



Yield stability under different management systems: water use efficiency and morphometric plasticity of poplar in agroforestry versus monoculture under Mediterranean conditions

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Received: 22 January 2026 / Accepted: 1 April 2026 / Published online: 16 April 2026
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Abstract In the face of escalating climate instability and water scarcity in the Mediterranean region, the transition from resource-intensive monocultures to resilient agroforestry systems is becoming imperative for sustainable biomass production. This study provides a comprehensive evaluation of the biometric performance, water use efficiency, growth performance and productivity indexes of Poplar (*Populus spp.*) cultivated in an agroforestry system versus a conventional high-density monoculture, under both irrigated and rainfed conditions. Field experiments

conducted in Central Italy revealed a critical trade-off between absolute yield and biometric performance. While the irrigated monoculture system maximized total biomass production (16.83 t ha⁻¹), it required substantial water inputs. Conversely, the rainfed agroforestry system, despite lower yields (11.59 t ha⁻¹), demonstrated remarkable yield stability, achieving a Water Use Efficiency (5.32 kg mm⁻¹ m⁻²) comparable to the high-input irrigated monoculture (5.21 kg mm⁻¹). Furthermore, trees in agroforestry systems exhibited superior individual growth traits, with significantly greater stem diameters and heights compared to monoculture stands, indicating a shift from “quantity-driven” to “quality-driven” biomass production. These findings challenge the conventional paradigm of yield maximization, suggesting that agroforestry offers a superior strategy for sustainable intensification. By decoupling biomass production from heavy water dependence, agroforestry emerges as a key solution for maintaining bioeconomy supply chains in water-limited future scenarios.

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Keywords Agroforestry · Poplar · Biomass production · Productivity indexes · Sustainable intensification

Introduction

In the current context of escalating climate instability, challenges such as desertification and land

degradation underscore the imperative for innovative land management strategies to enhance agricultural resilience (Tomar et al. 2021). Reintegrating trees into agricultural landscapes through agroforestry systems offers a promising pathway to achieve these objectives. These systems are increasingly recognized for delivering diverse ecosystem services (Alali et al. 2025; Comolli et al. 2024); they not only enhance regulatory services such as biodiversity and soil conservation but also improve provisioning services by increasing overall biomass productivity per unit of land (Arshad et al. 2024; Mantino et al. 2023; Piotto et al. 2023a, b). Specifically, silvoarable alley cropping or agroforestry, which co-produces food and non-food biomass, frequently demonstrates superior overall land-use efficiency compared to monoculture systems (Lehmann et al. 2020; Rezgui et al. 2023). This can be primarily attributed to the complementary utilization of resources such as light, water, and nutrients between arboreal and herbaceous components, contributing to enhanced nutrient cycling and soil organic matter dynamics (Clivot et al. 2019), improved water retention and aquifer recharge (Pulido-Esquivel et al. 2025), and greater microclimate stability (Brandolini et al. 2025). The development of agroforestry therefore improves ecosystem service delivery such as functional biodiversity enhancement, soil erosion reduction, and improved nutrient and water cycling—even mitigating nitrogen surplus in integrated animal-crop systems which ultimately results in effective climate change mitigation and adaptation strategies (Crous-Durán et al. 2019; Santos et al. 2023).

The conversion of conventional Short/Medium Rotation Forestry into silvoarable alley cropping constitutes a distinct and pertinent application of this concept. Critically, a distinct scientific knowledge gap persists regarding the specific biological performance of the forestry component within these mixed systems. While the societal benefits are clear, the morphometric response of trees specifically in terms of productivity and water demand when shifted from a high-density monoculture to an open agroforestry configuration is not fully characterized. This uncertainty is particularly acute in Mediterranean environments, where water availability acts as a severe limiting factor during hot, arid summers, significantly impacting tree biomass productivity (Cocozza et al. 2010; Fuertes et al. 2022; Scordia et al. 2023).

This study focuses on Poplar (*Populus* spp.), a species of strategic importance for the European bioeconomy and a sustainable local resource (ProPopulus Team 2023). In Italy, Short Rotation Forestry (SRF) for bioenergy production experienced a rapid expansion in the early 2000s. This boom was largely driven by the restructuring of the national sugar beet industry, which saw numerous processing facilities converted into biomass power plants (Bacenetti & Fiala 2011). However, initial enthusiasm waned as farmers faced economic losses due to the low market value of wood chips and the complex, costly logistics associated with transporting high-volume, low-density materials over long distances (Stefano et al. 2024).

Recently, unprecedented increases in fossil fuel prices have catalyzed a renewed interest in poplar SRF, which can also substantially contribute to doubling farmers' income when managed in mixed systems (Chavan & Dhillon 2019). The economic viability of these plantations is currently being rehabilitated through optimized mechanization and advanced logistical planning, such as the implementation of GIS-based supply chain management (Stefano et al. 2024). Cultivation practices also play a pivotal role in profitability. While existing literature demonstrates that supplementary irrigation can effectively double SRF biomass yields compared to rainfed conditions (Stape et al. 2004), escalating water scarcity in the Mediterranean region creates a direct and severe conflict between allocating water for food crops versus industrial biomass. Poplar is widely recognized for its exceptionally high water consumption. Ecophysiological literature indicates that a mature poplar tree can transpire between 50 and 100 L of water per day during peak summer conditions (Meiresonne et al. 1999). At the stand level, this translates to massive hydrological demands, with annual crop evapotranspiration rates for short-rotation coppice frequently exceeding 600–800 mm in Mediterranean and semi-arid climates (Guidi et al. 2008). Consequently, a typical high-density irrigated poplar monoculture in the Mediterranean requires an average of 5000 m³ ha⁻¹ of irrigation per year (Pari et al. 2023). Given that the economic and social value of water is inherently prioritized for food security and high-value agricultural commodities (Colby 2018; D'Odorico et al., 2020), utilizing such massive volumes solely for bioenergy is increasingly unsustainable. Therefore, it is no longer sufficient to merely maximize wood yield; developing

water-saving cultivation strategies is critical. By integrating poplar into agroforestry systems, biomass production can be decoupled from heavy water dependence, allowing the 'saved' water to be reallocated to food or herbaceous intercrops (Mantino et al. 2023). This paradigm shift is essential to sustain the bioeconomy without compromising local food security.

The primary objective was to comprehensively compare the biometric and productive performance of poplar grown in agroforestry systems versus conventional monoculture stands, considering both irrigated and non-irrigated approaches. Furthermore, given the critical necessity of resilient water management in Southern Europe, this study also sought to determine the Water Use Efficiency of the tree component (Rosso et al. 2021; Thevs et al. 2021). This and other aspects of biometric performance has received significantly less research attention compared to general ecosystem services, particularly regarding interactions and implications for Water Use Efficiency in different agroforestry systems ("Water-Use Efficiency: Advances and Challenges in a Changing Climate," 2019).

Based on these premises, this study was designed as a hypothesis-driven investigation to evaluate the trade-offs between production and yield stability.

Specifically, we tested the following three hypotheses: (H1) Reduced stand density increases individual tree biomass; (H2) Management systems that reduce stand density will enhance individual stem dimensions, leading to greater stem diameter and height growth; (H3) The interaction between management and irrigation systems will influence water use efficiency, biometric aspects, and productivity indexes.

Materials and methods

Study area and environmental conditions

The Poplar plantation is located in the experimental farm of the Research Center for Engineering and Agro-Food Processing (CREA-IT) in Rome, Italy. The site is located at coordinates 42°06'09" N, 12°37'43" E (WGS84) at an altitude of 25 m a.s.l. the sampling was conducted during July 2024 at the end of the 3rd year of the plantation cycle. The area is characterized by a typical Thermo-Mediterranean climate (Köppen-Geiger classification *Csa*), defined by

hot, arid summers and mild, rainy winters. The historical average annual temperature is approximately 15.6 °C, with January being the coldest month (mean minimum ~ 3 °C) and July/August the hottest (mean maximum ~ 31 °C). These conditions significantly influenced water availability and stress levels experienced by the poplar stands (Scordia et al. 2023). The mean annual precipitation is 780 mm, with a rainfall distribution pattern peaking in autumn (October–November) and spring. Crucially for this study, the site experiences a marked summer drought period (typically June to August), where precipitation drops below 30 mm per month, creating a significant water deficit that necessitates supplementary irrigation for biomass crops.

Soil characteristics

Before starting the test, five samples of 500 g of soil were collected from the field and shipped to the lab in order to study soil characteristics. Each sample was collected following the soil sampling methodology (ISO Soil 2018). Soil characteristics were uniform across the entire experimental site. Granulometric analysis classified the soil texture as Clay (USDA classification). The soil texture was classified as clay-dominant, with a composition of 58% clay, 22% sand, and 20% silt. Chemical analysis revealed a pH of 6.1 (slightly acidic), an organic matter content of 2.1%, and total Nitrogen (N) of 0.13%. Available phosphorus (P_2O_5 Olsen) was recorded at 7 mg kg⁻¹, and exchangeable potassium (K_2O) at 317 mg kg⁻¹. The entire experimental area was managed without the application of pesticides.

Experimental treatments and system design

This study compared two distinct management systems of three years cycle: a conventional Short Rotation Forestry (SRF) system and an agroforestry system, both subjected to irrigated and non-irrigated conditions. The experiment was established as a full factorial design with two factors: Management System (Monoculture vs. Agroforestry) and Water Regime (Irrigated vs. Rainfed), resulting in four distinct experimental treatments.

The total experimental area covered a contiguous 2 ha sector. Given the applied experimental nature of arboreal crops, which necessitate large-scale

machinery and extensive infrastructure for controlled irrigation, establishing multiple, spatially segregated multi-hectare fields is logistically unfeasible. Furthermore, utilizing distant sites risks introducing severe pedoclimatic variability that would confound the treatment effects. To ensure strict environmental uniformity, all treatments were applied within a single, highly controlled site sharing an identical pedological baseline. The experimental field was divided into designated treatment plots measuring approximately 0.5 ha each. This large surface area per treatment is more than sufficient to allow for robust spatial sampling. To ensure valid replication, each 0.5 ha plot was virtually divided into three distinct, separated sub-areas. Trees were randomly sampled from across these three sub-areas, which effectively acted as spatial replicate plots within the uniform pedoclimatic conditions of the broader treatment zone. Both experimental systems utilized the commercial poplar clone 'AF-48', an interspecific hybrid of *Populus deltoides* W. Bartram ex Marshall $\times$ *Populus nigra* L. (*Populus* $\times$ *canadensis* Moench). This specific genotype was strategically selected for this trial due to its widespread adoption in Mediterranean Short Rotation Coppice (SRC) and agroforestry systems. Agronomically, these interspecific hybrids are characterized by exceptional phenotypic plasticity, rapid early-stage cambial activity, and robust radial growth dynamics even in wide-alley configurations (Piotto et al. 2023b). Ecophysiologically, this hybrid exhibits a vigorous root system architecture that facilitates rapid below-ground resource acquisition and high physiological adaptability under varying environmental constraints (Marron et al. 2014), coupled with a notable field tolerance to major foliar pathogens (such as *Marssonina brunnea* and *Melampsora* rusts). Maintaining optimal canopy health is critical in these mixed systems to sustain high leaf area indices (LAI) and maximize radiation use efficiency throughout the prolonged Mediterranean vegetative season. The experimental stands consisted of a 12-year-old plantation currently in its second harvest cycle, with above-ground shoots aged three years at the time of biometric sampling..

The characteristics of the two management systems were as follows:

- **Monoculture system (MC)** This treatment consisted of a traditional high-density plantation with

an inter-row spacing of 3 m and distance between the plants of 2 m (3×2) for a total surface of 2 ha. The management strategy involved mechanical shredding of the herbaceous component in the inter-rows during the autumn-winter months. During the sampling period in July, the inter-row was characterized by natural vegetation in the flowering stage.

Agroforestry system (AF) This treatment was established through the conversion of the existing 12-year-old poplar plantation by the alternative removal of trees line, creating a cultivated inter-row space of 6 m (compared to the 3 m in the monoculture reference), while the distance among the plants was the same of the MC 2 m (layout 6×2). The widened inter-rows were cultivated each year with Safflower (*Carthamus tinctorius* L.). This specific herbaceous species was selected due to its pronounced rusticity, deep tap-root system, and high adaptability to Mediterranean water-limited environments, making it an ideal low-input crop for agroforestry configurations (Pari et al. 2024). The intercrop was managed on an annual rotation. Soil preparation was carried out in autumn using superficial chisel tillage prior to seeding. Pre-sowing fertilization was applied using diammonium phosphate (18% N, 46% P_2O_5) and urea (46% N). Sowing was performed in mid-February at a seeding rate of 25–30 kg ha⁻¹, achieving a final spatial layout of 3 cm along the row and 14 cm between rows. Crucially, the safflower was cultivated under strictly rainfed conditions with no supplementary irrigation. Detailing this standardized management strategy for the herbaceous component ensures complete transparency regarding below-ground resource interactions, confirming that the allometric and morphometric responses of the adjacent poplar trees were not confounded by asymmetrical irrigation or excessive nutrient leaching from the crop alleys.

Regarding water management, designated plots within both systems were subjected to a controlled irrigation regime totalling 350 mm per growing season. This protocol was consistently applied over the three years of the study preceding the field trials. The irrigation regime comprised 10 applications during the summer period, with one application delivered weekly from the first week of July to the second week of September (2022–2024). Specifically, the irrigation was carried out through a drip irrigation system

linked to an automated control valve. The system was equipped with emitters featuring a flow rate of 5 L h^{-1} and was programmed to deliver 35 mm per weekly application, the precise volume required to restore the soil to field capacity. Considering a mean coppice area of 1 m^2 , this corresponded to 35 L of water per week for each coppice. To minimize evaporative losses and ensure optimal soil infiltration, these automated applications were strictly scheduled during nighttime hours (Mondays from 00:00 to 07:00). This controlled approach minimized confounding variables related to heterogeneous soil moisture and allowed for precise quantification of water inputs for WUE calculations. Consequently, the study analyzed the following four treatments (Fig. 1):

1. Monoculture irrigated (MC-I)
2. Monoculture rainfed (MC-NO) (Rainfall only)
3. Agroforestry irrigated (AF-I)
4. Agroforestry rainfed (AF-NO) (Rainfall only)

Data acquisition

To evaluate the biometric and productive performance of the treatments, eight stumps were comprehensively harvested per treatment for a total of 32 stumps. Parameters recorded for each shoot included total fresh shoot weight, total height, and diameter at breast height (DBH). It is important to specify that the fresh weight measurements encompassed the total above-ground woody biomass, incorporating both the main stem and all lateral branches. This comprehensive biometric assessment was deliberately chosen because it accurately reflects the total carbon allocated to woody structures and represents the true harvestable yield utilized for industrial chipping in Short Rotation Forestry (SRF) bioenergy supply chains. Harvesting was performed manually using a chainsaw. Biomass yield (t ha^{-1}) for the agroforestry system was calculated based on the total land area, including both the tree rows and the intercropping

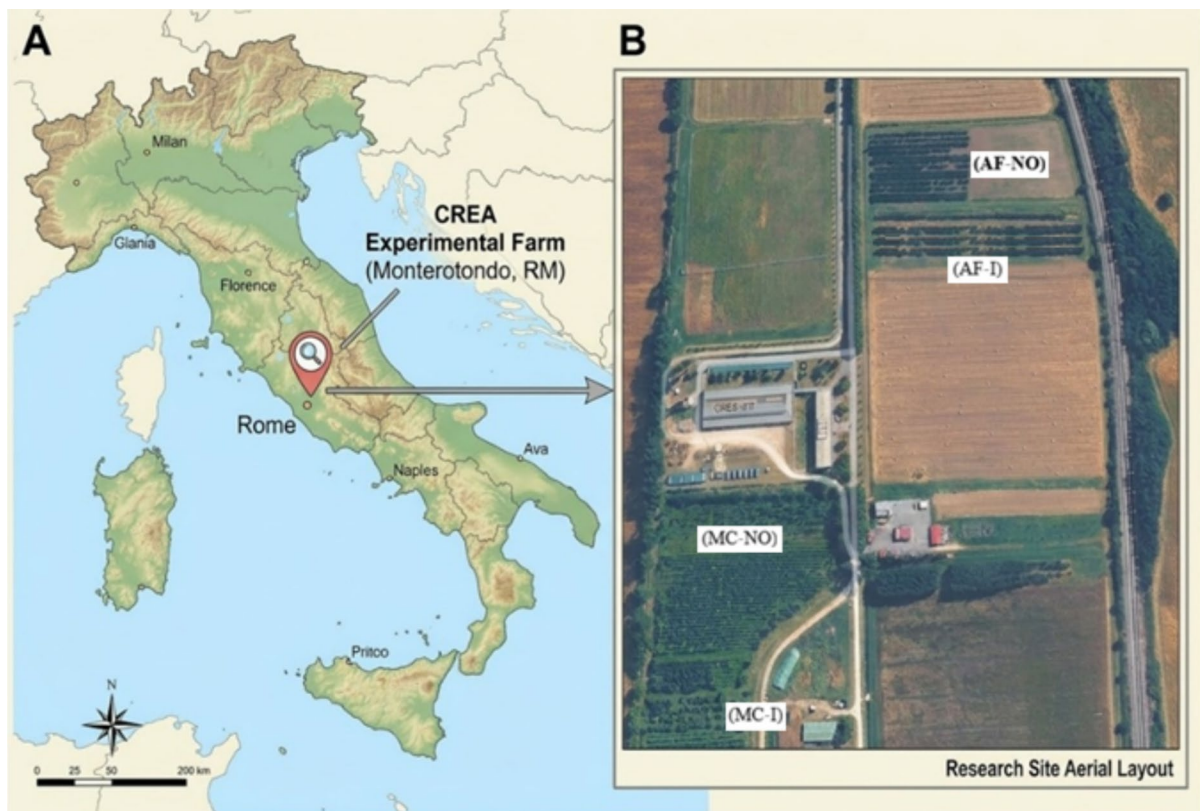


Fig. 1 Geographical location and spatial layout of the experimental site. **A** Location of the CREA-IT experimental farm in Monterotondo (Rome, Central Italy). **B** Aerial view detailing the reference experimental design and the distribution of the four treatments

alleys, to reflect the actual land occupancy. Following harvest, shoot height was measured in the field by aligning samples against a graduated measuring line.

Agronomic Water Use Efficiency was calculated to evaluate the biometric aspects of the tree component under different management regimes. Agronomic Water Use Efficiency (aWUE) was calculated as the ratio of aboveground biomass accumulation to total water input (precipitation plus irrigation) and is expressed in $\text{kg mm}^{-1} \text{m}^{-2}$. Higher values of this index represent higher water use efficiency. This metric isolates the physiological efficiency of the single plant, allowing for a direct comparison of the tree's water-to-biomass conversion capacity across systems with different planting densities. This methodology allowed for a nuanced assessment of how varied water availability and interspecific competition influence the intrinsic productivity of individual poplar stools (Marron et al. 2014).

To provide a functional understanding of tree plasticity and system yield stability, three derivative indices were calculated based on the primary biometric data:

- Slenderness coefficient (SC): This index was calculated to assess the mechanical stability and allometric response of trees to competition. It is defined as the ratio between tree height (H, in meters) and stem diameter at breast height (DBH, converted centimeters):

$$SC = \frac{H}{DBH} \quad (1)$$

Lower values indicate sturdier trees, while higher values suggest susceptibility to mechanical instability (tapering).

- Yield gap (YG): To quantify the vulnerability of each system to water scarcity, the Yield Gap was calculated as the percentage loss in biomass under rainfed conditions compared to the irrigated potential:

$$\text{Yield Gap (\%)} = \frac{(\text{Biomass}_{Irr} - \text{Biomass}_{Rainfed})}{\text{Biomass}_{Irr}} \times 100 \quad (2)$$

- Partial land equivalent ratio (LER_{tree}): To evaluate the specific land-use efficiency of the tree

component, the Partial LER_{tree} was computed. This metric compares the yield of the agroforestry system (Yield_{AF}) to the yield of the monoculture reference (Yield_{Mono}) under identical water regimes:

$$LER_{Tree} = \frac{Yield_{AF}}{Yield_{MC}} \quad (3)$$

Values > 1 indicate that the agroforestry configuration is more efficient per unit of land area than the monoculture.

Statistical analysis

Data were processed to calculate means and standard deviations (SD) for all biometric and physiological variables (n=8 replicates per treatment). To verify the assumptions of normality and homogeneity of variance, data were inspected prior to analysis. Prior to statistical analysis, the assumptions required for analysis of variance (ANOVA) were evaluated. Normality of residuals was tested using the Shapiro–Wilk test, and homogeneity of variance among groups was assessed using Levene's test. As these assumptions were satisfied for all response variables, to evaluate the variance in poplar productivity driven by the management strategy and water regime, a Two-Way Analysis of Variance (ANOVA) was applied. The stratified random sampling of shoots from three distinct spatial sub-areas within each 0.5 ha treatment plot accounts for spatial variability. This framework satisfies the requirements for variance analysis in large-scale applied forestry trials, where establishing completely independent, multi-site block replications is practically impossible and environmentally confounding.

The statistical model included two fixed factors:

- Management system (2 levels: Monoculture vs. Agroforestry).
- Water regime (2 levels: Irrigated vs. Rainfed).

The interaction term (Management \times Irrigation) was included to evaluate whether the two systems responded differently to water availability. Where the ANOVA indicated significant main effects or interactions ($p < 0.05$), means were separated using Tukey's HSD (Honest Significant Difference) post-hoc test to identify specific differences

among the four experimental groups (MC-I, MC-NO, AF-I, AF-NO). Because only one field was available for each cultivation system, the comparison between agroforestry and monoculture should be regarded as a site-specific preliminary case study rather than a fully replicated system-level experiment. Individual trees were treated as observational units for the purpose of exploring treatment-related patterns, while acknowledging that plot-level replication for the cultivation system was not available. Furthermore, to elucidate the multivariate relationships between growth traits (Height, Diameter, Biomass) and physiological efficiency (WUE), a Principal Component Analysis (PCA) was performed. Prior to PCA, data were standardized (z-scores) to eliminate scaling effects arising from different units of measurement. The selection of principal components was based on eigenvalues > 1 and the cumulative percentage of variance explained. All statistical analyses were performed using R 4.4.3 version and the PCA with Past 4.13 version (Hammer, Ø., et al. 2001).

Results

The Table 1 represents a comparative analysis of the parameters collected during the analysis of the different management systems studied: Monoculture Irrigated (MC-I) and Not Irrigated (MC-NO), Agroforestry Irrigated (AF-I) and Not Irrigated (AF-NO).

Descriptive statistics for biomass, tree height, and stem diameter showed clear differences across the

experimental groups. In the Table 1 was presented the biomass yield, where the irrigated monoculture group (MC-I) exhibited the highest value, 16.83 t ha^{-1} , while the group MC-NO showed the lowest value (9.64 t ha^{-1}). The agroforestry systems highlighted intermediate values, 12.22 t ha^{-1} and 11.59 t ha^{-1} for AF-I and AF-NO, respectively.

The biometric analysis reveals that Agroforestry systems, despite lower planting densities, produced trees with superior individual dimensions (both height and diameter) compared to their monoculture counterparts. The Agroforestry showed mean height values of 10.44 m and 8.90 m for AF-I and AF-NO respectively, while the conventional system highlighted values of 9.79 m and 7.96 m for MC-I and MC-NO. Similarly, the values of mean diameter were higher for the agroforestry system (14.04 cm and 11.55 cm for AF-I and AF-NO, respectively) with respect to the conventional system (10.72 cm and 8.99 cm for MC-I and MC-NO, respectively). Concerning the WUE, results highlighted that treatments AF-NO and MC-I reached values higher than 5 (i.e.: 5.32 and 5.21, respectively), while MC-NO showed a value of 4.42 and AF-I 3.78 as the lowest value.

Biomass production: stand yield versus individual growth

The analysis of biomass yield revealed a distinct trade-off between stand-level yield and individual tree growth. In fact, while regarding total productivity per hectare (Table 1), the Irrigated Monoculture (MC-I)

Table 1 Descriptive statistics for biomass, height, diameter and wue across experimental groups (mean of eight repetitions $\pm$ SD)

Group	Total biomass (t ha^{-1})	Stem biomass (kg)	Tree height (m)	Stem diameter (cm)	WUE (kg $\text{mm}^{-1} \text{m}^{-2}$)
MC-I	$16.83 \pm 0.62 \text{ b}$	$5.04 \pm 0.18 \text{ b}$	$9.79 \pm 0.21 \text{ b}$	$10.72 \pm 0.26 \text{ b}$	$5.21 \pm 0.19 \text{ c}$
MC-NO	$9.64 \pm 0.20 \text{ a}$	$2.89 \pm 0.06 \text{ a}$	$7.96 \pm 0.19 \text{ a}$	$8.99 \pm 0.29 \text{ a}$	$4.42 \pm 0.09 \text{ b}$
AF-I	$12.22 \pm 0.37 \text{ d}$	$7.33 \pm 0.22 \text{ d}$	$10.44 \pm 0.17 \text{ d}$	$14.04 \pm 0.29 \text{ d}$	$3.78 \pm 0.11 \text{ a}$
AF-NO	$11.59 \pm 0.25 \text{ c}$	$6.95 \pm 0.15 \text{ c}$	$8.90 \pm 0.23 \text{ c}$	$11.55 \pm 0.37 \text{ c}$	$5.32 \pm 0.12 \text{ c}$
Management effect	$F_{1,28} = 360.59$, $p < 0.001$	$F_{1,28} = 191.25$, $p < 0.001$	$F_{1,28} = 54.66$, $p < 0.001$	$F_{1,28} = 215.11$, $p < 0.001$	$F_{1,28} = 76.45$, $p < 0.001$
Irrigation effect	$F_{1,28} = 169.57$, $p < 0.001$	$F_{1,28} = 37.75$, $p < 0.001$	$F_{1,28} = 114.62$, $p < 0.001$	$F_{1,28} = 28.46$, $p < 0.001$	$F_{1,28} = 41.26$, $p < 0.001$
Interaction effect	$F_{1,28} = 63.39$, $p < 0.001$	$F_{1,28} = 19.93$, $p < 0.001$	$p = 0.45$	$F_{1,28} = 12.32$; $p = 0.0015$	$F_{1,28} = 32.21$; $p < 0.001$

Values within the same column followed by a different letter are statistically different at the level of $p \leq 0.05$ according to Tuckey's HSD test

achieved the highest yield driven by the higher planting density, the analysis of individual above-ground woody biomass showed the opposite trend, highlighting the superior growth of individual trees in Agroforestry systems.

The Two-Way ANOVA for total stem biomass indicated significant main effects for Management ($F_{1,28}=360.59$, $p<0.001$) and Irrigation ($F_{1,28}=169.57$, $p<0.001$), with a significant Interaction effect ($F_{1,28}=63.39$, $p<0.001$). As shown in Table 1, the Irrigated Agroforestry trees (AF-I) accumulated the highest individual biomass (letter 'd'), significantly surpassing the irrigated monoculture trees (MC-I, letter 'b'). Notably, even under rainfed conditions, the Agroforestry trees (AF-NO, letter 'c') showed higher values respect to Monoculture (letter 'a').

Vertical growth (tree height)

System design and water availability also significantly determined vertical growth. The ANOVA results highlighted significant main effects for both Management ($F_{1,28}=54.66$, $p<0.001$) and Irrigation ($F_{1,28}=114.62$, $p<0.001$). The interaction term was not statistically significant ($p=0.45$), suggesting that water availability enhances height similarly across both systems.

The pairwise comparisons shown distinct statistical groupings. Agroforestry trees were consistently taller than their monoculture counterparts. The irrigated agroforestry trees (AF-I) reached the maximum height (letter 'd'), significantly surpassing the irrigated monoculture (MC-I, letter 'c'). Similarly, under rainfed conditions, agroforestry trees (AF-NO, letter 'b') maintained superior vertical growth compared to the rainfed monoculture (MC-NO, letter 'a').

Stem diameter

The analysis of stem diameter provided the strongest evidence for the morphological plasticity of poplar in agroforestry systems. The ANOVA revealed an extremely high F-value for Management ($F_{1,28}=215.11$, $p<0.001$), confirming that lower planting density is the primary driver of secondary growth. Irrigation also played a significant role ($F_{1,28}=28.46$, $p<0.001$); also, significant interaction was observed ($F_{1,28}=12.32$; $p=0.0015$),

indicating that the positive effect of irrigation on stem diameter was magnitude-dependent on the cultivation system.

The Agroforestry trees (AF-I and AF-NO) exhibited significantly larger diameters compared to Monoculture trees. The irrigated AF trees achieved the highest mean diameter (letter 'd'). Notably, even the non-irrigated AF trees (letter 'c') developed significantly thicker stems than the irrigated monoculture trees (MC-I, letter 'b').

Agronomic water use efficiency (aWUE)

The agronomic Water Use Efficiency analysis revealed a complex physiological response, evidenced by a highly significant Management $\times$ Irrigation interaction identified by a Two-Way ANOVA.

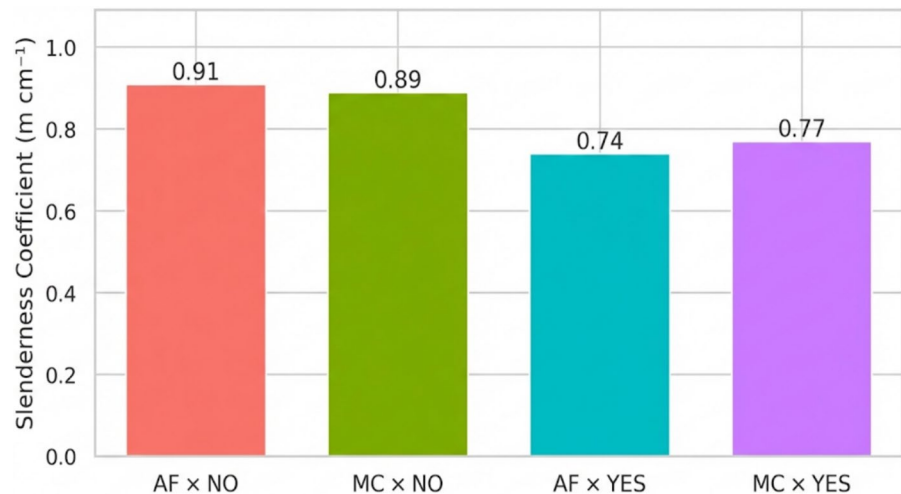
This interaction indicates that the two systems—Monoculture and Agroforestry—optimize water use differently. Specifically, in the Monoculture system, irrigation significantly improved efficiency (MC-I > MC-NO). Conversely, in the Agroforestry system, the highest efficiency was achieved under rainfed conditions (AF-NO). Pairwise comparisons confirmed that the rainfed Agroforestry system (AF-NO) achieved a WUE statistically comparable to the high-input Irrigated Monoculture (MC-I), with both treatments sharing the statistical letter 'c'. In contrast, the lowest efficiency was observed in the Irrigated Agroforestry system (AF-I, letter 'a').

Allometric plasticity and slenderness coefficient

To evaluate the structural response of poplar trees to varying competition levels and water availability, the Slenderness Coefficient (SC), defined as the ratio between tree height and stem diameter (H/DBH), was analysed and presented in the Fig. 2.

The analysis of the biometric data reveals two distinct morphometric strategies driven by the management system:

- *Competition-driven strategy (Monoculture)* Trees in the high-density monoculture system exhibited significantly higher slenderness coefficients, indicative of an imbalance between vertical and radial growth. Specifically, the Irrigated Monoculture (MC-I) recorded a mean value of 0.91 m cm^{-1} ,

Fig. 2 Results for Slenderness coefficient

and the Rainfed Monoculture (MC-NO) a value of 0.89 m cm⁻¹.

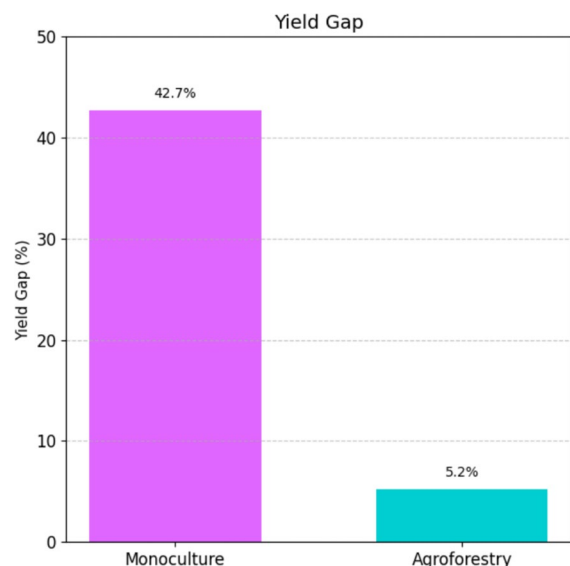
- *Structure-driven strategy (Agroforestry)* Conversely, the Agroforestry system induced a shift towards a more robust architecture. The slenderness coefficient dropped significantly to 0.74 m cm⁻¹ for the Irrigated AF and 0.77 m cm⁻¹ for the Rainfed AF.

Production assessment: yield gap analysis

To quantify the vulnerability of the two production systems to water scarcity, the Yield Gap, defined as the percentage loss in biomass under rainfed conditions compared to the irrigated potential was calculated.

The results highlighted a drastic divergence in system yield stability in the face of hydrological stress, as depicted in Fig. 3:

- *Monoculture system (High vulnerability)* In the conventional monoculture, the transition from irrigated to rainfed conditions resulted in a biomass collapse from 16.83 to 9.64 t ha⁻¹. This corresponds to a massive Yield Gap of 42.7%. Such a decline confirms that the peak productivity of high-density monocultures is strictly dependent on substantial water inputs, making the system highly fragile in drought-prone scenarios.

**Fig. 3** Results of yield gap analysis

- *Agroforestry system (High yield stability)* In contrast, the agroforestry system demonstrated remarkable stability. The biomass reduction from (AF-I) to (AF-NI) resulted in a minimal Yield Gap of only 5.2%. By maintaining nearly 95% of its productive potential even without irrigation, the agroforestry system is statistically validated as a climate-resilient strategy capable of buffering environmental stress.

Land use efficiency: partial LER_{tree} analysis

The efficiency of the tree component in utilizing available land resources was evaluated using the *Partial Land Equivalent Ratio* (LER_{tree}), calculated as the ratio of agroforestry yield to monoculture yield (Yield_{AF} / Yield_{Mono}) under identical water regimes.

The analysis reveals a functional inversion of land-use efficiency driven by water availability:

- *Irrigated conditions* (*Partial LER_{tree}* = 0.73) Under non-limiting water conditions, the Monoculture outperforms the Agroforestry system per unit of land area (LER_{tree} < 1). This indicates that when resources are abundant, the higher planting density of the monoculture successfully maximizes biomass capture per hectare.
- *Rainfed conditions* (*Partial LER_{tree}* = 1.20) Crucially, under water-limited conditions, the Agroforestry system becomes 20% more efficient than the monoculture.

Principal component analysis

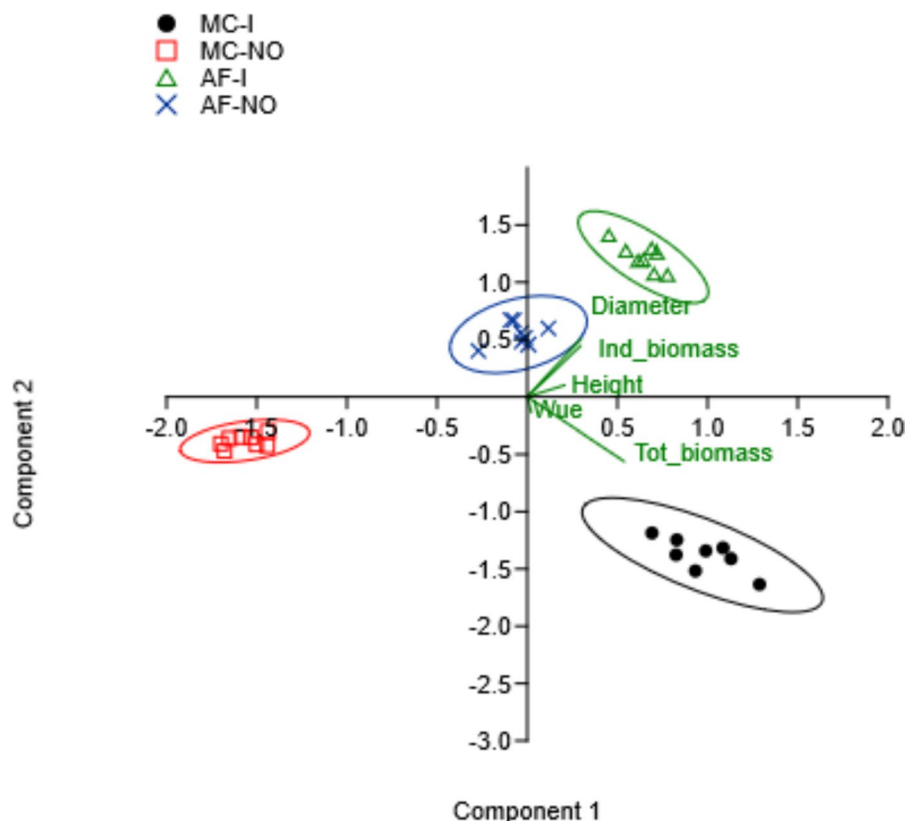
The Principal Component Analysis, graphically represented in Fig. 4, provides a multivariate perspective on the interplay between various growth traits, agronomic water use efficiency, and different management systems. This biplot illustrates how the various groups cluster and how different variables contribute to these clusters, offering a visual synthesis of the complex physiological responses observed.

Values of the eigenvalue and of variance explained by each PC are reported in Table 2.

Table 2 Eigenvalue table

PC	Eigenvalue	% variance
1	8.94041	57.979
2	5.70305	36.984
3	0.721885	4.6814
4	0.0357696	0.23197
5	0.0190704	0.12367

Fig. 4 Biplot of the results of principal component analysis. Black: MC-I; Green: AF-I; Red: MC-NO; Blue: AF-NO



The first two principal components explained 94.96% of the total variance (Table 2), indicating a robust representation of the dataset.

- *PC1 (57.98% variance)* This component, represented by the horizontal axis, primarily reflects overall growth performance. Groups positioned to the right exhibit higher values for growth traits. Figure 4 clearly shows the “high-performance” groups Monoculture Irrigated and Agroforestry Irrigated clustered on the right side of the biplot. Conversely, the stress-prone Monoculture Non-Irrigated group is located on the far left indicative of lower overall growth.
- *PC2 (36.98% variance)* This vertical axis differentiates between growth strategies. The Agroforestry groups cluster at the top of Fig. 4. They are strongly associated with vectors such as Diameter, Individual Biomass, and Height, suggesting an emphasis on “Individual Growth” and the development of larger individual tree dimensions. In contrast, the Monoculture Irrigated group is positioned at the bottom, closely aligned with the Total Biomass vector, indicating a strategy focused on maximizing “Stand Yield” or total biomass per unit area.

The length of WUE vector is moderate, suggesting that this index contributes significantly to the variance explained by the principal components, but it is not the dominant variable.

Discussion

This study investigated the comparative performance of monoculture and agroforestry management systems under both irrigated and non-irrigated conditions, providing valuable insights into biomass production, growth dynamics, water use efficiency, and overall system yield stability. The findings highlight distinct morphometric strategies and physiological responses shaped by management and water availability, confirming the core argument for agroforestry through the nuanced results in biomass and height.

Trade-offs in biomass production and growth strategies

Our results support totally the research hypothesis that stand density increases individual tree biomass due to lower resource competition. In fact, a fundamental trade-off was observed between stand-level biomass yield and individual tree growth. The Irrigated Monoculture demonstrated the highest total biomass yield (16.83 t ha^{-1}), primarily attributed to its higher planting density. This aligns with conventional agricultural principles that prioritize high-density planting for maximizing output in monocultures. However, this strategy came at the expense of individual tree development. In fact, agroforestry systems, despite having lower planting densities, fostered superior individual tree growth. The analysis of individual above-ground woody biomass showed that Irrigated Agroforestry trees accumulated the highest individual biomass, significantly surpassing irrigated monoculture trees. This trend was also evident in biometric parameters such as height and diameter. Notably, even non-irrigated agroforestry trees developed significantly thicker stems than irrigated monoculture trees, demonstrating that spatial arrangement overrides water availability in determining individual trunk thickness. The significant interaction observed for stem diameter confirms this mechanism: while irrigation boosted growth in both systems, its relative impact was modulated by competition. In the monoculture, water relief was critical for secondary growth, whereas in the agroforestry system, the wider spacing allowed trees to maintain high growth rates even under rainfed conditions, dampening the differential between irrigated and non-irrigated plots. This suggests a “structure-driven” growth strategy in agroforestry, promoting robust individual tree architecture, as opposed to the “high-density driven” strategy in monocultures which leads to more slender trees. The enhanced individual growth rates observed in AF systems, manifested in both stem diameter and tree height, suggest a superior wood quality potential, a distinct trait that can be differentiated using advanced analytical techniques (Heim et al. 2023).

The impressive vertical growth observed in the agroforestry trees (AF), despite the wider spacing, warrants specific ecophysiological interpretation. Typically, in high-density monocultures, intense competition for light alters the red to far-red radiation

ratio perceived by phytochromes, triggering a shade-avoidance syndrome (etiolation). This mechanism stimulates rapid vertical stem elongation as trees race to reach the upper canopy, frequently at the expense of radial growth (Ballaré & Pierik 2017). However, this standard forestry paradigm assumes that light is the primary limiting factor. In our Mediterranean system, below-ground competition for water supersedes light as the primary constraint on growth, fundamentally altering morphological responses (Fuertes et al. 2022), although factors like elevated CO₂ concentrations could partially interact with drought stress in juvenile stages (Orság et al. 2024). From a physiological perspective, primary (vertical) growth is exquisitely sensitive to water deficits, as stem elongation is physically driven by cell turgor pressure. In the high-density monoculture, severe root-level competition leads to rapid soil moisture depletion, inducing earlier stomatal closure and reducing the cell turgor necessary for apical expansion (Cocozza et al. 2010). Conversely, the wider spacing in the AF system drastically reduces this root-level competition (Forey et al. 2015). By maintaining access to a larger per-capita soil water reservoir, the AF trees can sustain optimal stomatal conductance and cell turgor for longer periods during the growing season. Concurrently, the open canopy structure allows for optimal light interception across the entire tree crown, maximizing whole-tree carbon assimilation (Forrester 2015). This physiological release allows individual trees to acquire sufficient resources to simultaneously maximize both robust radial expansion (diameter) and the superior apical dominance (height) inherent to the 'AF-48' genotype." The analysis of the slenderness coefficient further supports these distinct morphometric strategies: high-density monocultures exhibited significantly higher slenderness coefficients (0.89–0.91 m cm⁻¹), indicative of an imbalance between vertical and radial growth. In contrast, the agroforestry system induced a shift towards a more robust architecture (0.74–0.77 m cm⁻¹), reflecting a "Structure-Driven Strategy."

These findings support the research hypothesis that the management systems while reducing stand density leads to an increase in biomass quality.

These allometric responses strongly align with observations from extensive poplar agroforestry optimization of planting geometries (Chavan et al. 2024), yield indices assessments (Ahmadloo & Eskandari

2024; Yasin et al. 2018), and variable-density plantation trials in China, where optimized, wider tree spacing has been demonstrated to significantly enhance individual stem volume and mitigate severe interspecific resource bottlenecks (e.g., Fang et al. 2007). By alleviating root-level competition, such wide-alley configurations maximize per-tree cambial activity and biomass partitioning to the main stem. Furthermore, while this study focuses exclusively on 'AF-48', it is essential to contextualize its morphometric performance against 'I-214' (*Populus×euramericana*), the most historically prevalent and widely studied clone in Italian poplar cultivation. While 'I-214' is renowned for exceptional peak productivity under optimal irrigation, it frequently exhibits high vulnerability to hydraulic failure and severe drought stress under rainfed Mediterranean conditions (Jha 2018). The robust physiological plasticity and yield stability of 'AF-48' observed in our rainfed agroforestry setup suggest that it may offer a highly resilient and structurally superior alternative for maintaining biomass supply chains in future water-limited climatic scenarios.

Water use optimization and system yield stability

Agronomic Water Use Efficiency analysis revealed a complex physiological response, evidenced by a highly significant Management×Irrigation interaction identified by the Two-Way ANOVA. This interaction indicates that the two systems—Monoculture and Agroforestry—optimize water use differently. Specifically, in the monoculture system, irrigation notably improved WUE, with a significant increase in efficiency as also stated by Stape et al. 2004. This improvement was accompanied by an 18% rise in agronomic water use efficiency, highlighting the positive interaction between water availability and productivity under monoculture management as previously found in Stape et al. 2004. Conversely, in the agroforestry system, the highest agronomic water use efficiency was achieved under rainfed conditions. These results confirmed that agroforestry systems possess an inherent ability to optimize water use and reduce water losses under conditions of scarcity, potentially due to reduced inter-tree competition and improved microclimatic conditions (Blanchet, 2021, Hatfield & Dold 2019; "Water-Use Efficiency: Advances and Challenges in a Changing Climate,"

2019). The lowest efficiency was observed in the Irrigated Agroforestry system ($3.78 \text{ kg mm}^{-1} \text{ m}^{-2}$), indicating that continuous irrigation might not always translate to proportional gains in agronomic water efficiency within this system. In fact, irrigation in AF systems produced only a modest biomass increase of 5.4%, while agronomic water use efficiency declined by 29% confirming the results of Forrester 2015 and Thomas et al. 2022. These contrasting outcomes underscore that identical irrigation inputs can generate divergent effects depending on the management system, confirming that resource additions in low-density systems may yield diminishing returns in terms of efficiency compared to intensive monocultures (Forrester 2015; Thomas et al. 2022).

The yield stability assessment, quantified by the Yield Gap analysis, further underscored the contrasting adaptive capacities of the two systems to water scarcity. Monoculture systems exhibited a substantial biomass collapse under rainfed conditions, resulting in a massive Yield Gap of 42.7%. This profound vulnerability confirms the strict dependence of high-density monocultures on consistent water inputs, rendering them fragile in drought-prone environments. In stark contrast, the agroforestry system demonstrated remarkable stability, with a minimal Yield Gap of only 5.2% under rainfed conditions. Agroforestry maintained nearly 95% of its productive potential without irrigation. While specific microclimatic variables were not directly measured in this trial, we hypothesize that this yield stability is strongly associated with the system's capacity to buffer environmental stress (Thevs et al. 2021). Literature extensively suggests that agroforestry architectures can generate favourable microclimates that reduce canopy-level evaporative water losses, thereby mitigating drought impacts.

Land use efficiency and multivariate perspectives

The Partial Land Equivalent Ratio (LER_{tree}) analysis revealed a functional inversion of land-use efficiency driven by water availability. Under irrigated, non-limiting water conditions, the Monoculture outperforms the Agroforestry system per unit of land area. This indicates that when resources are abundant, the higher planting density of the monoculture successfully maximizes biomass production per hectare. Remarkably, under water-limited (rainfed)

conditions, the Partial LER_{tree} exceeded 1 (1.20), indicating that the agroforestry system produced higher absolute woody biomass per hectare than the monoculture, effectively overturning the density gap through superior individual tree biometric aspects. This finding stands in contrast to the results of Cozzolino et al. 2025, where the herbaceous species (*Carthamus tinctorius* L.) cultivated in intercropping, was found to be lower in each studied parameter. This overturning suggests a strong facilitation effect: in the absence of irrigation, the reduced inter-tree competition and improved microclimatic conditions of the agroforestry system allow individual trees to thrive. Conversely, the monoculture suffers from intense competition for limited soil moisture, leading to a system-level failure in resource conversion efficiency.

The Principal Component Analysis, provides a multivariate synthesis of the findings, effectively differentiating the management systems based on their growth traits and resource utilization strategies. The biplot suggested that the PCA was able to clearly distinguish between cropping systems and water conditions, highlighting the trade-off between absolute productivity and physiological efficiency. The first two principal components explained 94.96% of the total variance, indicating a robust representation of the dataset.

The MC-I group, situated in the bottom-right quadrant, is strongly aligned with the Total Biomass vector and is also positioned favourably in the direction of the WUE vector. This graphically supports the finding that irrigation significantly improves efficiency in monoculture systems, where the strategy is to maximize stand yield through high input. The AF-I group is in the top-right quadrant, showing high individual growth traits and overall good performance (positive PC1). While still performing well in terms of overall growth, its position relative to the WUE vector suggests it's less directly aligned with high WUE compared to MC-I, which aligns with the previous observation of diminished returns from irrigation in agroforestry systems. The AF-NO group is located in the top-left quadrant, associated with individual growth traits, but not strongly aligned with the WUE vector. This visual representation, when considered alongside the previous finding that rainfed Agroforestry achieved a WUE statistically comparable to high-input Irrigated Monoculture, highlights the unique physiological yield stability and efficient

resource use of these systems under non-irrigated conditions. The MC-NO group, located on the far left, is the furthest from the WUE vector, consistent with its characterization as a “stress-prone” group with lower efficiency.

The last research hypothesis (H3) was confirmed by the analysis of the results of agronomic water use efficiency and ecophysiological and productivity indexes, highlighting the effect of the interaction between management and irrigation systems.

Implications for sustainable land management and water scenarios

The findings underscore a crucial trade-off between land productivity and resource sustainability. While the MC-I system yielded the highest absolute biomass, this maximum yield is achieved at the expense of high-water consumption and is highly sensitive to water availability. The results clearly indicate that irrigation exerted a substantial influence on plant growth in monoculture systems, leading to significant increases in both height and diameter and ultimately enhancing total biomass production. In contrast, the AF-NO system, despite producing lower total biomass per hectare, exhibits superior water use efficiency and benefits from a stable microclimate that reduces evaporative water losses like other studies (Karlen & Rice 2017; Blanchet 2021). This makes it a more environmentally sound and resilient choice for long-term sustainable biomass production, particularly in regions with limited water resources (Thevs et al. 2021).

Although the reduced biomass yield per hectare observed in the AF-NO system may result in lower immediate economic returns, this limitation is mitigated through the intercropping of an herbaceous species in the alleys. This intercrop can be irrigated using the water ‘saved’ by the trees—defined here as the volume of water typically required by a high-density monoculture that is deliberately withheld from the resilient agroforestry trees, thereby keeping the total system-level water footprint neutral while diversifying output. In fact, a typical irrigated monoculture, such as MC-I, in this region requires an average of 5000 m³ ha⁻¹ of water irrigation per year (Pari et al. 2023). Applying AF-NO management system would allow to save this quantity of water to be valorised through further irrigation purposes of herbaceous species grown in

the alley. Additional farmer income could be generated considering that the economic value of water varies significantly by crop and region (Colby 2018; D’Odorico et al., 2020). For example, several studies have demonstrated that the marginal value of water can range from less than and \$21 per acre-foot for grain sorghum to \$536 for tomatoes in California, with other crops like wheat, barley, maize, and sugar beet also having quantifiable water footprints per unit monetary value (Colby 2018; Güney et al., 2024). This strategy is particularly relevant for agroforestry systems. While the tree canopy provides a shade effect that can beneficially reduce crop evapotranspiration during peak summer heat, it is critical to carefully manage the system to mitigate the inevitable reduction in radiation availability for the herbaceous layer (Mantino et al. 2023). Furthermore, the broader adoption of these agroforestry systems aligns with evolving European Commission policies advocating for carbon farming initiatives. However, significant technical, policy, and economic barriers remain for their full implementation in Europe (Mosquera-Losada et al., 2023; Mantino et al. 2023).

In addition, the production of woody material of higher quality within the AF-NO framework offers compensatory value, thereby enhancing the overall multifunctionality and sustainability of the system. Furthermore, the increasing uncertainty of water supply and the escalating frequency of prolonged summer droughts driven by climate change in the Mediterranean region necessitate a transition toward agricultural paradigms that do not rely on fixed, high-volume irrigation quotas (Santos et al. 2023). The pronounced yield stability (i.e., the minimal Yield Gap) demonstrated by the agroforestry system under rainfed conditions highlights a crucial ecological buffer (Blanchet 2021). This positions the integration of trees in lower-density, mixed spatial configurations not just as an immediate water-saving measure, but as a critical, long-term adaptation strategy against highly unpredictable hydrological futures (Hatfield & Dold 2019; Raihan 2023), ensuring the viability of biobased supply chains even under severe structural water deficits.

Conclusions

This study shows that agroforestry provides a more resilient and efficient strategy for poplar biomass

production under Mediterranean water limited conditions. While irrigated monoculture maximizes stand level yield, it suffers severe productivity losses when irrigation is removed. In contrast, agroforestry enhances individual tree growth, maintains high Water Use Efficiency under rainfed conditions, and exhibits minimal yield reduction during drought. These results demonstrate that reducing stand density and increasing spatial heterogeneity strengthen tree performance and system stability. Agroforestry therefore represents a robust alternative to conventional monoculture, offering a viable pathway for sustainable biomass production in increasingly water scarce environments.

Although this study explored several relevant parameters, it should be regarded as a case study, and conclusions must therefore be drawn with caution due to the lack of comparative data from other tree species. Future research should prioritize Life Cycle Assessment (LCA) (as highlighted by Quevedo-Cascante et al. 2022) and Life Cycle Costing (LCC) to more comprehensively assess the environmental and economic implications of the management practices investigated, and should rely on replicated trials to strengthen statistical robustness. Particular attention should be directed towards quantifying long-term carbon sequestration potential and the broader ecosystem services provided by agroforestry systems compared to conventional monocultures.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Luca Cozzolino, Francesco Latterini, and Simone Bergonzoli. The first draft of the manuscript was written by Luca Cozzolino and Simone Bergonzoli. Rodolfo Picchio and Luigi Pari provided supervision and critical revision throughout the entire process. Claudia Zaccaria contributed to the review of previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This research was carried out within the MIDAS project, which has received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No. 101082070. The APC was funded by MIDAS project.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request **,**

Declarations

Conflict of interest The authors declare no competing interests.

Consent to participate Not applicable.

Consent to publish Not applicable.

Ethics approval Not applicable.

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