 0.05$).

3.4.4. Maximum daily shrinkage (MSD) of poplar

The maximum daily shrinkage (MDS) of poplar stems during 2021 was comparable between the C and SA system between February to end May ($p > 0.05$; n.s.), suggesting a similar capacity in absorbing available soil water. Both C and SA exhibited an increase in MDS between April and June (Fig. 9), while later, from end-June to end-August, a greater increment of MDS was observed in C as compared to SA ($p \leq 0.05$). In particular, C revealed a MDS peak of 0.16 mm on July 30, as compared to 0.05 mm in SA.

By subtracting the seasonal growth trend to the stem daily fluctuations, it was possible to highlight the effects of soil water availability (Fig. 10). In general, the rehydration of poplar stem was consistently observed in correspondence with the main precipitation events on April 10, May 12, May 23, June 8, July 2, and August 30, which were related

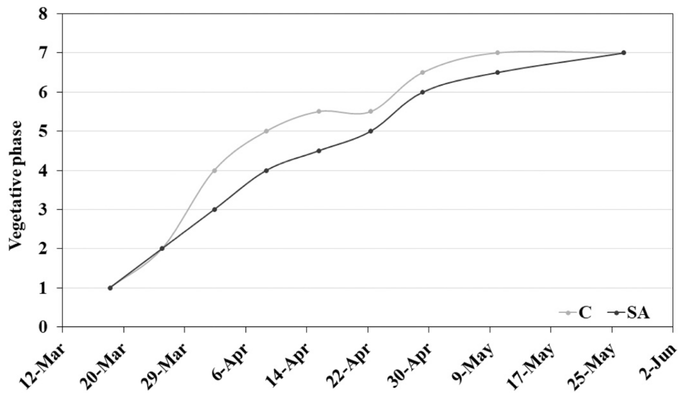

Fig. 6. Vegetative phenological stages according to the GFI scale (Giardini Fenologici Italiani) (Malossini, 1993; Table SI.1) of poplar trees clone Moncalvo (n=3) in the specialized poplar plantation (C) and the silvoarable system (SA) during 2021.

to the soil moisture dynamics (Fig. 5). The dynamics of radial stem fluctuations are in agreement with results on MDS: in C stems showed a greater capacity of rehydration/water retention than in SA, especially after the precipitation events of May 12 and July 2. The greatest differences between C and SA systems occurred after the precipitation of July 2 (15 mm), when in SA wheat was already harvested, and rehydration of poplars in SA was significantly lower than that observed in C ($p \leq 0.05$); for instance, on July 9, stem fluctuation was 0.002 mm in SA and 0.5 mm in C.

4. Discussion

4.1. Poplar growth

This study investigated the effect of an alley-cropping design on the growth of the new early-sprouting HES poplar clone Moncalvo by comparing it to the growth of a conventional poplar plantation. The effects of such alley-cropping design on the yield of two annual intercrops (both winter and summer) during the first half of the trees' rotation (4 years) was also investigated. Therefore, results from this trial provide useful information on the beginning of the poplar cycle, when poplars exert mild competition with the intercrop, but also give insights on future agronomic effects as the 4th year is considered the midway point of the expected rotation of this species in our environment for industrial uses. Indeed, from the 4–5th year of poplars, the tree crown volume is expected to stabilize, while the stem gradually approaches the final DBH. As such, we demonstrate that, within the first half of the poplars' rotation, the following effects are detectable: i) the annual growth rate of trees is higher in the SA system than in the C system; ii) annual poplar leaf expansion reaches completion later in SA, and the stems ceased to grow earlier in autumn; and iii) the effect of the poplars on intercrops yield is negative in soybean, while negligible (with young trees) or positive (with older trees) in winter wheat.

The annual growth rate of poplars was clearly characterized by the dynamics of DBH; poplars grew significantly wider stems in the sparse plantation scheme of SA compared to the high population density of the C system. As expected, the increasing intraspecific competition over time in the specialized poplar plantation C also promoted greater stem height as compared to the alley design of SA. In agreement with previous studies (Cabanettes et al., 1999, Toillon et al., 2013), a greater stem volume per tree, but not per hectare, is expected in SA as consequence of the lower intraspecific competition and the greater availability of soil resources and solar radiation. In accordance with our results, Thomas

Fig. 7. Field photos of the same branches of poplar trees (clone Moncalvo) in the specialized plantation (C) and silvoarable system (SA) during spring 2021, with the corresponding vegetative phenological stages according to the GFI scale (Giardini Fenologici Italiani) (Malossini, 1993; Table SI.1).

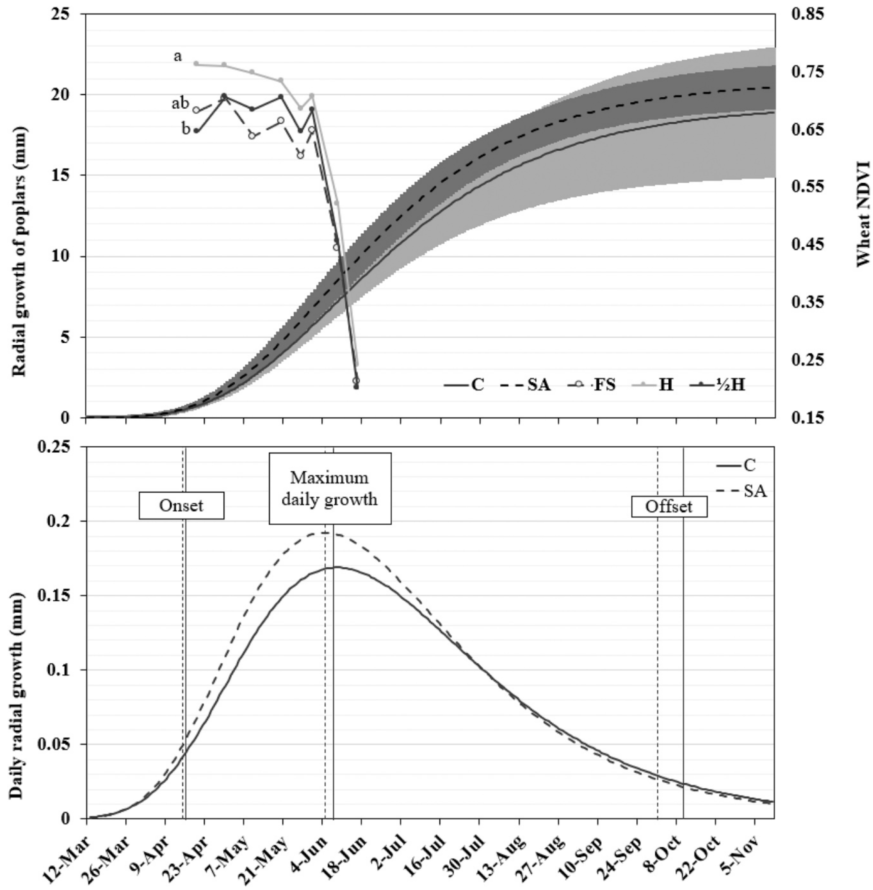

Fig. 8. Dynamics of stem radial growth of poplar trees clone Moncalvo (mean ± S.E. as shaded area around the curve; n=3) in the specialized poplar plantation (C) and the silvoarable system (SA) in 2021 growing season, and NDVI dynamics of wheat intercrop var. Arkeos (mean ± S.E.; n=3) at ½H, H and FS positions. For NDVI values of wheat, letters indicate significant difference among different positions at each time according to Tukey-HSD test ($p < 0.05$).

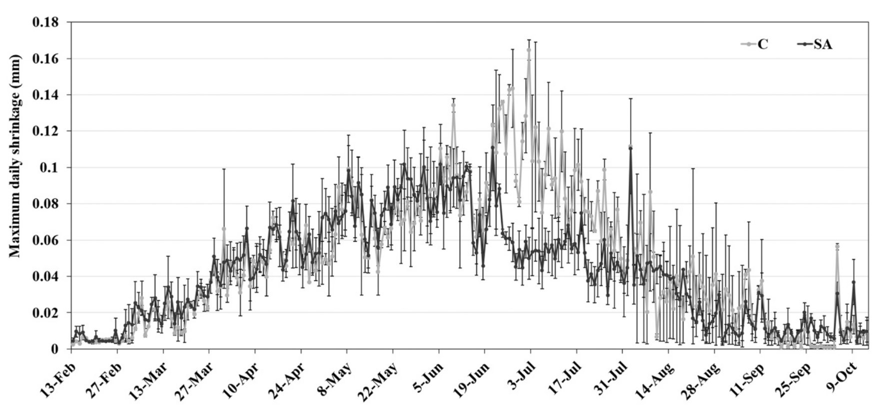

Fig. 9. Maximum daily shrinkage (MDS) of poplar trees clone Moncalvo (mean ± S.E.; n=3) in the specialized plantation (C) and the silvoarable system (SA) during 2021.

et al. (2021) showed greater HDR (Height to Diameter stem Ratio), an index of tree competition and stability, in six-year-old poplars grown in monoculture with respect to silvoarable systems. However, further monitoring of our systems is required to confirm this growth trend described by Thomas et al. (2021) since the radial growth is expected to decelerate in the second part of the poplars' rotation as a consequence of the increased intraspecific competition in plantations at canopy level (Zhang et al., 2022), but probably not in sparse plantations. Given that the HDR tends to be lower in silvoarable conditions, resulting in greater stability and reduced susceptibility to wind and snow damage, the adoption of these systems could help farmers in managing agricultural areas affected by strong winds in order to ensure tree stability and protection/windbreak of the arable fields. However, improvements of the wood production per hectare in silvoarable systems require a higher population density than that used here, but with some cautions. While the intra-row tree distance of 6 m should be maintained for guaranteeing optimal growth of trees and avoiding stem ovalization, the arable zone could be reduced to 30–15 m, as more commonly applied at more northern latitudes, although at the expense of the intercrop yield due to greater competition (Inurreta-Aguirre et al., 2018; Beuschel et al.,

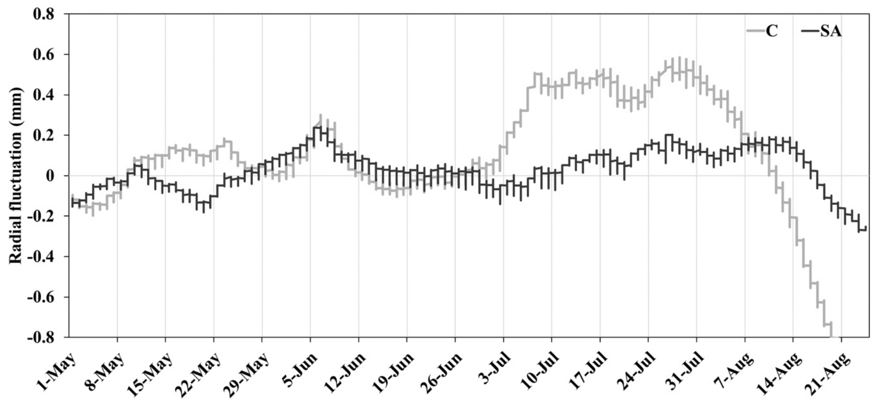

Fig. 10. Dynamics (15-minute interval) of the net mean daily stem growth (after deduction of the seasonal growth trend) of poplar trees clone Moncalvo (mean ± S.E.; n=3) in the specialized poplar plantation (C) and the silvoarable system (SA) during 2021.

2020). In this view, twin tree rows could be an interesting solution/compromise for doubling wood production per hectare by restricting the field size from 40 m to 34 m. Possible twin row designs have only recently come under consideration, with one tree row at either side of the field ditches or both rows on one side only. Planting both rows on one side is considered the most suitable candidate solution for facilitating tree management and maintenance of ditches. The overall production of such a system, costs and benefits, together with practical and logistic implications, however, should be adequately investigated in the near future.

The growth conditions for poplars are more favorable in agroforestry than in specialized plantations due to the greater light availability, the application of fertilizers to the intercrops, and symbiotic N-fixation by legume crops. The potential of *Populus* spp. and their hybrids to rapidly take advantage of crop fertilization, particularly nitrogen, within the SA system has been reported in previous studies (Rivest et al., 2009). Some authors also reported positive effects on tree diameter when the poplars are associated with N_2-fixing intercrops (Dupraz et al., 1999; Sisi et al., 2011; Thomas et al., 2021), and indeed, when soybean was intercropped in 2020 in our study, the annual increment of poplar DBH was much greater than in 2018 and 2021, when common wheat was cultivated. On the other hand, in 2019 the average DBH of poplars in SA was not significantly different from that of the control, possibly due to the stress caused by the first pruning in the two systems. It is hypothesized that specific pruning methods might be set-up in silvoarable systems as compared to a conventional plantation, particularly for the formation pruning, by adopting more timely interventions on lateral branches that tend to thicken faster than in a specialized plantation. Anyhow, investigations are still on-going at the Sasse Rami pilot farm and will provide further information in the upcoming future concerning the second part of the poplar cycle, from the 5th to ideally the 10th year of cultivation. However, the annual growth rate of poplar DBH reported here allow us to hypothesize that commercial diameters suitable for logs harvesting can be reached already at the end of 8th growing season in agroforestry systems, which is 2 years earlier compared to conventional plantations. This can potentially lead to a shorter rotation period and increased economic affordability.

The combined analysis of radial stem growth, soil water availability, and precipitation permits for the investigation into the correlations between the diametric growth of poplars and water availability in the two cultivation systems. Both higher soil water content and MDS, an index of water absorption capacity, were unexpectedly associated with lower radial growth in the specialized plantation C, probably due to the preferential vertical growth of the trees. Concurrently, as evidenced by the lower stem swelling, the trees in the SA system were less prone to absorb water after precipitations, especially after wheat harvest at end-June. This could be explained by elevated levels of evapotranspiration from the bare soil of the agricultural fields in SA and consequently the lower water availability for trees following wheat harvest. This hypothesis agrees with the study by Klocke et al. (2009), who observed a reduction in soil evaporation by up to 50% when the soil was shaded by a maize canopy or by maize residue post-harvest. Our observations only refer to a single growing season in 2021, but it nonetheless highlights the importance of ensuring permanent soil coverage of agricultural fields to limit water loss through evaporation and to maximize water conservation, especially during summer. Our results show that the maximum stem radial growth of poplars occurred around mid-June, in parallel with the harvest of wheat and straw removal. In the C system, although permanent shading by poplar canopies during summer allowed for greater soil water availability, this was not translated into higher stem radial growth. Our soil moisture measurements referred just to the top 30-cm layer however, and a good soil root colonization by poplar has been demonstrated in literature (Mulia and Dupraz, 2006), suggesting that water may not necessarily be the main limiting factor for poplar growth. Indeed, Toillon et al. (2013) reported a greater HDR, and lower water use efficiency of poplars cultivated in high-density plantations when water was not a limiting factor. Nevertheless, to fully elucidate the importance of soil water content on poplar growth, further investigations on leaf conductance, stomata sensitivity, and photosynthesis of this new poplar clone Moncalvo are required in both systems.

Tree density, which was significantly lower in SA vs. C, also has a potentially significant effect on wood quality, as observed in walnut grown in SA systems whose trees produce wood of low quality due to uneven competition between neighboring trees (Heim et al., 2022). However, evidence has shown that the wood quality of poplar grown in agroforestry systems is comparable to that obtained in standard poplar plantations (Kouakou et al., 2016). Considering that plywood is the main use of poplar wood, even annual diameter increments are not expected to be decisive for the quality of this wood. Quality and mechanical properties of poplars wood obtained in agroforestry remain to be evaluated at end cycle in comparison to specialized plantation, a topic still unexplored in the literature, but suitable felling and logging methods, as well as the logistic of harvesting should be defined to avoid intercrops damage and ensure timely interventions.

4.2. Poplar phenology and intercrop response

In agroforestry, the phenological development of trees and the growing season of intercrops are key factors in determining the pattern of interactions, particularly for shading (Broadhead, 2000). The choice of deciduous tree species, such as poplar, in combination with winter crops, such as winter wheat, shows reduced growth overlap, as evidenced here in Fig. 8, thereby allowing wheat to complete at least stem elongation and flag leaf formation before complete poplar leaf expansion. Wheat commonly shows minimal yield losses when neighboring trees, contrary to light-demanding summer crops like soybean (Reynolds et al., 2007; Gill et al., 2009; Jose et al., 2004; Pardon et al., 2018). The dynamics of wheat canopy greenness at the 4th year of poplar age in SA (year 2021) corroborated the complementary phenology of poplar and winter wheat, both leaf senescence of wheat and radial stem growth of poplar being appreciable at the end of May. Indeed, the one- to two-week delay in poplar phenology (leaf unfolding) observed in trees grown in the agroforestry system allowed for an attenuation of the competition with wheat. In fact, tree shading later became beneficial, retarding wheat senescence and resulting in positive effects on yield and protein content, as previously observed in various studies (Li et al., 2010; Xu et al., 2016; Arenas-Corraliza et al., 2019). In this view, tree leaf phenology should be considered as a relevant trait in screening poplar clones for suitability to agroforestry. Some authors suggested that the delayed poplar phenology in agroforestry could be due to lower soil water content (Myers et al., 1998), which indeed was also measured in the topsoil of our study. Preliminary measurements of the air temperature in 2023 (6th poplar growing season) (data not shown) also highlight lower night temperatures in spring in the silvoarable system as compared to high-density plantations, which may also contribute to the delay in leaf phenology in the SA system.

As regards the productivity of intercrops, it is expected that poplar growth in terms of height and crown volume will have a growing effect through the years in SA systems. Indeed, wheat productivity in proximity of the poplar rows (½H) was not affected neither at the 2nd nor the 4th year, while improvements in yield were documented at distances equal to the tree height (H). On the contrary, yield impairments were generally observed in soybean, with the exception at distance H on the east side of the tree row, highlighting a greater sensitivity of this crop to reduced solar radiation in the afternoon. Better yield response in winter wheat at distance H could be due to both lower root competition with poplar and shading as compared to ½H. These combined interactions would have created more favorable conditions for wheat at distance H as compared to FS, likely due to better soil water conservation associated to moderate shading at this position. Root competition between poplar trees and intercrops was not investigated in this trial, but limited interspecific interactions are generally expected in shallow soil layers, due to annual tillage/ploughing that disturbs tree root growth, and in further positions from the tree row (Hugenschmidt and Kay, 2023). As regards the side of the tree row, the higher aboveground biomass and grain yield were achieved at the eastern side in soybean in 2020 and in wheat in 2021. This could be associated to the beneficial effects of trees during the hottest time of the day, namely in the afternoon, leading to cooler temperatures during the late phases of the wheat cycle (grain filling) and in the summertime for soybean in the shaded eastern side. However, to corroborate these conclusions, microclimatic parameters through dedicated sensors should be investigated in more detail.

Our results on wheat partly conflict with literature studying agroforestry systems in temperate climates. These report wheat yield losses adjacent to tree rows (Dufur et al., 2013; Artru et al., 2017; Qiao et al., 2020; Yang et al., 2021), although these studies refer to SA systems with narrower arable zones and different climatic conditions than ours. Grain yield improvements comparable to ours were previously documented in field trails subjected to both artificial shading and drought (Thevathasan et al.2004; Li et al., 2010; Xu et al., 2016; Arenas-Corraliza et al., 2020). Nevertheless, it should be stressed that our SA system has both large tree inter-row and intra-row distances, allowing for mild inter-species competition. According to some studies (Graves et al., 2007; Sereke et al., 2014), in low-density SA systems, i.e., ~50 trees ha^{-1}, crop yield was similar to conventional agricultural fields until the midpoint of tree's rotation, which mirrors the results of our study with 35 trees ha^{-1}. Our poplar silvoarable system greatly differs from those present in India, the country with the largest surface area dedicated to such systems. Here the plantation design has narrower inter-row and intra-row distances, both approximately 4.5–6 m, with a shorter rotation period of 5–7 years. In such a context, the yield of the intercropped winter wheat is significantly impacted by tree competition, with reductions ranging from 15% to 65% as compared to controls, depending on the trees' age (Chauhan et al., 2011).

As regards soybean response, our results are in agreement with several studies in temperate SA systems, which explained yield losses by reduced light availability in the proximity to the tree rows, while excluding water competition (Reynolds et al., 2007; Carrier et al., 2019; Mantino et al., 2019). However, given that soybean has been studied for one year only with young two-year old poplars, a thorough assessment of its response in agroforestry has to be further validated.

For future perspectives, the introduction of trees in SA farming systems could be beneficial for mitigating the negative effects of climate change on field crops. In our studies, both 2020 and 2021 were characterized by unusual dryness, with few events of precipitation (573 mm in 2020 and 427 mm in 2021, vs. 727 mm as 1994–2022 average); the negative impact of shading by trees could therefore be attenuated by improving water balance of intercrops and reducing the air temperature (Thevathasan and Gordon, 2004). This can also explain why crop yield was greater on the eastern side of the poplar rows, where the crop was shaded by tree canopies during the hottest time of day (afternoon).

5. Conclusions

This study demonstrates that poplar grown in low population density can be successfully integrated into alley-cropping systems with negligible negative impact on yield of intercrops, at least within the first half of the trees' rotation. Some changes in the dynamics of poplar growth are expected in widely spaced tree rows compared to specialized plantation, such as faster radial stem growth and volume increment, which may attract farmers to introduce this fast-growing species along the drainage ditches of the agricultural fields. The retarded seasonal phenology of poplars grown in SA in respect to specialized plantation can also be positively exploited in agriculture for attenuating the competition with intercrops, although summer species such as soybean are more readily affected than winter-spring crops such as winter wheat. Our results demonstrate the importance of correctly designing the SA system and identifying the most suitable crops to be cultivated in the arable alleys as function of tree age. Although crop performance should be further investigated in the following second half of the poplar rotation, we can currently conclude with confidence that winter wheat, and probably other winter cereals such as barley and rye, can be efficiently cultivated in our agroforestry model, and these data can be useful to implement in currently available predictive models. In fact, improved yield and protein quality is more achievable than when wheat is cultivated under full sun conditions. Widely spaced silvoarable systems with poplars can also improve the use efficiency of natural resources, such as water, supporting a widespread application of this system across Europe, particularly in environmentally sensitive areas. Agroforestry systems thus represent an opportunity for agriculture to combat the imminent negative effects climate change will have on the agricultural sector in temperate regions in the next future.

CRediT authorship contribution statement

SP, AP, GB, GP and VC collected and analyzed the data. SP, AP and GP wrote the first draft of the manuscript. GM and LF helped design the experiment. TV and SSM revised the text. TV conceived the research idea, and corrected and arranged the final version of this work. All authors contributed to the interpretation and discussion of the results.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Teofilo Vamerali reports financial support was provided by University of

Padua Department of Agronomy Food Natural Resources Animals and Environment. Teofilo Vamerali reports financial support was provided by European Union.

Data Availability

Data will be made available on request.

Acknowledgments

AP was funded by a research grant from the Department of Agronomy Food Natural resources Animals and Environment (DAFNAE) of the University of Padova - BIRD210158/21.

This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108814.

References

Arenas-Corraliza, M.G., Rolo, V., López-Díaz, M.L., Moreno, G., 2019. Wheat and barley can increase grain yield in shade through acclimation of physiological and morphological traits in Mediterranean conditions. Sci. Rep. 9, 9547.
Arenas-Corraliza, M.G., López-Díaz, M.L., Rolo, V., Moreno, G., 2020. Wheat and barley cultivars show plant traits acclimation and increase grain yield under simulated shade in Mediterranean conditions. J. Agron. Crop Sci. 207, 100–119.
Artru, S., Garré, S., Dupraz, C., Hiel, M.P., Blitz-Frayet, C., Lassois, L., 2017. Impact of spatio-temporal shade dynamics on wheat growth andyield, perspectives for temperate agroforestry. Eur. J. Agron. 82, 60–70.
Beuschel, R., Piepho, H.P., Joergensen, R.G., Wachendorf, C., 2020. Effects of converting a temperate short-rotation coppice to a silvo-arable alley cropping agroforestry system on soil quality indicators. Agrofor. Syst. 94, 389–400.
Broadhead, J.S., 2000. Ecophysiology of Indigenous Trees in Agroforestry Systems in the Semi-arid Tropics (PhD Thesis). University of Nottingham, 267 pp.
Cabanettes, A., Auclair, D., Imam, W., 1999. Diameter and height growth curves for widely-spaced trees in European agroforestry. Agrofor. Syst. 43, 169–181.
Cannell, M.G.R., 1984. Woody biomass of forest stands. . Ecol. Manag. 8, 299–312.
Carrier, M., Gonzales, F.A.R., 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 Crops Res 239, 30–37.
Chauhan, S.K., Gupta, N., Walia, R., Yadav, S., Chauhan, R., Mangat, P.S., 2011. Biomass and carbon sequestration potential of poplar-wheat inter-cropping system in irrigated agro-ecosystem in India. J. Agric. Sci. Technol. A1, 575–586.
Chiarabaglio, P.M., Giorcelli, A., Allegro, G., 2014b. Environmental sustainability of poplar stands. In: Jornadas de Salicáceas 2014 - Cuarto Congreso Internacional de las Salicáceas en Argentina - "Sauces y Álamos para el desarrollo regional", 19-22 March 2014, Buenos Aires, Argentina.
Chiarabaglio, P.M., Allegro, G., Rossi, A.E., Savi, L., 2014a. Studi sulla sostenibilità della pioppicoltura in Lombardia. Sherwood - For. Ed. Alberi Oggi 206, 5–8.
Coaloa, D., Facciotto, G., Chiarabaglio, P.M., Giorcelli, A., Nervo, G., 2016. Cloni di pioppo a Maggior Sostenibilità Ambientale (MSA). Sherwood - For. Ed. Alberi Oggi 216, 31–34.
Corona, P., Bergante, S., Castro, G., Chiarabaglio, P.M., Coaloa, D., Facciotto, G., Gennaro, M., Giorcelli, A., Rosso, L., Vietto, L., Nervo, G., 2018. Linee di indirizzo per una pioppicoltura sostenibile. Rete Rurale Nazionale, Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria, Roma, ISBN: 978-88-99595-96-8.
Cruz-Garcìa, R., Balzano, A., Čufar, K., Scharnweber, T., Smiliani, M., Wilmking, M., 2019. Combining dendrometer series and xylogenesis imagery-DevX, a simple visualization tool to explore plant secondary growth phenology. Front. . Glob. Change 2, 60.
Dufur, L., Metay, A., Talbot, G., Dupraz, C., 2013. Assessing Light Competition for Cereal Production in Temperate Agroforestry Systems using Experimentation and Crop Modelling. J. Agron. Crop Sci. 199, 217–227.
Dupraz, C., Simorte, V., Dauzat, M., Bertoni, G., Bernadac, A., Masson, P., 1999. Growth and nitrogen status of young walnuts as affected by intercropped legumes in a Mediterranean climate. Agrofor. Syst. 43, 71–80.
Eichhorn, M.P., Paris, P., Herzog, F., Incoll, L.D., Liagre, F., Mantzanas, K., Mayus, M., Moreno, G., Papanastasis, V.P., Pilbeam, D.J., Pisanelli, A., Dupraz, C., 2006. Silvoarable systems in Europe – past, present and future prospects. Agrofor. Syst. 67, 29–50.
FAO- Food and Agriculture Organization of the United Nations, 2003. Food Energy - Methods of Analysis and Conversion Factors: Report of a Technical Workshop, Rome, 3-6 December 2002 (FAO Food and Nutrition Paper 77). Food and Agriculture Organization of the United Nations.
FAO-Food and Agriculture Organization of the United Nations, 2013. Advancing Agroforestry on the Policy Agenda: A guide for decision-makers, by G. Buttoud, in collaboration with O. Ajayi, G. Detlefsen, F. Place & E. Torquebiau. Agroforestry Working Paper no. 1. Food and Agriculture Organization of the United Nations. FAO, Rome. 37 pp.
FAO, 2016. Abstracts of Submitted Papers prepared for the 25 th Session of the International Poplar Commission, jointly hosted by FAO and the German Federal Ministry of Food and Agriculture, Berlin, Germany, 13-16 September 2016. International Poplar Commission Working Paper IPC/14. Forestry Policy and Resources Division, FAO, Rome. Published at http://www.fao.org/forestry/ipc/69946/en/.
Gill, R.I.S., Singh, B., Kaur, N., 2009. Productivity and nutrient uptake of newly released wheat varieties at different sowing times under poplar plantation in north-western India. Agrofor. Syst. 76, 579–590.
Graves, A.R., Burgess, P.J., Palma, J.H.N., Herzog, F., Moreno, G., Bertomeu, M., Dupraz, C., Liagre, F., Keesman, K., Van der Werf, W., Koeffeman de Nooy, A., Van den Briel, J.P., 2007. Development and application of bio-economic modelling to compare silvoarable, arable, and forestry systems in three European countries. Ecol. Eng. 29, 434–449.
Heim, L., Brancheriau, L., Marchal, R., Boutahar, N., Lotte, S., Denaud, L., Badel, E., Meghar, K., Candelier, K., 2022. Variation analyses of extractive contents by NIR-spectroscopy bring out the differences between agroforestry and forestry walnut (Juglans regia × nigra) trees. Holzforschung 76, 781–790.
Hugenschmidt, J., Kay, S., 2023. Unmasking adaption of tree root structure in agroforestry systems in Switzerland using GPR. Geoderma Reg. 34, e00659.
Inurreta-Aguirre, H.D., Lauri, P.É., Dupraz, C., Gosme, M., 2018. Yield components and phenology of durum wheat in a Mediterranean alley-cropping system. Agrofor. Syst. 92, 961–974.
Jose, S., Gillespie, A.R., Pallardy, S.G., 2004. Interspecific interactions in temperate agroforestry. Agrofor. Syst. 61, 237–255.
Klocke, N.L., Currie, R.S., Aiken, R.M., 2009. Soil water evaporation and crop residues. ASABE 52, 103–110.
Kouakou, S.S., Marchal, R., Brancheriau, L., Guyot, A., Guibal, D., 2016. The quality of poplar wood from agroforestry: a comparison with forest plantation. 3rd European Agroforestry Conference Montpellier, 23-25 May 2016 - Quantity, quality and diversity of agroforestry products (oral).
Kumar, M., Singh, H., 2020. Agroforestry as a nature-based solution for reducing community dependence on forests to safeguard forests in rainfed areas of India. Nature-based solutions for resilient ecosystems and societies 289–306.
Lawson, G., Christian, D., Wattè, J., 2019. Chapter 9 - Can silvoarable systems maintain yield, resilience, and diversity in the face of changing environments? Agrosystem Diversity. Academic press, pp. 145–178.
Li, H., Jiang, D., Wollenweber, B., Dai, T., Cao, W., 2010. Effects of shading on morphology, physiology and grain yield of winter wheat. Eur. J. Agron. 33, 267–275.
Malossini, A., 1993. Procedure per il rilevamento fenologico nei Giardini Italiani. Gruppo di Lavoro nazionale per i Giardini fenologici, Regione Emilia-Romagna, Bologna, 64 pp.
Mantino, A., Volpi, I., Micci, M., Pecchioni, G., Bosco, S., Dragoni, F., Mele, M., Ragaglini, G., 2019. Effect of tree presence and soil characteristics on soybean yield and quality in an innovative alley- cropping system. Agronomy 10, 52.
Mulia, R., Dupraz, C., 2006. Unusual fine root distributions of two deciduous tree species in southern france: what consequences for modelling OF TREE ROOT DYnamics? Plant Soil 281, 71–85.
Myers, B.A., Williams, R.J., Fordyce, I., Duff, G.A., Eamus, D., 1998. Does irrigation affect leaf phenology in deciduous and evergreen trees of the savannas of northern Australia? Austral J. Ecol. 23, 329–339.
Nerlich, K., Graeff-Hönninger, S., Claupein, W., 2013. Agroforestry in Europe: a review of the disappearance of traditional systems and development of modern agroforestry practices, with emphasis on experiences in Germany. Agrofor. Syst. 87, 1211.
Opio, C., Jacob, N., Coopersmith, D., 2000. Height to diameter ratio as a competition index for young conifer plantations in northern British Columbia, Canada. For. Ecol. Manag. 137, 245–252.
Ortuño, M.F., García-Orellana, Y., Conejero, W., 2006. Stem and leaf water potentials, gas exchange, sap flow, and trunk diameter fluctuations for detecting water stress in lemon trees. Trees - Struct. Funct. 20, 1–8.
Pantera, A., Mosquera-Losada, M.R., Herzog, F., Den Herder, M., 2021. Agroforestry and the environment. Agrofor. Syst. 95, 767–774.
Pardon, P., Reubens, B., Mertens, J., Verheyen, K., De Frenne, P., De Smet, G., Van Waes, C., Reheul, D., 2018. Effects of temperate agroforestry and yield and quality of different arable intercrops. Agric. Syst. 166, 135–151.
Paris, P., Giorcelli, A., Bosco, V., Cantamessa, S., Monteverdi, M.C., Vigani, G., Grendele, M., Lauteri, M., Chiarabaglio, P.M., 2022. Sensibilità alla siccità di cloni di pioppo. Risultati di prove in serra e pieno campo su cloni a maggior sostenibilità ambientale. Sherwood - For. Ed. Alberi Oggi 258, 47–50.
Paris, P., Camilli, F., Rosati, A., Mantino, A., Mezzalira, G., Dalla Valle, C., Franca, A., Seddaiu, G., Pisanelli, A., Lauteri, M., Brunori, A., Re, A., Sanna, F., Ragaglini, G., Mele, M., Ferrario, V., Burgess, P.J., 2019. What is the future for agroforestry in Italy? Agrofor. Syst. 93, 2243–2256.

Propopulus, 2021. Industrial applications of poplar wood. ⟨https://propopulus.eu/en/industrial-applications-of-poplar-wood/⟩. Last access: 22 December 2021.
Qiao, X., Chen, X., Lei, J., Sai, L., Xue, L., 2020. Apricot-based agroforestry system in Southern Xinjiang Province of China: influence on yield and quality of intercropping wheat. Agrofor. Syst. 94, 477–485.
Reisner, Y., de Filippi, R., Herzog, F., Palma, J., 2007. Target regions for silvoarable agroforestry in Europe. Ecol. Eng. 29, 401–418.
Reynolds, P.E., Simpson, J.A., Thevathasan, V.N., Gordon, A.M., 2007. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecol. Eng. 29, 362–371.
Rivest, D., Cogliastro, A., Olivier, A., 2009. Tree-based intercropping systems increase growth and nutrient status of hybrid poplar: A case study from two Northeastern American experiments. J. Environ. Manag. 91, 432–440.
Rois-Dìaz, M., Lovric, N., Ferreiro-Domìnguez, N., Mosquera-Losada, M.R., Den Herder, M., Graves, A., Palma, J.H.N., Paulo, J.A., Pisanelli, A., Smith, J., Moreno, G., Garcìa, S., Varga, A., Pantera, A., Mirck, J., Burgess, P., 2017. Farmers' reasoning behind the uptake of agroforestry practices: evidence from multiple case-studies across Europe. Agrofor. Syst. 92, 811–828.
Rossi, S., Deslauriers, A., Anfodillo, T., Morin, H., Saracino, A., Motta, R., Borghetti, M., 2005. Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. N. Phytol. 170, 301–310.
Santiago-Freijanes, J.J., Pisanelli, A., Rois-Dìaz, M., Aldrey-Vàzquez, J.A., Rigueiro-Rodrìguez, A., Pantera, A., Vityi, A., Lojka, B., Ferreiro-Domìnguez, N., Mosquera-Losada, M.R., 2018. Agroforestry development in Europe: Policy issues. Land Use Pol. 76, 144–156.
Sereke, F., Graves, A.R., Dux, D., Palma, J.H.N., Herzog, F., 2014. Innovative agroecosystem goods and services: key profitability drivers in Swiss agroforestry. Agron. Sustain. Dev. 35, 759–770.
Sisi, D.E., Karimi, A.N., Pourtahmasi, Taghiyari, H.R., 2011. The effects of agroforestry practices on fiber attributes in Populus nigra var. betulifolia. Trees 26, 435–441.
Smith, J., 2010. The History of Temperate Agroforestry. Org. Res. Cent., Elm. Farm, Hamstead Marshal, Newbury, Berks. 2010, 1–17.
Smith, J., Pearce, B.D., Wolfe, M.S., 2012. A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renew. Agric. Food Syst. 27, 323–332.
Sollen-Norlin, M., Bahadur, G., Rintoul, N.L.J., 2020. Agroforestry benefits and challenges for adoption in Europe and beyond. Sustainability 12 (17), 7001.
Thevathasan, N.V., Gordon, A.M., Simpson, J.A., Reynolds, P.E., Price, G., Zhang, P., 2004. Biophysical and Ecological Interactions in a Temperate Tree-Based Intercropping System. J. Crop Improv. 12, 339–363.
Thomas, A., Priault, P., Piutti, S., Dallé, E., Marron, N., 2021. Growth dynamics of fast-growing tree species in mixed forestry and agroforestry plantations. For. Ecol. Manag, 480-118672.
Toillon, J., Fichot, R., Dallé, E., 2013. Planting density affects growth and water-use efficiency depending on site in Populus deltoides × P. nigra. . Ecol. Manag. 304, 345–354.
Van der Maaten, E., Van der Maaten-Theunissen, M., Smiljanic, M., Rossi, S., Simard, S., Wilmking, M., Deslauriers, A., Fonti, P., Von Arx, G., Bouriaud, O., 2016. Dendrometer: Analyzing the puls of trees in R. Dendrochronologia 40, 12–16.
Xu, C.L., Tao, H.B., Wang, P., Wang, Z.L., 2016. Slight shading after anthesis increases photosynthetic productivity and grain yield of winter wheat (*Triticum a*estivum L.) due to the delaying of leaf senescence. J. Integr. Agric. 15, 63–75.
Yang, T., Ma, C., Lu, W., Wan, S., Li, L., Zhang, W., 2021. Microclimate, crop quality, productivity, and revenue in two types of agroforestry systems in drylands of Xinjiang, northwest China. Eur. J. Agron. 124, 126245.
Zhang, Y., Fang, S., Tian, Y., Wang, L., Lv, Y., 2022. Responses of radial growth, wood density and fiber traits to planting space in poplar plantations at a lowland site. J. For. Res. 33, 963–976.