



Climate-sensitive modelling of poplar short-rotation plantations: 3-PG growth predictions considering water limited-conditions

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ABSTRACT

The production of woody biomass for bioenergy and bioproducts is crucial in the transition towards sustainable energy systems in the context of bioeconomy development. Poplar short-rotation coppice (SRC) plantations represent a promising lignocellulosic resource. Climate-sensitive, process-based models are therefore essential for projecting biomass yields under global change. Their relevance becomes even more evident for SRC plantations under Mediterranean conditions, where irrigation is often required, given the upcoming scenarios of increasing water limitation.

This study adapt and validate the 3-PG (Physiological Principles in Predicting Growth) model for poplar SRC systems, focusing on the biomass-oriented hybrid *Populus* 'AF2' to improve yield predictions across successive rotations. We evaluated biomass production under contrasting irrigation scenarios: optimal (T1) and restricted water availability (T2), with a detailed analysis of net primary production allocation to foliage, stems, and roots. High precision was achieved for leaf area index, leaf and stem biomass, especially in rotation 1, while root estimates showed greater variability and remained the most challenging component to simulate.

Water limitation markedly reduced growth, decreasing stem, leaf, and root biomass by 39.25 %, 47.85 %, and 45.13 %, respectively. Future climate simulations (SSP3-7.0, 2040–2070) revealed site-specific responses: productivity declined slightly at the driest site, whereas northern locations experienced moderate gains where warming coincided with stable or increased precipitation. These results indicate that water availability will remain the dominant constraint on SRC productivity under future Mediterranean climates.

Overall, the adapted 3-PG model provides a valuable tool for assessing productivity, carbon allocation, biomass partitioning, and climate–water interactions in poplar SRC systems.

1. Introduction

The degree of future warming is intrinsically tied to the cumulative greenhouse gas (GHG) emissions released through to the end of this century [1,2]. This challenge aligns closely with the European Commission's ambitious objective of developing a competitive, resource-efficient, low-carbon economy by 2050 [3].

Forests are expected to play a major role in supplying the feed-stock and services required [4,5], while also serving as the primary habitat for terrestrial biodiversity, the largest terrestrial carbon (C) sink, and a major contributor to terrestrial precipitation [6]. The forest-based sector further supports energy transitions, with woody biomass being a crucial

resource for bioenergy and bioproducts [6–8].

In particular, planted forests, as an essential source of woody biomass, offer multifunctional benefits, including CO₂ sequestration in the biomass-soil complex, enhanced biodiversity compared to agricultural land, reduced soil erosion, improved landscape diversity, and phytoremediation. Properly managed plantations can yield more biomass per hectare than natural forests and serve as an efficient short-to medium-term C sequestration tool [9,10], reducing pressure on natural forests and promoting sustainable management practices [11].

The production of lignocellulosic biomass from short-rotation plantations (SRC), and the growing potential use of this biomass for bioproducts are among the most promising contributions of the forest-based

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sector [6–8]. Fast-growing species, particularly poplars (*Populus* spp.), are widely cultivated worldwide, including Southern Europe, due to rapid growth, ease of vegetative propagation, and availability of improved genetic material [12–15]. These plantations achieve high productivity in a short period of time [16], storing a large amount of C in the different biomass fractions [17,18]. Across Europe, quartile productivity ranges from 4.75 to 13.40 Mg dm (dry matter) ha⁻¹ year⁻¹, depending on site characteristics, genetic material, plantation design, and management practices [19,20]. Under Mediterranean climate, SRC plantations are notably productive due to a combination of factors, including the vegetative period, optimal average temperatures, and the irrigation applied during the summer months [20]. Productivity may be seriously limited by water deficit during the growing seasons [21], making irrigation essential to ensure the survival of poplar plantations in regions with summer drought [22]. In Spain, the average potential yield under standard management is estimated to be around 15.3 Mg dm ha⁻¹ year⁻¹ [23].

Despite the advantages of irrigation in terms of productivity enhancement, climate change increasingly raises concerns about water scarcity. As climate change progresses, water limitation and the need for irrigation are also becoming of concern in climatic zones where, until recently, such concerns did not exist [24–27]. Evaluating the impact of water limitation on plantation productivity is therefore essential. Optimizing management to maximize biomass and support market demands requires understanding tree growth and allometry, along with key factors influencing cultivation, including genotype, site conditions, and management practices [25,28–30].

Integrating these factors into predictive tools is crucial for reliable yield estimation. Climate-sensitive Process-Based Models (PBMs) simulate the interactions between plant growth and the environment, incorporating responses to changing conditions [31–35].

Several PBMs have been applied to biomass prediction for herbaceous and woody crops, such as switchgrass, (*Panicum virgatum* L.), miscanthus (*Miscanthus × giganteus* Greef & Deuter), sugarcane (*Saccharum officinarum* L.), willow (*Salix* spp.), or poplar (*Populus* spp.) [36]. For poplar SRC plantations, good predictions have been achieved using PBMs such as: SECRETS [37]; ECOPHYS, developed for poplars in the juvenile phase [38]; ForestGrowth, adapted and parameterized for both SRC poplar and willow [39] and, the 3-PG (Physiological Principles Predicting Growth) model, which has been successfully applied to predict forest productivity in plantations of fast-growing trees, including poplar and willow [40–42]. Despite their potential, PBMs are rarely used in routine forest management due to complexity, though they are valuable for climate change modelling [35].

Among these models, the 3-PG model is notable for its monthly time step captures long-term growth trends rather than daily fluctuations [43]. Designed in collaboration with end-users, it is simple, transparent, and suitable for management applications, allowing scenario testing [44,45]. The 3-PG model predicts growth and yield of stem, root, and foliage fractions based on environmental and management factors, particularly water availability, integrating physiological, soil, and climatic data to guide decisions on site selection, irrigation, planting density, and thinning. While the model is relatively simple and scalable, it requires local calibration to improve accuracy, and parameterization must be conducted at the species level.

Although the 3-PG model was originally developed for evergreen species [43], adaptations have been made to simulate growth for deciduous species, accounting for dormancy, bud burst, spring leaf growth, and leaf fall. It has successfully simulated growth in willow plantations [46,47], subtropical mixed-species stands [48], and deciduous forests including white birch and sessile oak [32,49]. However, few studies have specifically addressed poplar plantations, with adaptations to the 3-PG model primarily focused on simulating sprouting and regrowth. These adaptations often rely on species-specific parameters derived from literature [42,46,50–52]. Challenges remain in accurately predicting net primary production (NPP) allocation among leaves, stem, and roots, and

in simulating regrowth after harvest [47]. For instance, variations in biomass allocation under different irrigation regimes or changes in biomass growth across successive rotations can substantially influence productivity estimates. These difficulties highlight the need for species-specific adaptations, as presented in our study, to improve the reliability of 3-PG simulations for poplar SRC plantations.

This study builds upon our previous work [53], which focused on adapting and experimentally parameterizing foliar variables of the 3-PG model for poplar SRC plantations under contrasting irrigation regimes during the first rotation. While the previous study addressed leaf-specific variables such as SLA, litterfall rate (γF), and maximum canopy quantum efficiency (αC_x), the present research extends this framework by (i) analyzing the allocation of NPP among foliage, stem, and roots under contrasting irrigation scenarios (optimal vs. restricted irrigation), (ii) calibrating and validating all biomass fractions for SRC poplar plantations in Spain, and (iii) projecting growth for successive rotations. The main aim of this study is to improve the 3-PG model for poplar SRC plantations to provide a robust tool for predicting long-term productivity and biomass partitioning under Mediterranean conditions.

2. Materials and methods

2.1. Model description

Our study further develops the modifications performed in previous work [53] to version 2.7 of the 3PGpjs Microsoft Excel spreadsheet code [54], which focused on foliar parameters for *Populus* clone ‘AF2’ during the first rotation. Since the species under investigation in our study is deciduous and cultivated in short rotations for biomass production, adjustments were necessary to tailor the structure and equations of the 3-PG model accordingly. In particular, this work modifies the biomass distribution module by implementing an observed monthly variation pattern in the NPP allocation parameters to the different biomass components: foliage, stem, and root. Another important modification involved the explicit modelling of regrowth after each harvest, which is essential for accurately simulating short-rotation management systems across successive rotations. A detailed explanation of these adapted process models, along with the complete mathematical formulation and all equations, is provided in [Supplementary Material S1](#). A detailed explanation of these adapted process models is provided:

2.1.1. Assimilation of carbohydrates

We have followed the approach of Forrester et al. [55] and considered the fraction of ground shaded by the canopy to calculate the intercepted radiation (Eq. S(1) in [Supplementary Material S1.1](#)).

The Leaf Area Index (LAI) should be obtained alongside the plantation age (t , months) by multiplying the observed foliage biomass (W_f , Mg ha⁻¹) by the specific leaf area (SLA, m² kg⁻¹). It is important to note that LAI should vary monthly throughout the growing season rather than simply varying according to plantation age, as has been the common approach with evergreen species. To implement this approach, leaf fall should be simulated annually by considering the litterfall rate as a function of the month [53]. Furthermore, leaf development needs to be modelled each spring, beginning with 10 % of the root biomass ($\eta_r = 0.10$). This portion of root carbohydrate reserves generates W_f each spring, which guarantees that the model generates an appropriate LAI value to initiate a new growing season [56]. These modifications will ensure that LAI remains null during the dormant season, indicating no NPP production and preventing reductions in growth due to frost days. The frost modifier is retained to account for late frost that could affect new leaves. Moreover, with null LAI during the dormant season, evapotranspiration (ET) has not been considered during this period, even though direct soil evaporation would result in small losses in the water balance. We estimated that the presence of an anti-weed mesh in the trials would reduce losses to a negligible level.

NPP and growth modifiers were calculated following the 3-PG

framework, while the complete set of equations, including NPP calculation, the six growth modifiers (temperature, frost, nutrition, vapour pressure deficit, soil moisture, and age), and their dependency on site factors and observed monthly meteorological variables, is provided in [Supplementary Material S1.2](#).

2.1.2. Distribution of biomass

The temporal evolution of stem (W_s), foliage (W_f) and root (W_r) biomass is the result of the monthly process of allocation of NPP to each compartment and the losses derived from litterfall and root turnover. These carbon balance equations (Eq.S(10)–(12)), are provided in [Supplementary Material S1.3](#).

The leaf fall ratio γ_F must be adapted to the deciduous nature of the poplar species so that the parameters related to these species-specific variables can be estimated monthly. We used the calculated litterfall rates from Fuertes et al. [53] depending on the monthly variations in the total leaf count on the tree.

We implemented the observed monthly variation pattern in the NPP allocation parameters to the different biomass components (W_s , W_f , and W_r) over the first rotation (3 growing seasons). To achieve this, variables related to allometric relationships and partitioning, such as pFS2 (The foliage–stem partitioning ratio at diameter at breast height (B) 2 cm trees), pFS20 (The foliage–stem partitioning ratio for B = 20 cm trees), η_{Rx} (Maximum fraction of NPP to roots), and η_{Rn} (Minimum fraction of NPP to roots), were replaced with their corresponding observed monthly foliage, stem, and root NPP distribution rates (η_F , η_S , and η_R , respectively) throughout the growing seasons.

To determine the allocation rates of NPP to biomass components, the estimated NPP values for each month were progressively distributed to reduce the differences between the observed and estimated biomass components for the following month, always considering the constraint that the three rates should sum to unity.

Initially, the variation pattern of η_F , η_S , and η_R across the growing season was smoothed while considering the typical ranges of variation of these ratios (η_R is usually bound between 0.2 and 0.8), with the ratio η_F/η_S being close to 1 for young stands (in our case, the early growing season) and declining towards 0.2 with age (later growing season in our study).

We specifically analyzed the variations in allocation parameters between the two irrigation regimes: 100 % FC irrigation (T1) and 50 % irrigation restriction (T2), taking into account different plantation ages (1, 2, and 3 years) for each regime.

2.1.3. Water balance

The 3-PG model performs a monthly balance of the water inputs (rainfall R , mm m^{-2} and irrigation I_r , mm m^{-2}) and water losses due to canopy interception and evapotranspiration (I and E_T , respectively, mm m^{-2}). This balance determines the soil water availability (θ , mm), with any excess over the maximum available soil water (ASW_{max} , mm) being lost as runoff or drainage. In the present study, ASW_{max} was calculated based on soil data following the approach of Domingo Santos et al. [57], considering just the available fraction of soil water, (Eq.S(13)–(15) in [Supplementary Material S1.4](#)).

2.1.4. Stand biometry

Regarding the stand biometry sub-model, the adaptation consisted of considering the number of stools per ha (instead of the total number of shoots) as representative of SRC density, using the basal diameter (over bark at 10 cm) of the dominant shoot, defined as $D_{10}(mm)$, to characterize stand biometry, and calculating stem biomass W_s , which is the variable of interest for poplar SRC, rather than timber volume. This sub-model deals with the basic allometric relationships needed to convert the biomass values into variables of interest to forest managers (Eq. S (16) in [Supplementary Material S1.5](#)).

2.1.5. Stocking and mortality

Furthermore, we included mortality in accordance with the procedure by Landsberg and Sands [44], revealing that the total mortality rate at the end of the first rotations was 5 %, increasing to 7 % and 8 % for the third and fourth rotations, respectively, based on observed data and complemented by expert knowledge. While these rates are lower than those reported by other authors, such as Štochlová et al. [58], who observed mortality rates around 15 % for successive rotations, studies conducted in the Mediterranean region have consistently demonstrated that mortality rates remained below 15 %, even under the most adverse scenarios, across a wide range of planting densities varying from 6666 to 33,333 trees per hectare [59].

No self-thinning was considered, as the SRC stands are managed in very short rotations. In this approach the number of parameters related to self-thinning and mortality are limited to the average rate of mortality and the parameters m_F , m_S , m_R .

Lastly, another modification involved modelling regrowth after each harvest assuming a recommended plantation cycle of 12 years (4 rotations of 3 years each) [20]. In the 3-PG model, foliage is required for growth. However, after harvesting there is a large root mass but no foliage. In previous studies, Hart et al. [51] modelled post-coppice regrowth by a variable root contribution to shoot and leaf growth, up to a maximum of 15 % monthly. In our case, we assumed a fixed 10 % of the root biomass would contribute to regrowth, with 4 % allocated to leaf growth and 6 % to stem growth. It should be noted that, starting from the third rotation, root carbohydrate reserves for regrowth will have decreased to 0.075 and 0.05 (per-unit) in the third and fourth rotations, respectively, due to root decay [56,60].

For successive rotations, the NPP distribution rates to the different biomass components (W_f , W_s , and W_r) were based on the observed growth rates of the first rotation, excluding the year of implementation (first year). We applied the NPP distribution rates from the second year of the initial rotation to both the first and second years of the next rotation. The NPP distribution rates for the last year of the next rotation were aligned with those of the third year of the initial rotation.

Our research mainly concentrated on suggesting the majority of the parameters derived from observed data. The other parameters were estimated from existing literature on hybrid poplars, or determined through the best-fit of the model, while default 3-PG values were applied to the remaining parameters.

2.2. Data source and field measurements of calibration and validation sites

Data for calibration in this study were collected from a poplar SRC plantation (S1-trial1) established manually in early spring 2018 using hardwood cuttings of 25 cm in length. The plantation was designed for a three-year rotation with a planting density of 10,000 trees ha^{-1} (spacing of 2m $\times$ 0.5m). Within the S1-trial1, there are separate plots: T1, which was irrigated to field capacity (FC), and the adjacent plot, T2, which was irrigated at 50 % of FC using a drip irrigation system from May to October each year throughout the rotation. Each plot covered an area of 10 $\times$ 30 m and contained 300 trees arranged in five rows. For sampling, three trees per plot (T1 and T2) were harvested each month, together with edge trees used as a buffer. Measurements in S1-trial1 (T1 and T2) were consistently scheduled around the 21st $\pm$ 3 days, covering the three growing seasons of the rotation. In total, 138 trees were measured—72 of them with root extraction—across 23 campaigns during the first rotation (3 years). This resulted in a total of 138 trees measured, with 72 of these including root extraction, over 23 monthly campaigns during the first rotation (3 years).

The research was conducted in central Spain (40° 27' 27" N; 3° 45' 01" W) at an elevation of 592 m a.s.l. The region experienced an average annual temperature of 14.66 °C and receives about 425.5 mm of precipitation each year during the experiment. The soil is sandy loam with a pH of 8.6 and contains 0.86 % organic matter, has a good level of

fertility, and a maximum available water storage capacity (AWS_{max}) of 99 and 118 mm for T1 and T2 respectively (Tables 1 and 3).

The genotype used was ‘AF2’ (*Populus × canadensis* Mönch), which is commonly planted for chip biomass production in the Mediterranean area [61,62] due to its high yield and adaptability to various environmental conditions [12]. More details can be found in Fuertes et al. [53].

Validation data were obtained from a neighboring SRC plantation (S1-trial2) established one year earlier under comparable conditions and irrigated to FC, with trees grown in 30 L pots. Further details can be found in Fuertes et al. [53]. Field measurements were carried out monthly during the first year and every second month in years two and three, consistently scheduled around the $21st \pm 3$ days of the growing season. In total, 54 trees were sampled across 15 campaigns during the first rotation (3 years), all of which included root extraction.

Monthly measurements involved taking data from three trees per plot, which were destructively sampled and then dried in a forced-air oven at 60 °C until they reached a constant dry mass. This approach was utilized to determine the foliage biomass, W_f (kg tree⁻¹) and stem biomass, W_s (kg tree⁻¹) for each tree. The sampling frequency for root biomass (W_r in kg per tree) was adjusted to every other month over the three-year rotation due to the increasing complexity associated with the root extraction process. Roots were extracted with the assistance of a backhoe excavator. The soil samples containing the collected roots were cleaned and subsequently dried in a forced-air oven at 60 °C until a constant dry mass was achieved. Dry root biomass was measured using a balance (EU-C 7500PQ) to an accuracy of 0.1 g. To estimate the remaining root biomass in the soil, broken root tips were measured. Some biomass loss during the extraction process is unavoidable, so the allometric relationship between the diameter of the broken tips and the remaining root biomass in the soil, as established by Oliveira et al. [18] was applied. Total root biomass (W_r in kg tree⁻¹) was calculated by summing the extracted roots and the estimated remaining root biomass based on the diameter of the broken tips.

Furthermore, calibration were supported by an extensive dataset from the Poplar Plot Network (PPN) dataset collected by Sixto et al. [12, 63]. The PPN comprises 350 plots across 98 trials located at 30 different Spanish sites characterised by a pronounced summer drought (Fig. 1). During the growing season (April–September), the average temperature ranged from 15.9 to 22.5 °C, with an overall annual average of 14.4 °C for all sites. Rainfall during this season ranged from 120 to 308 mm, with an average of 543 mm for the whole year. As a result, all sites required irrigation during the summers. For the purpose of this work, different data from the PPN have been used including cultural operations, management, soil properties, stem and root biomass data.

To expand the validation dataset, data from three PPN trials, specifically datasets S2, S3, and S4, were employed (Tables 1 and 3, Fig. 1). These trials were planted with the ‘AF2’ genotype under similar density conditions as the calibration site (10,000 trees ha⁻¹). A summary of climatic conditions at calibration, and validation sites is provided in Table 1. The climatic data required as input for the model were obtained from the Spanish Meteorological Service (AEMET) database, utilizing the nearest station to each site. Detailed information on irrigation regimes and climate data for all sites can be found in the supplementary material (Table A.1 and Table A.2).

Table 1

Location and climatic conditions on the calibration and validation sites.

Site	Coordinates		Altitude (m a.s.l.)	R (mm)	R_{gs} (mm)	T_{mean} (°C)	T_{gs} (°C)	Hr (%)
	Latitude	Longitude						
S1	40°27'27.04"N	3°45'1.23"W	592	452	184	15.6	21.7	51.5
S2	37°11'43.10"N	3°46'3.70"W	554	335	120	15.9	21.6	56
S3	42°36'45.70"N	6°39'52.6"W	531	747	260	13.6	18.7	66.4
S4	41°35'29.65"N	4°10'20.48"W	795	461	202	13	18.6	63.5

R is annual accumulated rainfall; R_{gs} is average accumulated rainfall during the growing season; T_{mean} is average annual temperature; T_{gs} is average annual temperature during the growing season; Hr average annual relative humidity.

Furthermore, to assess model sensitivity under projected climate conditions, high-resolution climate variables (~1 km, 30 arc-second) from CHELSA V2.1 [64,65] were obtained for the validation sites (S2, S3, and S4). Monthly minimum, mean, and maximum air temperature (T_{min} , T_{mean} , T_{max}) and precipitation were extracted for the intermediate-emission scenario SSP3-7.0 for the period 2040–2070 were then incorporated into the analysis (supplementary material, Table A.3). Future-scenario simulations assumed no adaptation in irrigation management; therefore, the irrigation volumes applied in T1 and T2 correspond to those used under current climate conditions.

The validation dataset provided observed stem biomass data, at least for the first rotation, from all sites. Site S2 includes stem biomass data for three successive rotations spanning nine years, and S4 includes stem biomass data for two successive rotations spanning 7 years, because the first rotation was 4 years. Observed root and leaf biomass data for the first rotation were available for site S1-trial2, while root biomass was measured for both the first and second rotations at S4. Additionally, measurements of height, number of shoots per tree and basal diameter of the main shoot were collected from all sites. Further details regarding the metadata of the sites are presented in Table 3.

Due to the lack of observed below-ground biomass, leaf biomass and LAI values for successive rotations as validation data, two approaches were employed to increase the validation data set for sites S2, S3 and S4:

- Estimating below-ground biomass values based on the observed root-to-shoot ratio from PPN plots with identical planting densities [64] referred to as “estimated below-ground values (W_{re})” available only for the first and third rotation.
- Modeling “estimated leaf biomass (W_{le})” trends using data from the S1-trial1. This involved establishing an allometric relationship between the values for leaf biomass, basal diameter, and the number of shoots per tree. To approximate the observed response, a non-linear allometric relationship (Eq. (1)) was applied, fitting the model using nonlinear least squares through the statistical program R [65].

$$W_{le} = a D_{10}^b n_s^c \quad (1)$$

Where W_{le} (kg tree⁻¹) represents the leaf biomass, D_{10} is the basal diameter in mm (for cases with multiple shoots D_{10} was calculated based on the dominant shoot), n_s is the number of shoots per tree, and a, b, and c are fitting parameters. The equations considered achieved convergence and all estimated parameters a, b, and c as well as goodness-of-fit statistics are shown in Table 2.

2.3. Model inputs

The 3-PG model was applied to verify the proposed parameterization developed in this study, comparing the predictions derived from the identified parameterization in this study with the observed values of stem and root biomass recorded at the different validation sites. The foliar variables were validated in a previous study, pointing to realistic estimates for the changes in leaf biomass and LAI during the growing season [53]. The data used to initialize the simulation included the observed initial stem and foliage biomass, which were 1 and 2.5 g

Table 2

Parameter estimates and goodness-of-fit statistics for the leaf biomass (W_{fe} , kg tree⁻¹) as a function of the basal diameter (D_{10} , mm), and number of shoots per tree (n_s) model with Eq. (1).

Eq. 1	$W_{fe} = a D_{10}^b n_s^c$						
Fitting parameters	Estimate	Std. Error	t value	Pr(> t)	RMSE	pse-R ²	DF
a	0.001179	0.0004	2.799	<0.0068	0.083	0.914	61
b	1.4961	0.0866	17.256	<0.0001			
c	0.1968	0.0583	3.376	<0.0013			

Std. Error: standard error; RMSE: root of mean square error; pse-R²: pseudo coefficient of determination; DF: degrees of freedom.

Table 3

Metadata for calibration and validation sites.

	S1-trial1 (T1 and T2)	S1-trial2	S2	S3	S4
	Calibration	Validation			
Planting year	2018	2017	2009	2009	2011
Planting density (trees ha ⁻¹)	10,000	10,000	13,333	13,333	6666
Age measurement (years)	1,2,3	1,2,3	3,6,9	3	3,4,7
Destructive tree sampled	138	45	300	98	213
Trees with root extraction	72	45	–	–	14
Number of inventories	23	15	3	1	3
3-PG soil texture classes	SL	SL	SL	SCL	CL
AWS _{max} (mm)	99/118	99	193	113	144
AWS _{min} (mm)	85/43	80	80	40	60
3-PG Fertility Rate (FR)	1	1 ^a	1	0.7	0.6
NPP distribution rates ^b	T1/T2	T1	T1	T1	T1
OM (%)	0.84	0.84	0.90	0.90	1.38
pH (H ₂ O)	8.59	8.59	8.50	5.84	7.75
N (%)	0.07	0.07	0.09	–	0.08
K (ppm)	144	144	76	51	231
P (ppm)	9.35	9.35	4.1	4.4	7.21

ASW: available soil water at 1m depth; NPP: Net Primary Production; OM: organic matter; N: nitrogen; K: potassium; P: phosphorus; SL: sandy-loam; SCL: silty clay-loam; CL: clay-loam.

^a The value of FR was set as 0.7 for the third year because the trees were growing in pots, which reduced the volume explored by the roots compared to the S1-trial1. Soil parameters for the upper 30 cm layer.

^b NPP distribution rates, observed values shown in Fig. 2.

tree⁻¹, respectively, along with the observed initial root biomass, which was 13 g tree⁻¹. A summary of site-specific input data at the parameterization, calibration and validation sites used in this study can be found in Table 3.

2.4. Model evaluation

After parameter fitting, we evaluated the model performance of our final parameter set using both the calibration and the validation datasets (Tables 4 and 6). The evaluation criteria included: (2) pseudo coefficient of determination (Pse-R²), (3) coefficient of determination (R²), (4) the root of mean square error (RMSE), (5) the mean absolute error (MAE) and, (6) the average Bias (Bias):

$$Pse - R^2 = [cor(yi - \hat{y}i)]^2 \quad (2)$$

$$R^2 = 1 - \frac{\sum (yi - \hat{y}i)^2}{\sum (yi - \bar{y})^2} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (yi - \hat{y}i)^2}{n}} \quad (4)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |\hat{y}i - yi| \quad (5)$$

$$Bias = \frac{\sum_{i=1}^n (\hat{y}i - yi)}{n} \quad (6)$$

Where y_i is the observed value, $\hat{y}_i$ is the estimated value, $\bar{y}$ is the mean

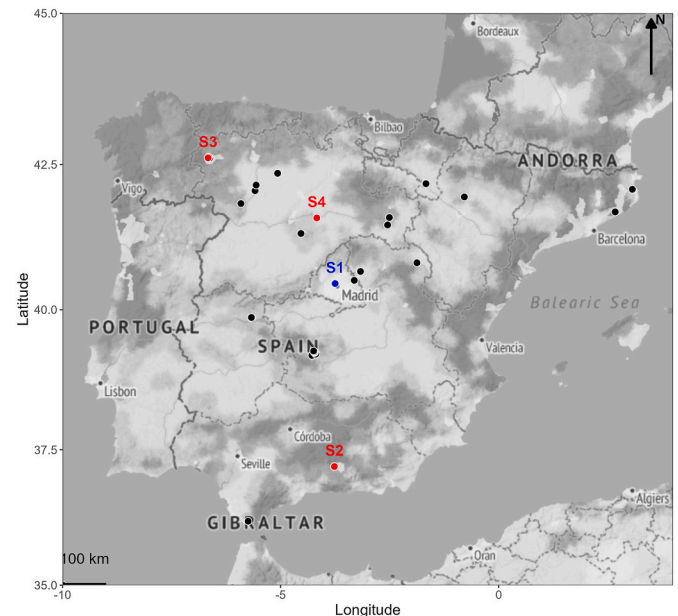


Fig. 1. Locations of sites in the Poplar Plot Network (PPN). Black points indicate network sites, red points represent validation sites, and the blue point denotes the calibration site. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4

Model performance indicators for evaluating the ability of the model to predict LAI, leaf, stem and root biomass for the first rotation and successive rotations with the calibration datasets.

Rotation (years):		Calibration site (S1-Trial1)			
		2018 (T1/ T2)	2019 (T1/ T2)	2020 (T1/T2)	Rot1 (T1/ T2)
		T1/T2	T1/T2	T1/T2	T1/T2
Leaf biomass (Mg ha ⁻¹)	Mean	0.97/0.68	4.06/2.59	6.46/4.31	3.96/2.61
	Max	2.21/1.73	8.83/4.29	9.36/6.95	9.36/6.95
	R ²	0.96/0.90	0.91/0.88	0.65/0.83	0.81/0.89
	RMSE	0.22/0.20	1.20/0.51	2.35/1.10	1.56/0.71
	MAE	0.16/0.12	0.98/0.37	1.92/0.89	1.06/0.47
	Bias	-0.03/- 0.04	-0.76/- 0.01	0.61/- 0.01	-0.1/- 0.02
LAI (m ² m ⁻²)	Mean	1.10/0.76	4.26/2.63	7.08/4.52	4.28/2.71
	Max	2.39/2.04	7.47/3.72	9.34/7.69	9.34/7.69
	R ²	0.98/0.80	0.85/0.83	0.52/0.74	0.79/0.88
	RMSE	0.20/0.3	1.14/0.66	2.65/1.18	1.70/0.82
	MAE	0.16/0.18	1.10/0.60	2.20/1.00	1.18/0.61
	Bias	-0.11/- 0.09	-0.58/ 0.25	0.95/0.52	0.10/0.24
Stem biomass (Mg ha ⁻¹)	Mean	2.55/1.30	18.46/ 9.37	52.56/ 25.73	25.48/ 12.60
	Max	5.77/3.46	32.84/ 16.19	73.17/ 56.17	73.17/ 56.17
	R ²	0.96/0.90	0.62/0.94	0.86/0.48	0.96/0.81
	RMSE	0.70/0.60	6.01/3.47	5.73/ 16.89	4.91/ 10.17
	MAE	0.49/0.47	4.29/3.00	4.99/ 14.13	3.39/6.10
	Bias	-0.42/ 0.41	-1.41/2.8	1.10/ 13.70	-0.24/ 5.89
Root biomass (Mg ha ⁻¹)	Mean	1.33/0.44	4.62/3.98	12.27/ 9.10	6.07/3.69
	Max	3.11/1.94	6.79/5.51	24.52/ 16.68	24.52/ 16.68
	R ²	0.96/0.52	0.41/0.97	0.91/0.61	0.85/0.84
	RMSE	0.63/0.57	3.60/2.23	6.76/4.62	4.44/2.68
	MAE	0.45/0.41	2.25/1.83	6.30/4.11	3.00/1.77
	Bias	-0.43/ 0.33	2.24/1.67	6.30/3.56	2.70/1.55

Mean: Represents the average of the observed values during the growing season. Max: Indicates the maximum value recorded among observations during the growing season. R²: Represents the coefficient of determination. RMSE: root of mean square error (units as variable). MAE: mean absolute error (units as variable). Bias: average of observed – predicted. T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50 % FC. The values shown are the averages for all observed months. Rot1: whole rotation 3 years.

value, n is the number of data used in the fitting.

All the analyses and graphing were performed using the R program [65].

3. Results

3.1. Monthly net primary production (NPP) distribution

The results for the observed allocation rates η_f , η_s , and η_r over the three growing seasons of both irrigation regimes in S1-trial1 are presented in Fig. 2. As poplar is established by planting hardwood cuttings, the total carbohydrates allocated to generate the root system ($\eta_r = 0.3$) are 20 % higher in that initial growing season than for the following growing season in the optimum irrigation regime (S1-trial1 T1), although the results differ slightly under water restricted conditions (S1-trial1 T2) where the allocation of carbohydrates to the root biomass was in general greater over the whole rotation (Fig. 2).

During Year 1, the allocation to leaves (η_f) is highest in the early growing season (May to June, $\eta_f = 0.4$ and 0.3 for T1 and T2, respectively) to establish the canopy. Stem growth (η_s) becomes dominant in

late summer, peaking in October for T1 ($\eta_s = 0.7$) and a month earlier for T2 ($\eta_s = 0.6$). Root allocation increases sharply in October, reaching its maximum in November in both treatments ($\eta_r = 0.9$ and 0.8 for T1 and T2, respectively) as the tree prepares for dormancy.

This trend shifts in Years 2 and 3, where the allocation to leaves diminishes (maximum $\eta_f = 0.5$ in April for both T1 and T2), and stem growth dominates during the active growing season, particularly under optimum irrigation (T1). Root allocation again peaks in the fall, with November values of $\eta_r = 0.9$ and 0.8 for T1 and T2, respectively, but consistently remains higher in T2 during the earlier months of the growing season.

As the tree matures, it begins to allocate more carbohydrates to above-ground biomass, such as stem and leaf development. However, from August onwards, the tree invests no additional carbohydrates towards the foliage fraction, as the full foliage development has already been attained ($\eta_f = 0$). This strategy allows the tree to allocate a high amount of carbohydrates to stem growth in the following months up until the dormancy period. It has been observed that under optimum conditions (T1), the contribution to stem growth is even higher than under restricted water conditions, where the tree invests slightly more towards root system development (Fig. 2).

3.2. Model calibration

The 3-PG model calibration was performed by adjusting leaf, stem and root biomass, and LAI based on monthly observed data from the S1-trial1 for both irrigation scenarios (T1 and T2), Fig. 3. Several statistical criteria (RMSE, MAE, Bias, R²) used to evaluate the model performance during the calibration steps are showed in Table 4.

After calibration, the 3-PG model successfully reproduced the main growth dynamics of leaf, stem, and root biomass, as well as LAI (Fig. 3). The calibration process was conducted concurrently to predict both scenarios (T1 and T2), utilizing the same set of species-specific parameters and the corresponding allocation rates for both scenarios T1 and T2 (Fig. 2). To ensure that the model captured the overall growth dynamics and final productivity, greater weight was given to the observed values at the end of each rotation, while intermediate measurements were considered with lower weight. Notably, the 3-PG model performed better for leaf biomass and LAI, exhibiting a good fit ($R^2 > 0.8$) and the smallest bias (percent bias $-1.55/-0.83$ % for leaf biomass for the whole rotation for the T1/T2 scenarios). Overall, the results indicated that T2 generally performs better in terms of predicting both leaf biomass and LAI compared to T1 (percent RMSE was 39.85/30.08 % for LAI for the whole rotation for the T1/T2 scenarios).

Stem and root also showed a good overall fit with $R^2 > 0.8$, as can be seen in Table 4. However, both variables showed higher errors in some months across the rotation, probably due to the small sample size, but these were considerably reduced at the last year of the rotation, when calibration was prioritized (Fig. 2).

For stem biomass, the mean percent RMSE in the last year of the first rotation was 10.91 % for T1 and 65.64 % for T2; however, in the last month of the rotation (the harvest moment) it decreased to 1.14 % and 3.11 %, respectively. Root biomass followed a similar trend, being the most challenging fraction due to the lower number of observations and the complexity of belowground measurements. Percent RMSE was 55.10 % and 50.74 % for T1 and T2 in the third year, but in the last month, it decreased to 11.76 % and 6.63 %, respectively. Therefore, despite some variability in intermediate months, the calibration successfully reproduced the final yields, which was the main target of the model adjustment.

The impact of the irrigation treatment becomes apparent when comparing the annual maximum biomass growth and the values at the end of the first rotation (Table 4). Under restricted water conditions, observed biomass yields declined by 25.75 %, 23.24 %, and 31.97 % for leaves, stems, and roots, respectively.

We determined as many parameters specific to 'AF2' as possible

Table 5List of 3-PG parameters and values applied to 'AF2' (*Populus × canadensis* Mönch), Default values are those used by Sands and Landsberg [40].

Meaning	Symbol (units)	Site/Species specific	Parameterization	Value
Allometric relationships and partitioning				
Ratio foliage:stem partitioning at B = 2 cm	p_2	Species	Observed	According to Fig. 2
Ratio foliage:stem partitioning at B = 20 cm	p_{20}	Species	Observed	According to Fig. 2
Constant in stem mass and basal diameter relationship over bark	a_S	Species	[66]	0.0758
Power in stem mass and basal diameter relationship over bark	n_S	Species	[66]	2.5787
Maximum fraction of NPP to roots	η_{Rx}	Species	Observed	According to Fig. 2
Minimum fraction of NPP to roots	η_{Rn}	Species	Observed	According to Fig. 2
Temperature and frost modifier				
Minimum temperature for growth	$T_{\min}$ (°C)	Species	Proposed	5
Optimum temperature for growth	T_{opt} (°C)	Species	Proposed	22
Maximum temperature for growth	$T_{\max}$ (°C)	Species	Proposed	40
Days of production lost for each frost day	d_F (days)	Species	Default	1
Litterfall and root turnover				
Litter fall rate for very young stands	γF_0 (month)	Both	Observed	[53]
Age at which litter fall rate = $\frac{1}{2}(\gamma F_x + \gamma F_0)$	γF (month)	Both	Observed	[53]
Average monthly root turnover	γR (month)	Both	Default	0.015
Conductance				
Maximum canopy conductance	g_{Cx} (m s ⁻¹)	Species	Default	0.02
Canopy LAI for maximum canopy conductance	L_{Cx} (m ² m ⁻²)	Species	Fitted	1
Defines stomatal responses to VPD	K_d (mbar)	Species	Fitted	0.03
Canopy boundary layer conductance	g_B (m s ⁻¹)	Both	Default	0.2
Fertility effects				
Value of m when FR = 0	m_0	Species	Default	0
Value of f_N when FR = 0	f_{N0}	Species	Default	1
Shape of the response of f_N to FR	f_{Nn}	Species	Default	1
Soil water modifier				
Moisture ratio deficit which gives $f_0 = 0.5$	c_0	Site	Sandy loam texture	0.6
Power of moisture ratio deficit in f_0	n_0	Site	Sandy loam texture	7
Specific leaf area				
Specific leaf area at age 0	SLA_0 (m ² kg ⁻¹)	Species	Observed	[53]
Specific leaf area for mature leaves	SLA_1 (m ² kg ⁻¹)	Species	Observed	10.4
Age at which $SLA = (SLA_0 + SLA_1)/2$	t_{SLA} (years)	Species	Observed	1.4
Stem mortality				
Mortality rate (constant)	γ_N (% year ⁻¹)	Site	Proposed	5
Fraction mean single-tree biomass lost per dead tree	m_F	Species	Default	0
	m_R	Species	Default	0.2
	m_S	Species	Default	0.2
Production and light interception				
Maximum canopy quantum efficiency	α_{Cx} (molmol ⁻¹)	Species	Observed	[53]
Ratio NPP/GPP	Y	No	Default	0.47
Extinction coefficient for absorption of PAR	k	Species	Fitted	0.7
Full canopy age	t_C (years)	Both	Proposed	2
Maximum proportion of rainfall evaporated from canopy	I_{Cx}	Species	Fitted	0.25
LAI for maximum rainfall interception	L_{IC}	Species	Fitted	8

based on our own measurements. Overall, 10 out of 33 were observed and 5 were fitted. The remaining parameters were estimated values from previously published research on hybrid poplars, proposed values based on expert knowledge and default 3-PG values (Table 5).

3.3. Model validation

In total, four sites were selected to implement the proposed parameterization of the 3-PG model (Table 3). Model performance, considering four outputs - leaf, stem and root biomass, and LAI- is presented in Figs. 3 and 4 and Tables 6 and 7.

Based on the proposed parameterization changes for the 3-PG, we compared the predicted LAI, stem, root and leaf biomass (W_s , W_r and W_l) with those observed in the calibration data set (S1-trial1) and the validation dataset (S1-trial2, S2, S3 and S4). In most cases, the slopes of the relationships between the predicted and observed values were close to 1, indicating a good fit. For the calibration dataset (black lines in Fig. 4), the slopes were 0.98 for leaf biomass, 1.01 for LAI, 1.01 for stem biomass, and 1.20 for root biomass.

For the validation datasets (red lines in Fig. 4), slopes of 0.90 and 0.87 for leaf biomass and LAI, respectively, indicated slight underestimation, while root biomass showed a nearly unbiased slope (0.99) but a positive intercept that led to a slight overestimation at lower values. Stem biomass showed slight overestimation with a slope of 1.12.

3.4. Growth projections for successive rotations

Utilizing the 3-PG parameters outlined in Table 5, simulations were conducted to predict leaf, stem, and root biomass for a 12-year plantation cycle of 'AF2' poplar SRC plantations in Spain across four rotations (Fig. 5). Generally, RMSE and MAE values display fluctuations across rotations, with higher values observed in Rotation 2 compared to Rotation 1. Limited availability of data from successive rotations contributes to greater errors and biases across all biomass variables compared to those of the first rotation (Table 6). Our simulations reveal an average increment in stem productivity of 21.69 % for the second rotation compared to the first (considering sites S2 and S3 with same rotation length). Furthermore, in the fourth rotation, site S2 and S3 shows an average increase of 23.13 %, while site S4 display an average decrease of 14.76 % compared to the first rotation.

The model showed consistent predictive performance for leaf, stem, and root biomass across sites (Table 6) and rotations (Table 7). For leaf biomass, the lowest errors were observed at S2 during first rotation (RMSE = 0.93 Mg ha⁻¹, percent RMSE 11.34 %) and S4 (RMSE = 0.51 Mg ha⁻¹, percent RSME 15.04 %), whereas larger deviations occurred at S1-trial2 in first rotation (RMSE = 0.51 Mg ha⁻¹, percent RSME 51.03 %). When aggregated across sites, prediction accuracy remained high ($R^2 > 0.9$), with RMSE values ranging from 0.84 to 1.80 Mg ha⁻¹ and biases ranging from slight underestimation (−0.09 Mg ha⁻¹ in first

Table 6

Model performance indicators for evaluating the ability of the model to predict LAI, leaf, stem and root biomass for the first and successive rotations with validation datasets.

		Validation sites						
		S1-trial2	S2				S3	S4
		Rot1	Rot1	Rot2	Rot3		Rot1	Rot2
Leaf biomass (Mg ha ⁻¹)	Mean	1.63	8.17*	6.34*	3.03*		5.08*	2.69*
	RMSE	0.51	0.93	2.22	1.10		1.57	0.51
	n	42	100	281	100		100	240
LAI (m ² m ⁻²)	Mean	3.01	–	–	–		–	–
	RMSE	1.31	–	–	–		–	–
	n	42	–	–	–		–	–
Stem biomass (Mg ha ⁻¹)	Yield	40.53	51.31	61.48	52.68		19.95	39.48
	RMSE	3.68	1.57	4.12	8.39		2.05	4.83
	n	42	100	100	100		98	138
Root biomass (Mg ha ⁻¹)	Yield	3.97	116.42*	33.82*	26.55*		6.38*	8.11*
	RMSE	4.01	2.44	4.35	6.81		1.22	2.98
	n	42	100	100	100		98	138

Mean: Represents the average of the observed values during the growing season of the rotation. Yield: Represents the mean observed value correspond to harvest time (end of the growing season). *represents estimated values derived from observed data, according to section 2.3. RSME: root of mean square error (units as variable). N: number of measured trees.

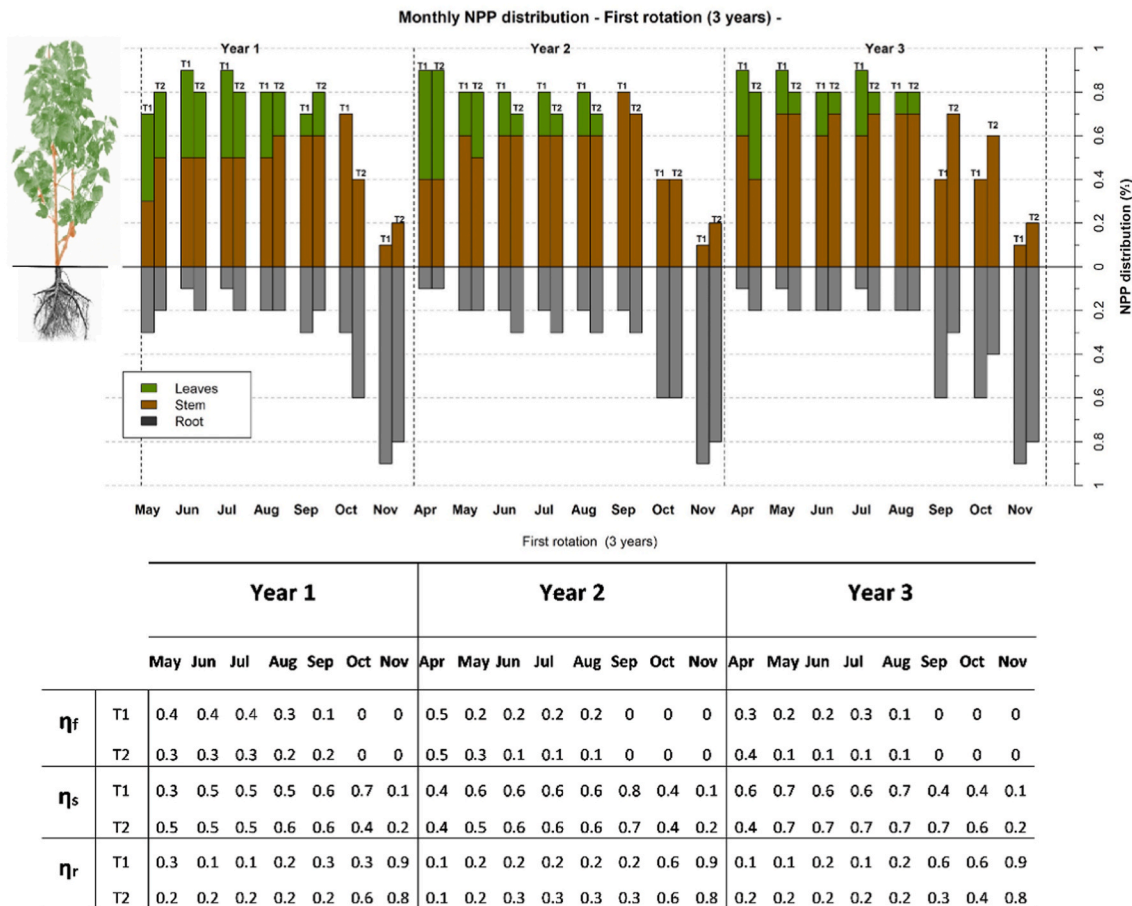


Fig. 2. Monthly observed allocation rates of Net Primary Production (NPP) over the first rotation (3 years) to the different fractions (leaves, stem and roots) under both irrigation regimes of S1-Trial1 (T1: optimum regime, irrigated to field capacity (FC); T2: Restricted irrigation, 50 % of FC).

rotation) to overestimation (1.45 and 1.10 Mg ha⁻¹ in the second and third rotations, respectively).

For stem biomass, the best agreement with observations was obtained at S2 during first rotation (RMSE = 1.57 Mg ha⁻¹, percent RSME 3.06 %), while larger deviations were found in successive rotations (RMSE = 4.12 and 8.39 Mg ha⁻¹, percent RSME 8.40 and 15.94 % for

the second and third rotations, respectively). At the aggregated level, accuracy was very high ($R^2 > 0.97$), although biases indicated slight overestimation in the first rotation (0.10 Mg ha⁻¹, percent Bias 0.47 %), and overestimation in the second and third rotation (1.73–8.40 Mg ha⁻¹, percent Bias 3.49 and 15.94 %, respectively).

For root biomass, errors were lowest at S2 during the first rotation

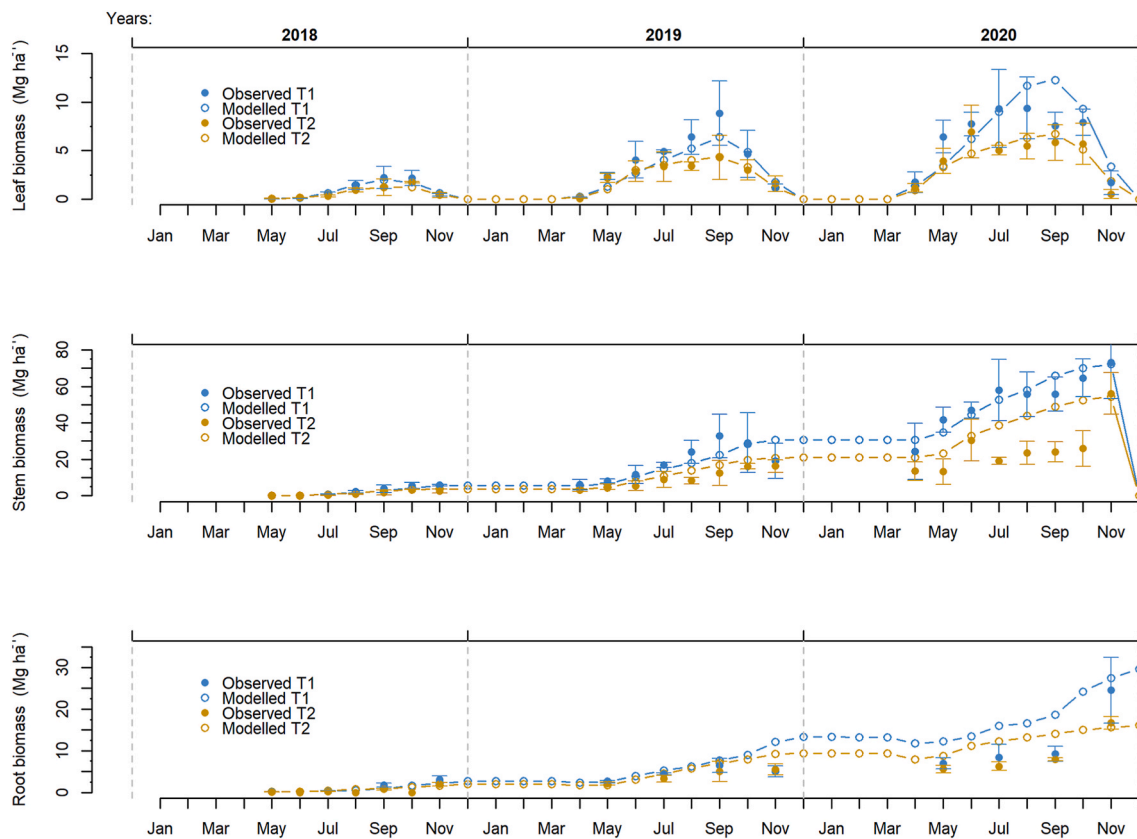


Fig. 3. Observed vs. modelled data points of leaf, stem and root biomass (Mg ha^{-1}) for the calibration data with 3-PG model using the proposed parameterization of both water scenarios of S1-Trial1 (T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50 % FC).

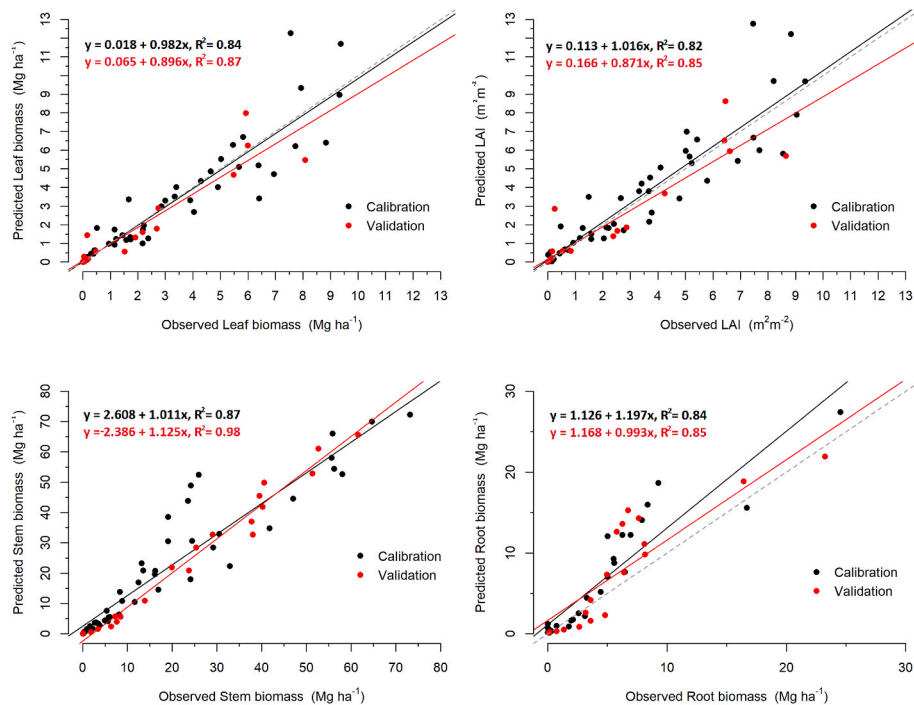


Fig. 4. Observed vs. modelled values of leaf, stem and root biomass (Mg ha^{-1}) and LAI ($\text{m}^2 \text{m}^{-2}$) for the calibration data (black (S1-Trial1)) and validation data (red (S1-Trial2, S2, S3 and S4 sites)), with 3-PG model using the proposed parameterization applied to 'AF2' (*Populus × canadensis* Mönch). The dashed line represents the 1:1 isoline and the solid lines are lines fitted to the data. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 7

Model performance indicators for evaluating the ability of the model to predict leaf, stem and root biomass across all validation sites.

		All validation sites		
		Rot1	Rot2	Rot3
Leaf biomass (Mg ha ⁻¹)	Mean	2.22*	5.19*	3.03*
	R ²	0.90	0.99	–
	RMSE	0.84	1.80	1.10
	MAE	0.50	1.50	1.10
	Bias	–0.09	1.45	1.10
Stem biomass (Mg ha ⁻¹)	Mean	19.79	49.6	52.68
	R ²	0.97	1	–
	RMSE	3.68	2.95	8.40
	MAE	2.96	2.39	8.40
	Bias	0.10	1.73	8.40
Root biomass (Mg ha ⁻¹)	Mean	10.30*	28.53	26.54*
	R ²	0.98	1	–
	RMSE	2.34	3.21	6.81
	MAE	2.22	2.83	6.81
	Bias	2.22	–2.83	6.81

Mean: Represents the average of the observed values during the growing season of the rotation. *represents results based on estimated values, according to section 2.3. R²: Represents the coefficient of determination. RSME: root of mean square error (units as variable). MAE: mean absolute error (units as variable). Rot: Rotation.

(RMSE = 2.44 Mg ha⁻¹, percent RSME 14.89 %) and S4 during second rotation (RMSE = 1.30 Mg ha⁻¹, percent RSME 5.61 %), and highest at S4 during the first rotation (RMSE = 2.98 Mg ha⁻¹, percent RSME 36.78

%). Across sites, the model achieved strong correspondence with observations, with RMSE values ranging from 2.34 to 6.81 Mg ha⁻¹. Biases indicated overestimation in the first rotation (2.22 Mg ha⁻¹, percent Bias 21.24 %), underestimation in the second rotation (–2.83 Mg ha⁻¹, percent Bias –9.90 %), and overestimation in the third rotation (6.81 Mg ha⁻¹, percent Bias –25.65 %).

Model projections under current conditions indicated the highest total stem biomass over a 12-year plantation cycle (4 rotations of 3 years each) at S2 (248.22 Mg ha⁻¹), followed by S4 (160.94 Mg ha⁻¹) and S3 (101.95 Mg ha⁻¹). Reducing irrigation to 50 % markedly decreased biomass at all sites, Table 8.

Under future climate conditions (SSP3-7.0 scenario), and maintaining the same irrigation inputs as under current conditions, results revealed site-specific responses to climate change. Productivity at S2 declined slightly (–2.4 % to –4.7 % under T1 and T2), consistent with projections of warmer and drier conditions. In contrast, S3 and S4 exhibited increases in stem biomass (+16.3 % and +3.6 % under T1; +35.0 % and +8.5 % under T2), reflecting future scenarios with higher temperatures and stable or increased precipitation. Root and leaf biomass followed similar patterns, Table 8.

4. Discussion

4.1. Growth projections and comparison to existing literature

While our previous study [53] demonstrated that the adapted 3-PG model effectively captured foliar responses of *Populus* ‘AF2’ to contrasting irrigation during the first rotation, the present work extends this

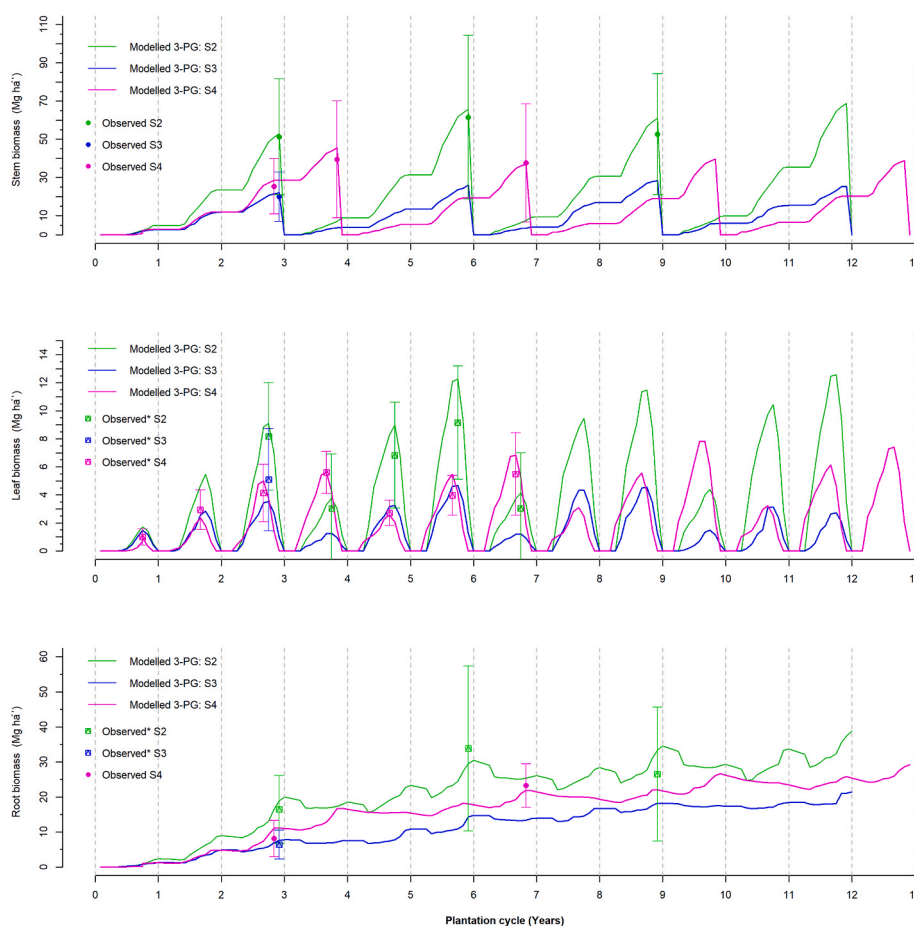


Fig. 5. 3-PG model predictions for a 12-year plantation cycle (4 rotations of 3 years each) for stem, leaf and root biomass, observed data for stem and root biomass and estimated values. Different colours of the data represent different measurement sites (green-S2, blue-S3 and magenta-S4). Different types of points indicate the nature of the data: solid points represent observed values, square points represent estimated values derived from observed variables, and the solid line represents modelled values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

framework to multiple rotations and whole-tree dynamics. By integrating an extensive database within the adapted model, this study provides a more comprehensive assessment of long-term growth, biomass allocation, and carbon accumulation of poplar short rotation plantations under Mediterranean conditions.

The effect of the irrigation treatment can be observed by comparing the predictions using the proposed parameterization with the T1 distribution rates to a hypothetical scenario where only 50 % of the water is applied, and the T2 distribution rates are used (Fig. 2, Table 8). Under this scenario, stem yield reductions of 24.77 %, 11.76 %, 43.7 %, 27.05 %, and 47.01 % would occur at the S1-trial1, S1-trial2, S2, S3, and S4 sites, respectively, highlighting the strong sensitivity of SRC poplar plantations to water availability.

To further evaluate model sensitivity to climatic variation, simulations were extended to a future climate scenario (SSP3-7.0, 2040–2070) while maintaining current irrigation inputs. Responses were site-specific: the southern site (S2) showed slight reductions in productivity, reflecting the combined effects of higher temperatures and increasing water deficit. In contrast, northern sites (S3 and S4) exhibited moderate productivity gains, likely due to warming accompanied by stable or slightly enhanced precipitation. These results suggest that climate–water interactions will play a key role in future biomass productivity, with water availability remaining a limiting factor, while rising temperatures may enhance growth where water remains sufficient. Similar trends have been reported for poplar SRC plantation in Brandenburg, north-eastern Germany, where simulation studies under projected climate conditions indicated biomass reductions of up to 18 % due to increasing temperatures and declining summer precipitation [67]. Conversely, a throughfall-exclusion experiment conducted in the Czech Republic indicated that poplar SRC plantation with longer rotations (8 years) and well-developed root systems showed limited declines in aboveground productivity under reduced rainfall, suggesting greater drought resilience once root systems are established [68]. Together, these studies emphasize that the response of poplar SRC systems to future climate conditions will largely depend on site-specific factors such as water availability, rooting depth, and rotation length, which collectively influence their capacity to withstand or adapt to changing environmental conditions.

Overall, both under optimal conditions and those of irrigation restrictions, the predicted growth aligns with findings in existing literature [21,69]. Furthermore, research conducted in Belgium highlighted the potential for biomass gains even without irrigation. This research

revealed yields of up to 12.4 Mg ha⁻¹ year⁻¹ with rotation lengths of 3–4 years [60], demonstrating the adaptability of poplar species to diverse environmental challenges. For instance, investigations into poplar clone ‘AF2’ conducted by Oliveira et al. [20] with similar plantation densities, rotation lengths, and optimal irrigation conditions in Mediterranean climates yielded comparable results, ranging from 13.47 to 24.72 Mg dm ha⁻¹ year⁻¹. Similarly, our findings align with those of Di Matteo et al. [69] in Central Italy, who reported yields of 8.74 Mg dm ha⁻¹ year⁻¹ under water irrigation restrictions. However, it is important to note that considerable variability exists in biomass production, which is associated with the previously mentioned factors [70–72].

4.2. Model performance

The 3-PG model can provide accurate descriptions of tree growth patterns [73], which are currently based only on average stem diameter [74]. However, for fast-growing species, especially those established using cuttings, the monthly NPP distribution rates are sensitive parameters for improving estimates of tree growth patterns. To the best of our knowledge, there have been no publications to date that define these parameters on a monthly basis for fast-growing species, and in particular for poplar. This study aims to fill this gap and improve the estimation of the different biomass components (foliar, stem, and root). The modifications to the partitioning address the changes in the distribution of allocated carbohydrates, primarily because the model needs to account for annual leaf production, which is characteristic of deciduous species. The proposed values for the minimum (5 %) and maximum (10 %) proportion of NPP allocated to roots closely align with the range observed in previous studies [41]. The distribution of NPP during the first rotation is reasonable as it aligns with the typical parameters considered by the 3-PG model: η_R varies from 0.2 to 0.8, and the ratio of η_F/η_S decreases as diameters increase [40].

The proposed parameterization allows realistic estimates of the changes in the different biomass fractions over the growing season, showing an especially good fit for leaf biomass (RMSE between 0.20 and 2.35 Mg ha⁻¹) and LAI variables (RMSE between 0.20 and 2.65 m² m⁻²) in the calibration and validation data set. These modifications allow null values for both variables during the months of dormancy, reflecting the natural cycle of plant growth and dormancy, which is crucial for capturing the full dynamics of this type of plantations system.

The chosen sample size aimed to strike a practical balance between resource constraints and statistical validity. A larger sample size would likely offer a more comprehensive representation of the entire population, reducing the impact of outliers and better reflecting the overall trial performance. In particular, the inherent variability in tree growth due to factors such as microclimatic differences, soil heterogeneity, and individual tree development can lead to significant deviations when only a few trees are observed.

Moreover, since LAI changes monthly, estimation of GPP (Gross Primary Productivity) and later NPP would be more accurate when considered on a monthly timescale, since the 3-PG model relies on the interception of photosynthetically active radiation by the leaf surface [75]. Consequently, predictions of carbon assimilation and subsequent productivity become more temporally accurate and reflective of site-climate conditions.

The proposed parameterization effectively addresses the fluctuations in foliar biomass and LAI, characterized by an initial increase (from May, reaching a maximum in September) followed by a decrease (dropping to near-zero values in December), due to shifts in biomass allocation and increased litterfall during the growing season. This approach facilitates accurate predictions of foliar litterfall and, consequently, the nutrient contributions to the soil from senescent leaves.

As regards above ground biomass, RSME for the validation and calibration data (Tables 4, 6 and 7) are in line with those reported by other authors using the 3-PG model to simulate hybrid poplar biomass [42]. Notably, increased variability is observed in successive rotations,

Table 8

Total leaf, stem, and root biomass simulated by the 3-PG model over a 12-year plantation cycle (4 rotations of 3 years each) for the validation datasets, under current climate conditions and the intermediate-emission scenario SSP3-7.0 (2040–2070), for two irrigation regimes: T1 (optimum irrigation to field capacity) and T2 (restricted irrigation at 50 % of field capacity).

Scenario (Irrigation)	Total Biomass (Mg ha ⁻¹)	Validation sites		
		S2	S3	S4
Current climate (T1)	W _s	248.22	101.95	160.94
	W _r	119.05	61.10	93.36
	W _i	45.40	15.47	27.69
Current climate (T2)	W _s	139.75	74.37	85.29
	W _r	66.77	33.92	49.49
	W _i	24.01	9.20	12.22
Future Climate: SSP3-7.0 (T1*)	W _s	242.16	118.60	166.67
	W _r	117.34	79.52	91.83
	W _i	44.68	19.33	28.71
Future Climate: SSP3-7.0 (T2*)	W _s	133.19	100.76	92.54
	W _r	62.90	60.98	53.82
	W _i	23.24	12.26	13.84

Stem (W_s), leaf (W_r) and root (W_i) biomass. T1* and T2* in the future climate simulations, irrigation amounts for T1 and T2 were kept equal to those used under the current climate.

as documented by other researchers [47]. Furthermore, a higher error rate in successive rotations was attributed to limited data availability for these rotations and the inherent variability in the sampled trees.

Large variation exists in predicted biomass among sites, confirming the significant impact of environmental interactions on poplar yield, as previously reported in the literature [76,77]. The S2 site was the most productive, followed by S4 and S3. The least productive site had the highest relative humidity and was affected by *Melampsora* rust during the first two years. This site also had the most acidic soil. In contrast, the S2 site had the highest average growing season temperature, with the rainfall deficit fully compensated by irrigation.

The estimated below-ground values (W_{re}) across different rotations indicate a good fit of the model to simulated data with the 3-PG model, exhibiting lower RMSE and Bias. Due to the lack of observed root biomass data, comparing our results with those from other similar studies was challenging.

Plant mortality, which ranged between 5 % and 8 % over the 12-year plantation cycle, was found to be slightly lower. In particular, Štochlová et al. [58] suggested that treatments such as irrigation, even under restrictive conditions, could contribute to low mortality rates, which may partly explain the trend observed here. From a modeling perspective, accounting for these relatively small losses is essential, since even moderate differences in survival can influence stand-level estimates of biomass accumulation and carbon capture.

In this context, the adaptation and parameterization of the climate-sensitive, process-based 3-PG model were undertaken to improve the accuracy of the estimation of lignocellulosic biomass production derived from the cultivation of fast-growing forest species, specifically focusing on the *Populus* genus. Despite the limitations due to the lack of extensive information on successive rotations and detailed data beyond the first rotation regarding the behavior of regrowth, this model provides the best available approach to date. It has demonstrated acceptable error margins and proven to be an invaluable tool for managing such plantations. Furthermore, it facilitates the estimation of crucial ecosystem services, such as the carbon capture capacity in all biomass fractions of these plantations. However, it also underscores the need for more comprehensive studies on biomass allocation and allometry in regrowth during successive rotations, which are critical for improving model accuracy and advancing our understanding of these systems.

5. Conclusions

This study presents an adaptation of the 3-PG model to simulate the growth and biomass allocation in poplar SRC systems, with a particular focus on the biomass-oriented hybrid 'AF2'. The adapted model accuracy captures leaf biomass and LAI dynamics across successive rotations (RMSE 0.20–2.65 Mg ha⁻¹) and adequately represents stem and root growth (RMSE 3.43–8.39 Mg ha⁻¹), supporting its use for estimating productivity and biomass partitioning in these plantations.

Despite this overall performance, root biomass remains the most challenging component to simulate, with increasing errors across successive rotations, highlighting the need for additional parameter refinement and more extensive belowground data.

Water limitation clearly constrained plantation performance. Under a 50 % irrigation reduction, stem, leaf, and root biomass in the validation sites (S2, S3 and S4) decreased by 39.25 %, 47.85 %, and 45.13 %, respectively, by biomass fraction, compared with well-irrigated conditions, Table 8. Nevertheless, yields of approximately 12 Mg ha⁻¹ year⁻¹ remained achievable under 50 % irrigation restrictions for a 12-year plantation cycle (4 rotations of 3 years each).

Climate-sensitivity simulations further revealed divergent site-specific responses under a mid-century scenario (SSP3-7.0, 2040–2070). Productivity slightly declined at the driest site, whereas northern locations experienced moderate gains where warming coincided with stable or increased precipitation. These findings confirm that water availability will remain the dominant constraint on SRC

productivity under future climates, and that climate-driven productivity gains are only expected where moisture supply is not critically limited. This underscores the importance of water-adaptive management strategies under Mediterranean conditions.

Overall, the adapted 3-PG model can be used to support management planning and ecosystem service assessments in poplar SRC plantations. Further validation across different soils, genotypes, climates, and longer rotation periods is required to improve accuracy.

CRedit authorship contribution statement

A. Fuertes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **R. Rodríguez-Soalleiro:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **C. Pérez-Cruzado:** Validation, Supervision, Methodology, Investigation, Conceptualization. **I. Cañellas:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **H. Sixto:** Writing – review & editing, Validation, Methodology, Funding acquisition, Conceptualization. **N. Oliveira:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of generative AI in scientific writing

During the preparation of this manuscript, the authors made use of generative AI tools to assist with improving readability and language. All content was subsequently reviewed, revised, and approved by the authors, who take full responsibility for the final published version.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2025.108736>.

Data availability

Data will be made available on request.

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