USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

INTERNATIONAL DOCTORAL SCHOOL OF THE USC

Alicia
Fuertes Sánchez

PhD Thesis

Assessing the potential of short-rotation poplar plantations for a low-carbon bioeconomy: modelling sustainable lignocellulosic biomass and carbon stocks under water-limited conditions

Lugo, 2023

Doctoral Programme in Engineering for Rural and Civil Development

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

DOCTORAL THESIS

ASSESSING THE POTENTIAL OF SHORT-ROTATION POPLAR PLANTATIONS FOR A LOW-CARBON BIOECONOMY: MODELLING SUSTAINABLE LIGNOCELLULOSIC BIOMASS AND CARBON STOCKS UNDER WATER-LIMITED CONDITIONS

Alicia Fuertes Sánchez

ESCUELA DE DOCTORADO INTERNACIONAL DE LA UNIVERSIDAD DE SANTIAGO DE COMPOSTELA

PROGRAMA DE DOCTORADO EN INGENIERÍA PARA EL DESARROLLO RURAL Y CIVIL

LUGO

AÑO 2023

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

DECLARACIÓN DEL AUTOR DE LA TESIS

Assessing the potential of short-rotation poplar plantations for a low-carbon bioeconomy: modelling sustainable lignocellulosic biomass and carbon stocks under water-limited conditions.

Yo, **Alicia Fuertes Sánchez**, presento mi tesis siguiendo el procedimiento adecuado al Reglamento y declaro que:

1. La tesis abarca los resultados de la elaboración de mi trabajo.
2. De ser el caso, en la tesis se hace referencia a las colaboraciones que tuvo este trabajo.
3. Confirmo que la tesis no incurre en ningún tipo de plagio de otros autores ni de trabajos presentados por mí para la obtención de otros títulos.
4. La tesis es la versión definitiva presentada para su defensa y coincide la versión impresa con la presentada en formato electrónico.

Y me comprometo a presentar el Compromiso Documental de Supervisión en el caso de que el original no esté depositado en la Escuela.

En Lugo, a 8 de septiembre de 2023

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

AUTORIZACIÓN DEL DIRECTOR /TUTOR DE LA TESIS

Assessing the potential of short-rotation poplar plantations for a low-carbon bioeconomy: modelling sustainable lignocellulosic biomass and carbon stocks under water-limited conditions.

D. Roque Rodríguez Soalleiro (Director/Tutor)

Dª. Hortensia Sixto Blanco (Directora)

Dª. Nerea de Oliveira Rodríguez (Directora)

INFORMAN:

Que la presente tesis, se corresponde con el trabajo realizado por **Dª. Alicia Fuertes Sánchez**, bajo nuestra dirección/tutorización, y autorizamos su presentación, considerando que reúne los requisitos exigidos en el Reglamento de Estudios de Doctorado de la USC, y que como directores de esta no incurre en las causas de abstención establecidas en la Ley 40/2015.

De acuerdo con lo indicado en el Reglamento de Estudios de Doctorado, declaramos también que la presente tesis doctoral es idónea para ser defendida en base a la modalidad de **«Monográfica con reproducción total o parcial de publicaciones»**, en la que la participación del doctorando fue decisiva para su elaboración y las publicaciones se ajustan al Plan de Investigación.

En Lugo, a 8 de septiembre de 2023

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA









FUNDING

This doctoral thesis was supported by the Spanish Ministry of Universities through the framework of the INIA-CSIC Project RTA2017-00015-C02 (PRE2018-083764) and PID2020-119204RB-C21. The experimental Poplar Plot Network and the economic data were partially supported by the PSE-On Cultivos, Decocel, RTA-2011- 00006, RTA2014-0007 and the LIGNOCROP project.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

AGRADECIMIENTOS

"*Todo gran sueño comienza con un soñador. Siempre recuerda que tienes dentro de ti la fuerza, la paciencia y la pasión para alcanzar las estrellas y cambiar el mundo.*" - Harriet Tubman

El viaje que me lleva a escribir estas líneas no comenzó en Madrid, sino en una estancia de investigación en Berlín, que inicialmente estaba planeada para seis meses. Sin embargo, sin apenas darme cuenta, transcurrieron más de ocho años, ¡ocho!. Durante ese tiempo, aprendí las impresionantes características de las turberas, lo duro de la toma de datos y lo frustrante que resulta cuando las mediciones no salen como se esperaba, también descubrí mi entusiasmo por la ciencia, la intriga de descubrir los secretos que los datos ocultan y lo complicado que puede ser expresarlos. En este tiempo tuve la suerte de conocer a personas extraordinarias que, me ayudaron a iniciarme en el mundo de la investigación (gracias Este Fü, el Spanish Team, Martina, Tim, Gawan, Jörgi, Jan y Prof. Matthias). Sin su ayuda, esta tesis doctoral no habría sido más que un sueño inalcanzable.

Recuerdo estar de vuelta en Madrid, por fin, después de estar tanto tiempo fuera de casa y con la presión de buscar un hueco en el mundo laboral. Estaba completamente despreocupada de regresar a la investigación y, mucho menos, pensaba en hacer un doctorado. Entonces, como si la vida estuviera jugando al escondite, aparece una oferta para realizar un doctorado en Madrid... ¡sí, con los queridos chopos de nuevo! Y, para colmo, en el INIA, ese misterioso centro de investigación del que en la escuela de Agrónomos siempre nos habían hablado como si fuera el paraíso de la ciencia. ¡Lo solicité! No podía dejarlo escapar.

Al poco tiempo conocí a Hortensia, directora de mi tesis, y a quien le estoy profundamente agradecida. Ella fue quien logró convencerme de regresar al mundo de la investigación, aunque lo hizo sin darse cuenta. Recuerdo claramente nuestra primera reunión, en la que empezó diciéndome que se jubilaría pronto y que no podría estar al 100% a mi disposición. Sin embargo, a medida que me explicaba el proyecto y compartía su línea de investigación, su entusiasmo era evidente. No podía ocultar todas las ideas y desafíos emocionantes que tenía en su mente. Desde aquel primer día, supe que no estaría comprometida al 100%, sino al 200%. Hortensia, gracias por todo lo que me has enseñado y por transmitirlo siempre con un cariño inmenso.

Semanas después conocí a Roque, director de mi tesis, que tiene el poder especial de enseñarte, tutorarte, dirigirte, asesorarte, escucharte y hacerte reír desde más de 400 km de distancia. Ha sido un referente durante todo este tiempo. He aprendido, buah ,un montón con él y siempre viendo como le emociona su trabajo y se divierte en cada paso

que avanzamos! Gracias Roque por todo y ya te voy también agradeciendo por todo lo que nos falta ☺

Entremedias conocí a Nerea, directora de mi tesis. Nerea ha sido un auténtico salvavidas dándome un apoyo incondicional en cada paso hacia la finalización de este proyecto. No solo ha sido mi directora, sino también mi compañera, consejera, referente, fuente de información y al mismo tiempo, te acompaña a hacer el mono al cole de tus hijos, para enseñarles a los pequeños lo maravillosa que es la ciencia y cómo los árboles son verdaderos glotones de CO_2 y todo esto mandándote la revisión de tu artículo por la tarde. En fin, Nerea tiene una energía y capacidades impresionantes, que comunica de una manera verdaderamente especial. He tenido mucha suerte de haber cruzado su camino. Mil gracias Nerea. Ha sido un verdadero placer compartir esta etapa contigo.

Si ya de por sí fui afortunada por tener a tres directores que han sido mi gran apoyo en estos años, puedo decir que mi suerte se multiplicó al contar también con el respaldo de César e Isabel C., siempre estuvieron ahí para ayudarme y perfeccionaron cada trabajo que les enviaba. A ambos les agradezco de corazón por estar siempre disponibles.

No me puedo olvidar de mis dos compis del grupo de los chopos, Isabel G. y José Pablo por recabar gran parte de la información en la que se basa esta tesis, por toda la ayuda en el procesado de muestras, por su trabajo minucioso, por poder contar con su apoyo en todo momento, su humor y muchas cosas más. Ha sido un placer trabajar con ellos.

Quiero agradecer a todos los compañeros del ICIFOR por su apoyo y empuje (Fernando, Patricia, Icíar, María, Guille, Edu, …). Especialmente a nuestro grupo de divulgación 11F que tan buenos y emocionantes momentos hemos pasado juntos acercando la ciencia a los más pequeños. Gracias Laura, Ana Carmen, Cristina, Rafa, Nerea, Isa, Marta C., Azu y Aida. Sin duda esas pequeñas semillas en las cabecitas de los peques florecerán con el tiempo.

También quiero expresar un agradecimiento muy especial al despacho 216. Siento que nuestro despacho tiene mucha energía positiva gracias a todas las personas extraordinarias que han pasado por él (Isa, Maca, Marta V., Álvaro, …). Especialmente quiero agradecer a los compañeros que han compartido conmigo la recta final de la tesis. Gracias a los chicos del noventa (Rafa y Przemek) por ser tan graciosos y estar ahí escuchando cada tropezón. Gracias, Isa, por compartir esta recta final conmigo y estar de apoyo con tu humor curativo. Aunque te hayas mudado de despacho nos cuesta no poner tu nombre en la puerta. Gracias, Sira, por estar ahí para escucharme y aguantar mi monologo en nuestros viajes a la ofi, y por último gracias Dani, porque has estado al inicio y al final en este camino, siempre ayudando con una sonrisa y es que claro del barrio tenías que ser ☺.

USC
DE SANTIAGO
DE COMPOSTELA

No puedo olvidar mencionar a mis tutores durante mi estancia en Alemania. Quiero agradecer a Dominik y Marc por brindarme la oportunidad de conocer a su grupo de investigación (Rasoul, Anja, Lucas, Juan Carlos, Arne,..). También quiero expresar mi gratitud por su apoyo en una parte fundamental de esta tesis. Especialmente a Dominik, por acogerme con cariño y por enseñarme algo nuevo en cada una de sus revisiones, siempre sacándome una sonrisa. Espero que no me haya quedado un poor tiny little paragraph :)

Ya en un plano más personal, me gustaría agradecer a mis amigos, quienes, a pesar de habernos tocado vivir una época socialmente complicada, siempre he tenido su respaldo. A las agros, las reinonas de Usera, las mamas del parque y las vecis por aguantar tantas charlas de tesis, artículos y estancias.

Quiero expresar mi más sincero agradecimiento a mi familia, y en particular a mis padres, Ramón y Alfonsi. Su constante apoyo y amor incondicional han sido el sólido cimiento en el que he construido mi vida y mis logros. Junto a mi hermana Silvia y mis sobris, han sido mi fuente inagotable de fortaleza y apoyo a lo largo de mi camino. Gracias también Abuela, por estar siempre pendiente y no cansarte de preguntar que por qué no puedes encontrar en el kiosco de abajo esas revistas raras en las que escribo ☺.

Y por último, gracias a José, mi compañero de vida, por acompañarme a Berlín, por volverse a Madrid, por irnos a Canadá, enfrentarnos al desafío del teletrabajo en la pandemia, compartir la alegría de dos embarazos y por no dudar en que nos íbamos la familia al completo de estancia. Porque si está tesis tiene un patrocinador ese es su hueco. Tu apoyo me ha aportado la tranquilidad que he necesitado para llevar a cabo este trabajo. No creo que esos 6 meses de beca en Berlín se hubiesen convertido en 8 años si él no hubiese estado allí, y así podría sumar y seguir todo este tiempo. Gracias por escucharme muuucho tiempo hablar de modelos, de chopos, de carbono y de los papers. Por escuchar cada presentación mil veces y corregírmelas. Eso sí hablando bajito que no se despierten los niños :). Como dijo Ralph Waldo, "*Nunca podemos decir gracias lo suficiente a la persona que nos ha permitido ser lo que somos.*". Dedico esta tesis a nuestros hijos Leo y Nico, por ser una fuente constante de desconexión y recarga de pilas, porque verlos crecer te da energía para lograr tus sueños y ser un ejemplo para su futuro.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

INDEX

PREFACE 19
ABSTRACT 23
RESUMEN 25
RESUMO 33
CHAPTER 1: INTRODUCTION 44
1.1. BACKGROUND 44
1.2. POPLAR SHORT ROTATION COPPICE (SRC) SYSTEMS FOR BIOMASS PRODUCTION 46
1.3. JUSTIFICATION FOR THE THESIS WITHIN THE GENERAL CONTEXT 47
1.4. OBJECTIVES 47
1.4.1. Process-based models 49
1.4.2. Economic potential and carbon stocks 53
1.5. DATA BASE 54
1.5.1. Poplar Plot Network 54
1.5.2. SRC-Trial to obtain monthly parameters 55
CHAPTER 2: TIME-COURSE FOLIAR DYNAMICS OF POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS. RESPONSES TO DIFFERENT WATER SCENARIOS 60
2.1. INTRODUCTION 60
2.2. MATERIAL AND METHODS 62
2.2.1. Data source 62
2.2.2. Foliage fraction measurements 63
2.2.3. Leaf area estimation 64
2.2.4. Specific Leaf Area (SLA) and Leaf Area Index (LAI) 64
2.2.5. Leaf nutrient analysis 65
2.2.6. Foliar gas exchange measurements 65
2.2.7. Statistical analysis 66
2.3. RESULTS AND DISCUSSION 66
2.3.1. Monthly foliage productivity, distribution and individual leaf area 66
2.3.2. Monthly LAI and SLA analysis 72
2.3.3. Monthly dynamics of foliar nutrient concentrations: carbon, nitrogen, phosphorus and potassium 75
CHAPTER 3: ADAPTING 3-PG TO DECIDUOUS TREES IN RESPONSE TO WATER RESTRICTION: POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS 90
3.1. INTRODUCTION 90
3.2. 3.2. MATERIAL AND METHODS 94

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

3.2.1. Model description....94
3.2.2. Data source, field measurements and model inputs....100
Model inputs....102
3.2.3. Adapting the 3-PG to a deciduous SRC....103
3.2.4. Temporal change in Specific Leaf Area (σt)....104
3.2.5. Temporal change in Litterfall rate (γF)....105
3.2.6. Canopy conductance....106
3.2.7. Gas exchange measurements....106
3.2.8. Allocation of Net Primary Production (NPP) to biomass components (foliage, W_F; stem, W_S; roots, W_R)....107
3.2.9. Statistical analyses....107
3.2.9.1. Model evaluation....107
3.2.9.2. Model evaluation between irrigation scenarios....108
3.3. RESULTS AND DISCUSSION....109
3.3.1. Specific Leaf Area (SLA)....109
3.3.2. Litterfall rate (γF)....112
3.3.3. Maximum canopy quantum efficiency (αCx)....116
3.3.4. Monthly Net Primary Production (NPP) distribution....118
3.3.5. Model calibration and validation....119
3.4. CONCLUSIONS....126
CHAPTER 4: AN ECONOMIC OVERVIEW OF *POPULUS* SPP. IN SHORT ROTATION COPPICE SYSTEMS UNDER MEDITERRANEAN CONDITIONS: AN ASSESSMENT TOOL FOR DECISION-MAKING....132
4.1. INTRODUCTION....132
4.2. MATERIAL AND METHODS....134
4.2.1. Data sources....134
4.2.2. Yield data....136
4.2.3. Cultural operation inventory....137
4.2.3.1. Chip biomass sale price....139
4.2.4. Economic Feasibility....140
4.2.4.1. Cultural operation cost analysis....140
4.2.5. Financial analysis....140
4.2.5.1. Net present value....140
4.2.5.2. Land Expectation Value....141
4.2.6. Analysis of different discount rates and biomass prices linked to an evaluation of the Internal Rate of Return....142
4.2.7. Simple assessment tool for decision-making....143

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.3. RESULTS AND DISCUSSION 143
4.3.1. Cultural operation cost analysis 143
4.3.2. Financial Analysis 147
4.3.3. Sensitivity analyses 149
4.3.3.1. Land rental costs 149
4.3.3.2. Drip irrigation costs (water and electricity) 149
4.3.3.3. Cut-and-chip harvesting costs 151
4.3.4. Analysis of different discount rates and biomass prices linked to an evaluation of the Internal Rate of Return (IRR) 152
4.3.5. Simple assessment tool for decision-making 155
4.4. CONCLUSIONS 157
CHAPTER 5: ASSESSING THE POTENTIAL OF POPLAR SHORT ROTATION PLANTATIONS TO CONTRIBUTE TO A LOW-CARBON BIOECONOMY UNDER WATER-LIMITED CONDITIONS 162
5.1. INTRODUCTION 162
5.2. MATERIAL AND METHODS 164
5.2.1. Study design 164
5.2.2. SRC-Trial 165
5.2.3. PPN trial 165
5.2.4. Biomass estimation 166
5.2.4.1. Above-ground biomass 166
5.2.4.2. Below-ground biomass 166
5.2.5. Quantification of carbon sequestration 168
5.2.6. Economic impact analyses 168
5.2.6.1. Irrigation regime evaluation 168
5.2.6.2. Carbon benefits 169
5.2.6.3. Analyses of uncertainty in the socio-economic framework 169
5.2.7. Life cycle analyses of carbon emission 170
5.2.7.1. Carbon stored in biomass-derived products 170
5.2.7.2. Conditions and assumptions for life cycle analyses of carbon emission 172
5.2.8. Statistical analyses 173
5.3. RESULTS AND DISCUSSION 174
5.3.1. Experimental results for above and below-ground biomass during the first rotation 174
5.3.2. Above and below-ground biomass for one complete plantation cycle 175
5.3.3. Above and below-ground carbon stocks 176
5.3.3.1. Fractions of C concentrations (%) in above and below-ground biomass 176
5.3.3.2. C sequestration potential in above and below-ground biomass 177

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.3.4. Economic evaluation of revenues from biomass (BAU) and additional revenues from potential carbon payments (BAU+C) 179
5.3.5. Economic and environmental implications of the root-extraction practice 181
5.3.6. Addressing uncertainty in our socio-economic framework through sensitivity analyses 183
5.3.7. Analysis of the climate mitigation potential of alternative biomass uses 185
5.4. CONCLUSIONS 186
CHAPTER 6: GENERAL DISCUSSION 192
6.1. IMPROVED BIOMASS PREDICTIONS 192
6.2. ECONOMIC VIABILITY 195
6.3. FUTURE PERSPECTIVES 198
CHAPTER 7: CONCLUSIONS 203
REFERENCES 210

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

PREFACE

This doctoral thesis, submitted under the modality «monograph with total or partial reproduction of publications», summarizes 4 years of research work and includes 4 main articles (partially and/or totally reproduced), all of which are published in journals indexed in the Journal Citation Reports (JCR). The monograph also includes other results, discussions and conclusions derived from the research work and supported by the findings reported in the articles. In addition to the main articles, all other research activities derived from this research (other articles, conference communications, etc.) are listed in this preface.

MAIN ARTICLES INCLUDED IN THE THESIS:

1. Fuertes, A., Sixto, H., González, I., Pérez-Cruzado, C., Cañellas, I., Rodríguez-Soalleiro, R., Oliveira, N., 2022. Time-course foliar dynamics of poplar short rotation plantations under Mediterranean conditions. Responses to different water scenarios. Biomass and Bioenergy 159, 106391. https://doi.org/10.1016/j.biombioe.2022.106391

This article has been totally reproduced in the following sections:

- Introducction (2.1)
- Material and methods (2.2)
- Results and discussion (2.3)
- Conclusions (2.4)

The Journal *Biomass and Bioenergy,* belonging to Elsevier editorial, allows reuse of the article (**Open Access** - CC BY 4.0 License) by the author as part of her thesis:

- https://creativecommons.org/licenses/by/4.0/

2. Fuertes, A., Oliveira, N., Pérez-Cruzado, C., Cañellas, I., Sixto, H., & Rodríguez-Soalleiro, R. (2023). Adapting 3-PG foliar variables to deciduous trees in response to water restriction: poplar short rotation plantations under Mediterranean conditions. Forestry: An International Journal of Forest Research, 1–13. https://doi.org/10.1093/forestry/cpad022

This article has been totally reproduced in the following sections:

- Introducction (mainly 3.1)
- Material and methods (3.2.1 - 3.2.7 and mainly 3.2.9)
- Results and discussion (3.3.1 - 3.3.3 and mainly 3.3.5)
- Conclusions (mainly 3.4)

The Journal *Forestry: An International Journal of Forest Research,* belonging to Oxford University Press editorial, allows reuse of the article (**Open Access** - CC BY 4.0 License) by the author as part of her thesis:

https://creativecommons.org/licenses/by/4.0/

3. Fuertes, A., Oliveira, N., Cañellas, I., Sixto, H., Rodríguez-Soalleiro, R., 2021. An economic overview of *Populus* spp. in Short Rotation Coppice systems under Mediterranean conditions: An assessment tool for decision-making. Renew. Sustain. Energy Rev. 151. https://doi.org/10.1016/j.rser.2021.111577

This article has been totally reproduced in the following sections:

- Data base (1.5)
- Introducction (4.1)
- Material and methods (4.2)
- Results and discussion (4.3)
- Conclusions (4.4)

The Journal *Renewable and Sustainable Energy Reviews*, belonging to Elsevier editorial, allows reuse of the article (**Subscription** -CC BY-NC-ND License) by the author as part of her thesis:

- https://www.elsevier.com/about/policies/copyright#Author-rights

4. Fuertes, A., Oliveira, N., Cañellas, I., Sixto, H., Rodríguez-Soalleiro, R., Hanewinkel, M., Sperlich, D., 2023. Assessing the potential of Poplar Short Rotation plantations to contribute to a low-carbon bioeconomy under water-limited conditions. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2023.119062

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

This article has been totally reproduced in the following sections:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

- Introducction (5.1)
- Material and methods (5.2)
- Results and discussion (5.3)
- Conclusions (5.4)

The Journal: *Journal of Environmental Management,* belonging to Elsevier editorial, allows reuse of the article (**Open Access** - CC BY 4.0 License) by the author as part of her thesis:

https://creativecommons.org/licenses/by/4.0/

Authors contribution

In the above articles, the authors responsibilities were, according to the CRediT (Contributor Roles Taxonomy) framework:

- **Alicia Fuertes Sánchez:** Ideas, Formal analysis, Data Curation, Writing - Original Draft, Methodology, Visualization and Writing - Review & Editing**.**
- **Nerea de Oliveira Rodríguez:** Ideas, creation of models, Data Curation, Writing - Original Draft, Visualization and Writing - Review & Editing.
- **Hortensia Sixto Blanco:** Methodology, Conceptualization, Resources, Writing - Review & Editing, Funding acquisition, Project administration and Supervision**.**
- **Roque Rodríguez-Soalleiro:** Methodology**,** Conceptualization, Validation, Writing - Review & Editing, Funding acquisition, Project administration and Supervision.
- **Isabel Cañellas:** Resources, Writing - Review & Editing, Funding acquisition.
- **César Pérez Cruzado:** Methodology**,** Conceptualization, Validation, Writing - Review & Editing.
- **Isabel Gonzalez:** Data Curation, Writing - Original Draft, Methodology.
- **Marc Hanewinkel:** Validation, Writing - Review & Editing and Supervision.
- **Dominik Sperlich:** Ideas, Methodology**,** Conceptualization, Validation, Writing - Review & Editing and Supervision.

Journal's performance

Study	Journal	Category	Impact Factor
1	Biomass and Bioenergy	Agronomy and Crop science - Forestry	6 (Q1)
2	Forestry: An International Journal of Forest Research	Forestry	2.8 (Q2)
3	Renewable and Sustainable Energy Review	Renewable Energy, Sustainability and the Environment	16.8 (Q1)
4	Journal of Environmental Management	Environmental Science	8.7 (Q1)

Latest information is taken from the Journal Citation Reports (Source Clarivate, 2023).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

ABSTRACT

In recent years, accumulating evidence suggests that our current economic model, which heavily relies on finite resources and fossil fuels, is both unsustainable and harmful to the planet. To address these pressing concerns, the concept of the bioeconomy has surfaced, presenting a new way of thinking about the way we produce and its relationship to the environment, identify circularity as a key component of the bioeconomy vision.

As we move toward a sustainable circular bioeconomy, European forestry is expected to play a crucial role in supplying feedstock and services while generating co-benefits like landscape diversity, reduced soil erosion, increased biodiversity, and job creation, contributing to smart green growth.

Poplar Short Rotation Coppice (SRC) systems achieve high productivity in a short period of time, being important for short- to medium-term carbon (C) sequestration in the different biomass fractions, contributing to a low-carbon bioeconomy and thus helping to mitigate global warming. The productivity and profitability of these plantations are, however, challenged under restrictive irrigation associated with climate change.

This thesis has a dual objective: improving climate-sensitive biomass predictions for these particular plantation systems in response to water restrictions and promoting awareness of their economic viability and ecosystem services. This study aims to improve the 3-PG model (Physiological Principles Predicting Growth) estimation for poplar SRC systems, not only by determining the required species-specific parameters, mainly from observed data, but also by further adapting the model architecture to these specific plantations. The response of plantation to irrigation restriction on the 3-PG model parameters were also considered. Additionally, the study includes an economic analysis, addressing cost factors associated with plantation management and establishment, along with uncertainties related to discount rates, biomass and C market prices.

The data used in this thesis was obtained from a comprehensive Poplar Plot Network (PPN) under SRC management. These plots are strategically distributed throughout Spain with favourable conditions for cultivating such crops. The network comprises 30 different locations, ranging in size from less than 1 to 8 has, with trial densities varying between 5,000-33,333 cuttings ha^{-1}.

Additionally, a SRC plantation was specifically established to obtain monthly parameters. A total of 138 trees were sampled from this plantation of the highly productive hybrid *Populus* x *canadensis* Mönch ('AF2') over a first rotation (3-years) at a planting density of 10,000 trees ha^{-1}. Two irrigation scenarios: field capacity (FC) and

50% FC, were considered to take into account the impact of climate change in the context of irrigation restrictions.

The proposed parameterization and adaptation of the 3-PG model demonstrated good agreement with the validation dataset, accurately predicting Leaf Area Index (LAI), stem, root, and leaf biomass of this type of short-rotation and high-density poplar plantations. Our results showed that Specific Leaf Area (SLA) follows a similar declining trend throughout each year of the rotation. No significant differences in SLA and litterfall rates were found between water scenarios (T1 and T2), over the three-year rotation period, allowing the resulting parameters to be applied to both irrigation scenarios. The selected genotype 'AF2' has tight stomatal control under reduced water conditions, maintaining high photosynthetic levels. Its adaptive strategies, which mitigate production losses, make it a promising candidate not only for modelling biomass production but also for breeding programs in response to water restrictions.

In terms of economic analysis concerning the multifunctionality of Mediterranean poplar SRC plantations, critical cost factors include land rental, irrigation-related water and electricity costs, and cut-and-chip harvesting. Among these factors, land rental is the most crucial one, accounting for 31.88 % of the total costs. This study reveals that economic viability of poplar SRC can be achieved either by maximizing productivity or through increased market prices, associated with more diversified energy use and/or bioproducts. Additionally, quantifying ecosystem services, which currently lack a market price, plays a vital role. Profitability is influenced by introducing an extra payment for C sequestration, diversifying income and recovering the initial investment a year earlier, even under water restriction. Despite reduced productivity due to experimental water limitations, the plantations remain profitable.

This understanding provides a broad knowledge base for the development of more accurate predictive management tools, aimed at promoting the establishment of poplar SRC systems, optimizing biomass production and meeting market demands in the transition to a low-carbon bioeconomy.

Keywords: Poplar Short Rotation Coppice systems, Lignocellulosic biomass, 3-PG model, Carbon sequestration, Bioeconomy.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

RESUMEN

En los últimos años, cada vez son más las evidencias de que nuestro modelo económico actual, altamente dependiente de recursos finitos y combustibles fósiles, es insostenible y dañino para el planeta. En respuesta a estas preocupaciones, ha surgido el concepto de la bioeconomía, que presenta una nueva forma de pensar sobre nuestra forma de producir y su relación con el medio ambiente. La Unión Europea, muchos gobiernos nacionales, así como diferentes empresas en todo el mundo identifican además la circularidad como un componente clave de la visión de la bioeconomía (European Commission, 2018).

A medida que avanzamos en su desarrollo, es crucial considerarla bajo el marco de lo que supone el cambio climático, creando oportunidades de empleo y estableciendo fuentes renovables de productos, servicios y energía derivados de los recursos biológicos (Hetemäki et al., 2022; OCDE, 2009). Dentro de esta bioeconomía circular, se espera que el sector forestal desempeñe un papel importante al suministrar una materia prima relevante, la madera, así como los servicios asociados (Commission, 2022; Freer-Smith et al., 2019). El ámbito forestal constituye el principal hábitat de la biodiversidad terrestre, el mayor sumidero de carbono terrestre y la principal fuente terrestre de precipitación (Hetemäki et al., 2022). Desde esta perspectiva, se comprende que el sector forestal tiene una relevante contribución que realizar (Hetemäki et al., 2017; Palahí et al., 2020a, b), ya que la producción de biomasa leñosa como fuente de energía y/o bioproductos es ampliamente reconocida como una parte crucial de la transición hacia sistemas de energía y productos sostenible (Scarlat et al., 2015b).

Las plantaciones son una fuente esencial de biomasa leñosa. En los últimos años, ha habido un creciente interés en los usos multifuncionales asociados a estas plantaciones (Pelkmans et al., 2015), así como su potencial para mitigar el calentamiento global al capturar CO_2 en el complejo biomasa-suelo (Grafton et al., 2021). Estas plantaciones pueden ser gestionadas de manera que se maximice su potencial de producción al tiempo que se favorecen diversos servicios ecosistémicos. Entre estos se encuentran la diversidad del paisaje, la reducción de la erosión del suelo y el lavado de nutrientes, la capacidad para albergar biodiversidad en el entorno agrario en el que se establecen, la habilidad para actuar en la fitorremediación o su contribución al manejo de llanuras inundables (Haughton et al., 2016; Henri y Johnson, 2005; Oliveira, 2019). Los estudios también han demostrado que las plantaciones bien gestionadas pueden proporcionar un mayor rendimiento de biomasa por hectárea que los bosques naturales y que son la herramienta de captura de carbono más efectiva a corto y medio plazo (Bastin et al., 2019; Grafton et al., 2021), reduciendo así la presión sobre los bosques naturales y promoviendo prácticas sostenibles de manejo forestal (FAO, 2010).

El European Green Deal reconoce de manera clara y evidente el papel que los bosques, pueden desempeñar como sumideros de carbono y sugiere medidas para mejorar la restauración y conservación forestal. En el marco de esta perspectiva, este documento tiene como objetivo adaptar un modelo sensible al clima de predicción de biomasa lignocelulósica con especies leñosas para los sistemas de plantación de 'Short Rotation Coppice' (SRC) de chopo, establecidos en alta densidad y con turno corto, en respuesta a las restricciones de agua. Al mismo tiempo, se busca crear conciencia sobre la viabilidad económica y los beneficios, así como la diversa gama de ventajas asociadas a los servicios ecosistémicos que ofrecen estos sistemas. Estas plantaciones con especies de crecimiento rápido se gestionan bajo esquemas de manejo intensivos en monte bajo, con ciclos de recepe de entre 3 y 5 años hasta el declive de la productividad de la cepa, lo que sucede en un rango de entre 9 y 14 años (Aylott et al., 2010).

Entre las especies más utilizadas en este tipo de plantaciones, destaca la familia *Salicaceae* y, en particular, el género *Populus*, el cual involucra especies e híbridos de importancia para la producción de madera en muchas partes del mundo (Bradshaw et al., 2000), incluido el ámbito mediterráneo (Pecchioni et al., 2020; Sixto et al., 2015). El género, presenta una serie de características que lo convierten en una opción ideal para este uso productivo, como la disponibilidad de un amplio abanico de material genético mejorado, en parte debido a su facilidad de hibridación, así como tasas de crecimiento rápido y facilidad para la multiplicación vegetativa.

Por ello, estas plantaciones logran una alta productividad en un corto período de tiempo (Meyer et al., 2021), y consecuentemente gran capacidad de almacenar carbono en las diferentes fracciones de biomasa (Berhongaray et al., 2017; Oliveira et al., 2018). En particular, en condiciones mediterráneas con aplicación de riego son notablemente productivas (Oliveira et al., 2020). A pesar de estas ventajas, la presión del cambio climático hace que sea cada vez más importante considerar la escasez de agua. De hecho, la productividad puede verse seriamente limitada por el déficit hídrico durante las estaciones de crecimiento (González-González et al., 2017), lo que hace que el riego sea un requisito necesario para garantizar su supervivencia, especialmente en regiones mediterráneas (Padrón y Orensanz García, 1987). Sin embargo, a medida que avanza el cambio climático, la escasez de agua y la necesidad de riego también se están convirtiendo en una preocupación en zonas climáticas que actualmente no tienen esta problemática (Coyle y Coleman, 2005; Dimitriou et al., 2009; Schweier y Becker, 2013; Yan et al., 2016). En este contexto, dada la importancia de la biomasa leñosa obtenida de plantaciones como materia prima clave para el desarrollo de la bioeconomía, esta tesis persigue mejorar las herramientas predictivas de la producción de forma más precisa considerando su sensibilidad al clima. Por todo ello, a lo largo de este estudio, se ha tenido en cuenta la respuesta de estas plantaciones frente a la escasez de agua en los distintos objetivos planteados.

USC DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Otro aspecto fundamental a la hora de optimizar la rentabilidad de estas plantaciones y que es el segundo gran objetivo de esta tesis, es evaluar la viabilidad económica, considerando la multifuncionalidad de estas plantaciones, así como las diversas ventajas asociadas a los servicios ecosistémicos que ofrecen, evaluando cómo estas contribuciones pueden potencialmente impulsar la transición hacia una bioeconomía baja en carbono más respetuoso con el medio ambiente y sostenible.

Para dar respuesta a estos objetivos se ha contado con información procedente de i) una amplia red de parcelas de plantaciones de especies leñosas en turno corto y alta densidad, distribuida por aquellas zonas de la península con aptitud para este tipo de sistemas. La red abarca un total de 30 localidades en las que se han testado 48 genotipos diferentes con un rango de densidades que va desde los 5,000 hasta los 33,333 pies ha^{-1}. Así como, ii) una plantación de chopo a alta densidad y turno corto específicamente establecida para obtener parámetros mensuales utilizando el genotipo 'AF2' (*Populus* × *canadensis* Mönch) a una densidad de 10,000 pies ha^{-1} (2m x 0.5m) en el centro de España. Este genotipo se usa ampliamente para la producción de biomasa lignocelulósica en el área mediterránea (Pannacci et al., 2009; Sabatti et al., 2014) debido a su alta productividad y adaptabilidad a las condiciones mediterráneas (Sixto et al., 2015). El ensayo se estableció manualmente utilizando estaquillas de 25 cm de longitud y se definieron dos regímenes de riego. El primero (T1) se irrigó hasta la capacidad de campo y sirvió como régimen óptimo. El segundo (T2) se irrigó al 50% de la capacidad de campo.

La mejora en la estimación de la producción de biomasa lignocelulósica requiere una comprensión profunda de la alometría y el crecimiento de los árboles, especialmente en plantaciones SRC de chopo debido a su alta densidad, al carácter caducifolio que exhiben y su dependencia del clima. En el contexto actual, es crucial tener en cuenta las respuestas fisiológicas de los árboles, como los cambios en la alometría, ya que la productividad de estas plantaciones, especialmente bajo condiciones mediterráneas, se ve desafiada como ya hemos indicado ante posibles escenarios de riego restrictivo. Por lo tanto, es necesario profundizar en nuestra comprensión del comportamiento de cada fracción de la planta y el papel que desempeñan en el crecimiento del árbol. Específicamente, la fracción foliar tiene una importancia significativa, ya que constituye la principal interfaz entre los árboles y su entorno atmosférico, desempeñando así un papel clave en las relaciones ecofisiológicas (Landsberg y Sands, 2011).

En el Capítulo 2, se realizó un análisis mensual exhaustivo para examinar los cambios en variables importantes a nivel foliar durante los periodos vegetativos de un turno completo (3 años) en la plantación experimental mencionada que incluía dos regímenes de riego, optimo y restrictivo. Las variables estudiadas fueron: el número y distribución de hojas, la biomasa foliar, el índice de área foliar (LAI), el área foliar específica (SLA), el contenido en macronutrientes foliares (NPK y C) y parámetros de intercambio gaseoso

foliar (conductancia estomática, tasa de asimilación fotosintética y tasa de transpiración instantánea). Los resultados de este capítulo proporcionaron una base sólida para mejorar las predicciones de biomasa. Se observó que, bajo condiciones de riego restringido, el clon 'AF2' adoptó una estrategia de producir más ramas en el año de establecimiento, lo que llevó a una reducción en la producción foliar en comparación con el régimen de riego óptimo. Además, se destacó la capacidad de la hoja para regular la fotosíntesis y la conductancia estomática bajo condiciones de estrés hídrico, lo que permitió mantener niveles fotosintéticos elevados. Este genotipo implementa estrategias para mitigar las pérdidas en producción en escenarios de cambio climático, lo que lo convierte en un candidato prometedor para modelar la producción de biomasa.

Todas las variables estudiadas en el Capítulo 2 tienen una importancia significativa en numerosos modelos ecofisiológicos, incluido el modelo 3-PG (Physiological Principles Predicting Growth) adaptado y parametrizado para chopo en esta tesis (Fuertes et al., 2022), que calcula el crecimiento basado en la radiación interceptada, siendo la relación entre el área foliar y la masa foliar de gran importancia (Feikema et al., 2010).

El modelo 3-PG es una herramienta sencilla y basada en procesos para estimar el crecimiento forestal de forma mensual. Este modelo consta de diversos submodelos, incluyendo la asimilación de carbohidratos, la distribución de biomasa entre hojas, raíces y tallos, el balance de agua en el suelo y la conversión de los valores de biomasa en variables relevantes para los gestores forestales. Para iniciar la simulación, se requiere información específica de cada especie en términos de parámetros, así como datos del sitio y del clima (Sands y Landsberg, 2002a).

Originalmente, el modelo 3-PG fue desarrollado para especies de hoja perenne (Landsberg y Waring, 1997). Se han realizado propuestas para su adaptación a especies caducifolias, como es el caso de plantaciones de sauce (Amichev et al., 2011; Jégo et al., 2017), bosques subtropicales de especies mixtas (Forrester y Tang, 2016), bosques caducifolios dominados por abedules blancos (Potithep y Yasuoka, 2011) o plantaciones de roble albar (Nölte et al., 2020). Algunos estudios también se han centrado específicamente en plantaciones de chopo, incorporando adaptaciones al modelo 3-PG para simular la brotación y el rebrote. En estos casos, los parámetros específicos de la especie necesarios para ejecutar el modelo 3-PG se derivan principalmente de la literatura (Amichev et al., 2010; Hart, 2014; Hart et al., 2015; Headlee et al., 2012; Zalesny et al., 2012). No obstante, aún falta una adaptación completa para poder predecir con precisión el crecimiento de plantaciones de chopos de alta densidad y con turnos cortos.

El objetivo del Capítulo 3 fue mejorar las predicciones de biomasa de este tipo de plantaciones de chopo utilizando un modelo basado en procesos respaldado por el análisis de datos foliares mensuales bajo diferentes regímenes de riego estudiados en el capítulo anterior. Para lograr esto, se adaptó y parametrizó específicamente el modelo

3-PG. Este proceso implicó no solo determinar, principalmente a partir de datos observados, los parámetros específicos de la especie necesarios para iniciar las simulaciones, sino también adaptar en mayor medida la arquitectura del modelo 3-PG a las características particulares de estas plantaciones. Entre estas características se incluye el hecho de que todas las hojas caen cada año, así como las variaciones mensuales del LAI a lo largo del período vegetativo, en lugar de considerarlas durante toda la vida de la plantación.

Además, se simuló el crecimiento de las hojas cada primavera. También se analizó el patrón de variación mensual en los parámetros de asignación de la producción primaria neta (NPP) a los diferentes componentes de la biomasa. Asimismo, se consideraron los efectos de diferentes regímenes de riego en los parámetros del modelo 3-PG para abordar la respuesta de las plantaciones de chopos a las posibles limitaciones de agua en el contexto del cambio climático.

La propuesta de parametrización y la adaptación de la estructura del modelo 3-PG mostraron una buena concordancia con el conjunto de datos de validación, prediciendo de manera precisa el LAI, la biomasa del fuste, raíz y hojas en la dinámica particular de este tipo de plantaciones a turno corto y alta densidad.

Desde la perspectiva de promover el establecimiento de plantaciones que contribuyan a una bioeconomía baja en carbono, es fundamental contar con estimaciones fiables de producción de biomasa. Sin embargo, además de esto, también es necesario realizar un análisis económico sólido para minimizar las incertidumbres financieras y garantizar la viabilidad de estos proyectos teniendo en cuenta la multifuncionalidad. En el Capítulo 4, se llevó a cabo un análisis económico detallado basado en datos reales bajo condiciones mediterráneas, donde se destaca el uso de riego. El análisis profundiza en los principales costes y los divide en tres categorías diferentes (operaciones culturales, alquiler de tierras y costes de riego). El objetivo es identificar los costes que tienen mayor impacto en la rentabilidad de estas plantaciones y analizarlos. Adicionalmente, se ofrece una herramienta sencilla que permite evaluar la rentabilidad de las plantaciones SRC de chopo con riego por goteo de una manera rápida, comparando el Valor Presente Neto (NPV) derivado de distintos niveles de productividad y precios de biomasa. Entre los costes identificados, el arrendamiento de tierras se destaca como el más significativo, representando el 31.88% del coste total. El segundo factor más relevante es el gasto en agua y electricidad asociado con el riego, representando el 16.61%. Finalmente, la operación de corta y astillado contribuyó con el 11.87% del coste total.

En el capítulo 5, se aborda la consideración de la multifuncionalidad de las plantaciones de chopo al evaluar su rentabilidad considerando el carbono almacenado. Entre los principales servicios ecosistémicos de estas plantaciones destaca su capacidad para mitigar los gases de efecto invernadero (Hillier et al., 2009; Smith, 2004; Walter et al., 2015) mediante la captura de carbono.

Por ello, el capítulo 5 se centra en cuantificar la producción de biomasa de todo el árbol, incluyendo tanto la biomasa aérea leñosa como la biomasa subterránea, así como el potencial de captura de carbono de una plantación SRC de chopo con un ciclo de 12 años (4 turnos de corta de 3 años cada uno) bajo condiciones óptimas y de restricción de riego, observando que desempeñan un papel activo en la mitigación del calentamiento global a partir del tercer año de cultivo, tanto bajo regímenes de riego óptimos como restrictivos. Esto se debe a las rápidas tasas de crecimiento alcanzadas en un corto período de tiempo. Además, examina las implicaciones económicas asociadas con el pago adicional por la captura de carbono. Asimismo, aborda las incertidumbres relacionadas con los precios de la biomasa y el carbono, así como las variaciones en las tasas de descuento, ofreciendo un enfoque práctico que brinda información valiosa a los gestores para evaluar los posibles retornos económicos de su inversión en plantaciones SRC de chopo.

En los resultados, se pudo observar que la rentabilidad de las plantaciones de chop o se vio afectada por la implementación de un pago adicional por la captura de carbono, diversificando los ingresos y recuperando la inversión un año antes en ambos regímenes de riego (restrictivo y óptimo). A pesar del impacto negativo en la productividad debido a la restricción del agua, las plantaciones se mantuvieron rentables.

Además, el capítulo destaca los diferentes usos finales posibles de la biomasa, y la necesidad de diversificarlos, examinando el potencial de mitigación del cambio climático según el destino final de la biomasa recolectada, ya sea para la generación de bioenergía o la producción de bioproductos. Esta última ofrece una alternativa prometedora a los productos derivados de combustibles fósiles, lo que amplía aún más el potencial de captura de carbono de estos sistemas. Las políticas derivadas del European Green Deal probablemente aumentarán la demanda de biomasa, ya sea en forma de bioenergía renovable o productos bio-basados para reemplazar los productos fósiles (Herold et al., 2021). Esto abre oportunidades para que agricultores y silvicultores adopten prácticas agrícolas y forestales que capturen carbono de manera sostenible, lo que a su vez puede crear un nuevo modelo de negocio para ellos (Commission, 2022).

Desde esta perspectiva, es importante abordar los factores de coste críticos asociados con el establecimiento y la gestión de las plantaciones, así como las incertidumbres económicas relacionadas con las tasas de descuento, los precios del mercado de la biomasa y del carbono. Además, también se deben tener en cuenta las incertidumbres ecológicas relacionadas con posibles restricciones futuras de agua.

Dado el contexto del cambio climático, las plantaciones SRC de chopo desempeñan un papel significativo en la captura de carbono, ayudando a reducirlos niveles de CO_2. Con la creciente demanda de bioproductos basados en lignocelulosa, el carbono absorbido por estas plantaciones puede permanecer almacenado durante períodos prolongados

en los bioproductos derivados. Esto amplifica aún más el potencial de mitigación del cambio climático de las plantaciones de chopo SRC.

En resumen, al reconocer el valor de los servicios ecosistémicos proporcionados por los sistemas de chopo SRC y en concreto el derivado del secuestro de carbono en la biomasa subterránea y en los bioproductos derivados de la biomasa aérea leñosa, estos sistemas podrían formar parte de estrategias más amplias para abordar de manera efectiva los desafíos del cambio climático.

Indudablemente, a pesar del notable progreso en la investigación en relación a estas plantaciones, aún hay un amplio campo por explorar, y los logros alcanzados en esta tesis doctoral serán de gran valor para impulsar futuras investigaciones. Estudios que analicen la respuesta a la restricción de agua serán especialmente relevantes en el contexto del cambio global, y los resultados obtenidos aquí proporcionarán una base sólida para avanzar en este ámbito.

Esta tesis contribuye con herramientas de estimación de la producción sensibles al clima y herramientas de evaluación de la viabilidad económica, cuantificando uno de los servicios ecosistémicos más demandados en la actualidad, el carbono. Estas contribuciones tienen como objetivo mejorar la eficiencia de las plantaciones y ofrecer soluciones sólidas y adaptadas al contexto del cambio climático y las exigencias del mercado.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

RESUMO

Nos últimos anos, cada vez hai máis evidencia de que o noso modelo económico actual, moi dependente dos recursos finitos e dos combustibles fósiles, é insostible e prexudicial para o planeta. En resposta a estas inquedanzas, xurdiu o concepto de bioeconomía, que presenta unha nova forma de pensar a nosa forma de producir e a súa relación co medio. A Unión Europea, moitos gobernos nacionais, así como diferentes empresas de todo o mundo identifican aínda máis a circularidade como un compoñente clave da visión da bioeconomía (European Commission, 2018).

A medida que avanzamos no seu desenvolvemento, é fundamental consideralo no marco do que supón o cambio climático, creando oportunidades de emprego e establecendo fontes renovables de produtos, servizos e enerxía derivados dos recursos biolóxicos (Hetemäki et al., 2022; OCDE, 2009). Dentro desta bioeconomía circular, espérase que o sector forestal desempeñe un papel importante ao subministrar unha materia prima relevante, madeira, así como servizos asociados (Commission, 2022; Freer-Smith et al., 2019). O medio forestal constitúe o principal hábitat da biodiversidade terrestre, o maior sumidoiro de carbono terrestre e a principal fonte terrestre de precipitación (Hetemäki et al., 2022). Desde esta perspectiva, enténdese que o sector forestal ten unha contribución relevante que facer (Hetemäki et al., 2017; Palahí et al., 2020a), xa que a produción de biomasa leñosa como fonte de enerxía e/ou bioprodutos é amplamente recoñecida como unha parte crucial da transición cara a sistemas e produtos enerxéticos sostibles (Scarlat et al., 2015b).

As plantacións son unha fonte esencial de biomasa leñosa. Nos últimos anos, houbo un interese crecente polos usos multifuncionais asociados a estas plantacións (Pelkmans et al., 2015), así como polo seu potencial para mitigar o quecemento global mediante a captura de CO_2 no complexo biomasa-solo (Grafton et al., 2021). Estas plantacións pódense xestionar de forma que se maximice o seu potencial de produción favorecendo ao mesmo tempo diversos servizos ecosistémicos. Entre eles atópanse a diversidade da paisaxe, a redución da erosión do solo e o lavado de nutrientes, a capacidade de acoller biodiversidade no medio agrícola no que se establecen, a capacidade de actuar na fitorremediación ou a súa contribución á xestión das chairas inundables (Haughton et al., 2016; Henri e Johnson, 2005; Oliveira, 2019). Os estudos tamén demostraron que as plantacións ben xestionadas poden proporcionar un maior rendemento de biomasa por hectárea que os bosques naturais e que son a ferramenta de secuestro de carbono máis eficaz a curto e medio prazo (Bastin et al., 2019; Grafton et al., 2021), reducindo así a presión sobre os bosques naturais e promovendo prácticas de xestión forestal sostible (FAO, 2010).

O Pacto Verde Europeo recoñece de forma clara e evidente o papel que poden desempeñar os bosques como sumidoiros de carbono e suxire medidas para mellorar a restauración e conservación dos bosques. Dentro desta perspectiva, este documento pretende adaptar un modelo sensible ao clima para a predición de biomasa lignocelulósica con especies leñosas para sistemas de plantación de 'Short Rotation Coppice' de Chopo (SRC), establecido en alta densidade e con rotación curta, en resposta ás restricións de auga. Ao mesmo tempo, búscase dar a coñecer a viabilidade económica e os beneficios, así como a diversa gama de vantaxes asociadas aos servizos ecosistémicos que ofrecen estes sistemas. Estas plantacións con especies de crecemento rápido son xestionadas baixo esquemas de manexo intensivo en monte baixo, con quendas de recepe de entre 3 e 5 anos ata o descenso da produtividade da cepa, que ocorre nun intervalo entre 9 e 14 anos (Aylott et al. , 2010).

Entre as especies máis utilizadas neste tipo de plantacións destaca a familia *das Salicaceae*, en particular, o xénero *Populus*, que inclúe especies e híbridos de importancia para a produción de madeira en moitas partes do mundo (Bradshaw et al., 2000), incluída a zona mediterránea (Pecchioni et al., 2020; Sixto et al., 2020). O xénero presenta unha serie de características que o converten nunha opción idónea para este uso produtivo, como a dispoñibilidade dunha ampla gama de material xenético mellorado, en parte pola súa facilidade de hibridación, así como as rápidas taxas de crecemento e facilidade de multiplicación vexetativa.

Polo tanto, estas plantacións acadan unha alta produtividade nun curto período de tempo (Meyer et al., 2021), e consecuentemente gran capacidade para almacenar carbono nas diferentes fraccións da biomasa (Berhongaray et al., 2017; Oliveira et al., 2018). En particular, en condicións mediterráneas con aplicación de regas son notablemente produtivos (Oliveira et al., 2020). A pesar destas vantaxes, a presión do cambio climático fai que sexa cada vez máis importante considerar a escaseza de auga. De feito, a produtividade pode verse seriamente limitada polo déficit hídrico durante as épocas de crecemento (González-González et al., 2017), o que fai da rega un requisito necesario para garantir a súa supervivencia, especialmente nas rexións mediterráneas (Padrón e Orensanz Garcia, 1987). Non obstante, a medida que avanza o cambio climático, a escaseza de auga e a necesidade de rega tamén se están a converter nunha preocupación nas zonas climáticas que actualmente non teñen este problema (Coyle e Coleman, 2005; Dimitriou et al., 2009; Schweier e Becker, 2013; Yan et al., 2016). Neste contexto, dada a importancia da biomasa leñosa obtida das plantacións como materia prima fundamental para o desenvolvemento da bioeconomía, esta tese busca mellorar as ferramentas preditivas de produción con maior precisión tendo en conta a súa sensibilidade ao clima. Por todas estas razóns, ao longo deste estudo tívose en conta nos diferentes obxectivos marcados a resposta destas plantacións á escaseza de auga.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Outro aspecto fundamental á hora de optimizar a rendibilidade destas plantacións, e que é o segundo obxectivo principal desta tese, é avaliar a viabilidade económica, tendo en conta a multifuncionalidade destas plantacións, así como as distintas vantaxes asociadas aos servizos ecosistémicos, avaliando como estas contribucións poden impulsar potencialmente a transición cara a unha bioeconomía baixa en carbono máis respectuosa co medio ambiente e sostible.

Para dar resposta a estes obxectivos obtívose información de i) unha ampla rede de parcelas de plantacións de especies leñosas de rotación curta, de alta densidade, distribuídas por aquelas zonas da península aptas para este tipo de sistemas. A rede abrangue un total de 30 localizacións nas que se probaron 48 xenotipos diferentes cun rango de densidades que vai de 5.000 a 33.333 pés ha^{-1}. Así como, ii) unha plantación de chopo de alta densidade e quenda curta establecida especificamente para obter parámetros mensuais utilizando o xenotipo 'AF2' (*Populus* × *canadensis* Mönch) nunha densidade de 10.000 pés ha^{-1} (2 m x 0,5 m) no centro de España. Este xenotipo é moi utilizado para a produción de biomasa lignocelulósica na zona mediterránea (Panacci et al., 2009; Sabatti et al., 2014) debido á súa alta produtividade e adaptabilidade ás condicións mediterráneas (Sixto et al., 2015). A proba estableceuse manualmente mediante esquexes de 25 cm de lonxitude e definíronse dous réximes de rega. No primeiro (T1) regouse ata a capacidade do campo e serviu como réxime óptimo. No segundo (T2) regouse ao 50% da capacidade do campo.

A mellora na estimación da produción de biomasa lignocelulósica require un profundo coñecemento da alometría e do crecemento das árbores, especialmente nas plantacións de chopo SRC pola súa alta densidade, ao carácter caducifolio que exhiben e asúa dependencia do clima. No contexto actual, é fundamental ter en conta as respostas fisiolóxicas das árbores, como os cambios na alometría, xa que a produtividade destas plantacións, sobre todo en condicións mediterráneas, está condicionada xa indicamos fronte a posibles escenarios restritivos de rega. Polo tanto, é necesario afondar na comprensión do comportamento de cada fracción da planta e do papel que xogan no crecemento da árbore. En concreto, a fracción foliar é de importante significativa, xa que constitúe a principal interface entre as árbores e o seu medio atmosférico, xogando así un papel fundamental nas relacións ecofisiolóxicas (Landsberg e Sands , 2011).

No capítulo 2 realizouse unha exhaustiva análise mensual para examinar os cambios de variables importantes a nivel foliar durante os períodos vexetativos dunha quenda completa (3 anos) na mencionada plantación experimental que incluía dous réximes de rega, óptimo e restritivo. As variables estudadas foron: número e distribución de follas, biomasa foliar, índice de área foliar (LAI), área foliar específica (SLA), contido de macronutrientes foliares (NPK e C) e parámetros de intercambio gaseoso foliar (condutividade estomática, taxa de asimilación fotosintética e taxa de transpiración instantánea). Os resultados deste capítulo proporcionaron unha base sólida para

mellorar as predicións de biomasa. Observouse que, en condicións de rega restrinxida, o clon 'AF2' adoptou unha estratexia de producir máis pólas no ano de establecemento, o que provocou unha redución da produción de follas en comparación co réxime óptimo de rega. Ademais, destacouse a capacidade da folla para regular a fotosíntese e a condutancia estomática en condicións de estrés hídrico, o que permitiu manter altos niveis fotosintéticos. Este xenotipo implementa estratexias para mitigar as perdas de produción en escenarios de cambio climático, o que o converte nun candidato prometedor para modelar a produción de biomasa .

Todas as variables estudadas no capítulo 2 teñen unha importancia significativa en numerosos modelos ecofisiolóxicos, entre eles o modelo 3-PG (Physiological Principles Predicting Growth) adaptado e parametrizado para chopo nesta tese (Fuertes et al., 2022), que calcula o crecemento en función da radiación interceptada, sendo de gran importancia a relación entre a superficie foliar e a masa foliar (Feikema et al., 2010).

O modelo 3-PG é unha ferramenta sinxela e baseada en procesos, para estimar o crecemento forestal mensualmente. Este modelo consta de varios submodelos, incluíndo a asimilación de carbohidratos, a distribución da biomasa entre follas, raíces e talos, o balance hídrico do solo e a conversión dos valores de biomasa en variables relevantes para os xestores forestais. Para iniciar a simulación, requírese información específica da especie en termos de parámetros, así como datos do sitio e do clima (Sands e Landsberg, 2002a).

Orixinalmente, o modelo 3-PG foi desenvolvido para especies de folla perenne (Landsberg e Waring , 1997). Fixéronse propostas para a súa adaptación a especies caducifolias, como as plantacións de salgueiros (Amichev et al., 2011; Jégo et al., 2017), bosques subtropicais de especies mixtas (Forrester e Tang, 2016), bosques caducifolios dominados por bidueiros brancos (Potithep e Yasuoka , 2011) ou de carbas (Nölte et al., 2020). Algúns estudos tamén se centraron especificamente nas plantacións de chopo, incorporando adaptacións ao modelo 3-PG para simular o agromado e o rebrote. Nestes casos, os parámetros específicos da especie necesarios para executar o modelo 3-PG derívanse principalmente da literatura (Amichev et al., 2010; Hart, 2014; Hart et al., 2015; Headlee et al., 2012; Zalesny et al., 2012). Non obstante, aínda falta unha adaptación completa para prever con precisión o crecemento das plantacións de chopo de alta densidade con quendas curtas.

O obxectivo do capítulo 3 foi mellorar as predicións de biomasa deste tipo de plantacións de chopo mediante un modelo baseado en procesos apoiado na análise de datos foliares mensuais baixo diferentes réximes de rega estudados no capítulo anterior. Para conseguilo, adaptouse e parametrizouse especificamente o modelo 3-PG. Este proceso implicou non só determinar, principalmente a partir dos datos observados, os parámetros específicos da especie necesarios para iniciar as simulacións, senón tamén adaptar aínda máis a arquitectura do modelo 3-PG ás características particulares destas

plantacións. Entre estas características destaca o feito de que todas as follas caen cada ano, así como as variacións mensuais do LAI ao longo do período vexetativo, en lugar de consideralas ao longo da vida da plantación.

Ademais, simulouse o crecemento das follas cada primavera. Tamén se analizou o patrón de variación mensual dos parámetros de asignación da produción primaria neta (NPP) aos diferentes compoñentes da biomasa. Así mesmo, consideraronse os efectos dos diferentes réximes de rega nos parámetros do modelo 3-PG para abordar a resposta das plantacións de chopo ante posibles limitacións hídricas no contexto do cambio climático.

A proposta de parametrización e a adaptación da estrutura do modelo 3-PG mostraron unha boa concordancia co conxunto de datos de validación, predicindo con precisión o LAI, a biomasa do talo, raíz e follas na dinámica particular deste tipo de plantacións de quendas curtas e de alta densidade.

Desde a perspectiva de promover o establecemento de plantacións que contribúan a unha bioeconomía baixa en carbono, é fundamental contar con estimacións fiables da produción de biomasa. Non obstante, ademais disto, tamén é necesario realizar unha análise económica sólida para minimizar as incertezas financeiras e garantir a viabilidade destes proxectos tendo en conta a multifuncionalidade. No capítulo 4 realizouse unha análise económica detallada a partir de datos reais en condicións mediterráneas, onde se destaca o uso da rega. A análise afonda nos principais custos e divídeos en tres categorías diferentes (explotacións culturais, aluguer de terreos e custos de rega). O obxectivo é identificar os custos que teñen maior impacto na rendibilidade destas plantacións e analizalos. Ademais, ofrécese unha ferramenta sinxela que permite avaliar de forma rápida a rendibilidade das plantacións de chopo SRC con rego por goteo, comparando o Valor Actual Neto (NPV) derivado de diferentes niveis de produtividade e prezos da biomasa. Entre os custos identificados, o arrendamento de terreos destaca como o máis significativo, que representa o 31,88% do custo total. O segundo factor máis relevante é o custo da auga e da electricidade asociado ao rego, que representa o 16,61%. Finalmente, a operación de colleita e astelado aportou o 11,87% do custo total.

No capítulo 5 abórdase a consideración da multifuncionalidade das plantacións de chopo á hora de avaliar a súa rendibilidade tendo en conta o carbono almacenado. Entre os principais servizos ecosistémicos destas plantacións destaca a súa capacidade para mitigar os gases de efecto invernadoiro (Hillier et al., 2009; Smith, 2004; Walter et al., 2015) mediante a captura de carbono.

Por este motivo, o capítulo 5 céntrase na cuantificación da produción de biomasa de toda a árbore, incluíndo tanto a biomasa aérea leñosa como a biomasa subterránea, así como o potencial de secuestro de carbono dunha plantación de chopo SRC cun ciclo de 12 anos (4 quendas de corta de 3 anos cada unha) en condicións óptimas e restrición de

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

rega, sinalando que xogan un papel activo na mitigación do quecemento global a partir do terceiro ano de cultivo, tanto en réximes de rega óptimos como restritivos. Isto débese ás rápidas taxas de crecemento acadadas nun curto período de tempo. Ademais, examina as implicacións económicas asociadas ao pago adicional pola captura de carbono. Tamén aborda as incertezas relacionadas cos prezos da biomasa e do carbono, así como as variacións das taxas de desconto, ofrecendo un enfoque práctico que proporciona información valiosa para que os xestores avalíen os posibles retornos económicos do seu investimento en plantacións de chopo SRC.

Nos resultados púidose observar que a rendibilidade das plantacións de chopo viuse afectada pola implantación dun pago adicional por captación de carbono, diversificando os ingresos e recuperando o investimento un ano antes en ámbolos réximes de rega (restritivo e óptimo). A pesar do impacto negativo na produtividade debido á restrición de auga, as plantacións seguían sendo rendibles.

Ademais, o capítulo destaca os diferentes usos finais posibles da biomasa, e a necesidade de diversificalos, examinando o potencial de mitigación do cambio climático en función do destino final da biomasa recollida, xa sexa para a xeración de bioenerxía ou a produción de bioprodutos. Esta última ofrece unha alternativa prometedora aos produtos derivados dos combustibles fósiles, ampliando aínda máis o potencial de captura de carbono destes sistemas. As políticas derivadas do Pacto Verde Europeo probablemente aumentarán a demanda de biomasa, xa sexa en forma de bioenerxía renovable ou de produtos de base biolóxica para substituír os produtos fósiles (Herold et al., 2021). Isto abre oportunidades para que os agricultores e silvicultores adopten prácticas agrícolas e forestais que capturen de forma sostible o carbono, o que á súa vez pode crear un novo modelo de negocio para eles (Commission, 2022).

Dende esta perspectiva, é importante abordar os factores de custo críticos asociados co establecemento e xestión das plantacións, así como as incertezas económicas relacionadas coas taxas de desconto, os prezos da biomasa e do mercado de carbono. Ademais, tamén se deben ter en conta as incertezas ecolóxicas relacionadas con posibles futuras restricións de auga.

Dado o contexto do cambio climático, as plantacións de chopo SRC xogan un papel importante na captura de carbono, axudando a reducir os niveis de CO_2. Coa crecente demanda de bioprodutos a base de lignocelulosa, o carbono absorbido por estas plantacións pode permanecer almacenado durante longos períodos nos bioprodutos derivados. Isto amplifica aínda máis o potencial de mitigación do cambio climático das plantacións de chopo SRC.En resumo, ao recoñecer o valor dos servizos ecosistémicos proporcionados polos sistemas de chopo SRC e, concretamente, o valor derivado do secuestro de carbono na biomasa subterránea e nos bioprodutos derivados da biomasa leñosa aérea, estes sistemas poderían formar parte de estratexias máis amplas para afrontar eficazmente os desafíos do cambio climático.

Sen dúbida, a pesar do notable avance na investigación en relación a estas plantacións, aínda queda un amplo campo por explorar, e os logros desta tese doutoral serán de gran valor para impulsar futuras investigacións. Os estudos que analicen a resposta á restrición hídrica serán especialmente relevantes no contexto do cambio global, e os resultados aquí obtidos proporcionarán unha base sólida para o progreso nesta área.

Esta tese contribúe con ferramentas de estimación da produción sensibles ao clima e ferramentas de avaliación da viabilidade económica, cuantificando un dos servizos ecosistémicos máis demandados na actualidade, o carbono. Estas achegas están dirixidas a mellorar a eficiencia das plantacións e ofrecer solucións sólidas adaptadas ao contexto do cambio climático e ás demandas do mercado.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

Chapter 1

Introduction

"What you do makes a difference, and you have to decide what kind of difference you want to make."

Jane Goodall

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

The degree of future warming will depend strongly on the cumulative CO_2 emissions released through to the end of this century (Agreement, 2015; Delbeke et al., 2019). The European Commission has set a long-term goal to develop a competitive, resource efficient, low-carbon economy by 2050 (EC, 2011). They have proposed a reduction of at least 55% in net greenhouse gases with respect to 1990 by 2030, with the aim of achieving climate neutrality by 2050. These measures form the basis of the European Green Deal, which includes strategic goals to address climate change and environmental sustainability within the European Union. In this regard, the business-as-usual model, the policies, production and consumption habits we have been following, need to change (Hetemäki et al., 2022). In recent years, there has been a growing recognition that our current economic model, heavily dependent on finite resources and fossil fuels, is unsustainable and harmful to the planet. In response to these concerns, the concept of the bioeconomy has emerged, presenting a new way of thinking about our economy and its relationship with the environment.

There are many definitions of the bioeconomy, as well as usage of similar terms, such as bio-based economy. One useful definition from a global perspective is from the Global Bioeconomy Summit (2018): "bioeconomy is the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy". The European Union, several national governments and many businesses around the world identify circularity as a key component of the vision for a Bioeconomy (European Commission, 2018). The circular economy is a closed-loop system in which resources are continuously recycled and reused, reducing the need for new inputs and minimizing the environmental impact (D'Amato and Korhonen, 2021). According to Hetemäki et al. (2022), utilizing the circular bioeconomy as a hybrid approach, which combines the separate concepts that are commonly viewed independently, could lead to significant synergistic effects.

As we progress towards the development of development of a much needed innovative and sustainable circular bioeconomy, it becomes crucial to address climate change, create job opportunities, establish renewable sources of bio-based products, services, and energy derived from biological resources (Hetemäki et al., 2022; OECD, 2009). Within this circular bioeconomy, European forestry is expected to play a major role in supplying the feed-stock and services required (Commission, 2022; Freer-Smith et al., 2019) as well as being the main host for terrestrial biodiversity, the largest terrestrial

carbon (C) sink and main terrestrial source of precipitation (Hetemäki et al., 2022). From this perspective, the forest-based sector is understood to have an important contribution to make (Hetemäki et al. 2017; Palahí et al. 2020a, b). The production of woody biomass as a source of energy and/or bioproducts is widely recognized as a crucial part of the transition towards sustainable energy systems (Scarlat et al., 2015b).

Planted forests are an essential source of woody biomass. There has been growing interest over recent years in the multifunctional uses of this biomass production (Pelkmans et al., 2015) as well as its potential to mitigate global warming by sequestering CO_2 in the biomass-soil complex (Grafton et al., 2021). These plantations can be managed to maximize their potential for biomass production while maintaining their ecological and environmental benefits such as landscape diversity, reduction in soil erosion and nutrient leaching, increased biodiversity compared to agricultural land, phytoremediation or floodplain management (Haughton et al., 2016; Henri and Johnson, 2005; Oliveira, 2019). Studies have also shown that well-managed plantations can provide a higher biomass yield per hectare than natural forests and that they provide the most effective short to medium term C sequestration tool (Bastin et al., 2019; Grafton et al., 2021), thus reducing the pressure on natural forests and promoting sustainable forest management practices (FAO, 2010).

The European Green Deal clearly acknowledges the role forests can play as C sinks and suggests measures to enhance forest restoration and conservation. The production of lignocellulosic biomass, such as that from short-rotation plantations, and increasing the potential use of biomass in the form of bioproducts, are among the most promising possible contributions of the forest-based sector.

From this perspective, the aspect addressed in this document is that of lignocellulosic biomass production from short-rotation high density plantations defined in scientific literature as ‘Short Rotation Coppice’ (SRC) and more specifically, the SRC developed under Mediterranean conditions (Figure 1.1).



Figure .1.1 View of a short-rotation high density poplar plantation in Spain.

1.2. POPLAR SHORT ROTATION COPPICE (SRC) SYSTEMS FOR BIOMASS PRODUCTION

In general, the cultivation of fast-growing tree species, such as those belonging to the *Salicaceae* family, and in particular the *Populus* genus, involves species and hybrids of importance for wood production in many parts of the world (Bradshaw et al., 2000) including those grown under Mediterranean conditions (Pecchioni et al., 2020; Sixto et al., 2015). The genus *Populus* has many traits (abundant supply of improved genetic material largely as a result of their ease of hybridization, fast growth rates, facility for vegetative multiplication) that make it suitable for the production of biomass under SRC systems (Dickmann et al., 2002).

These plantations are managed as coppices, with cutting cycles of between 3 and 5 years until the productivity of the stump declines. This normally occurs between 9 and 14 years of age (Aylott et al., 2010), depending on the site quality and genotype (Dillen et al., 2013; Vanbeveren and Ceulemans, 2018). Poplar SRC systems are planted using hardwood cuttings and are able to regrow after harvesting by sprouting from stumps (Figure 1.2).

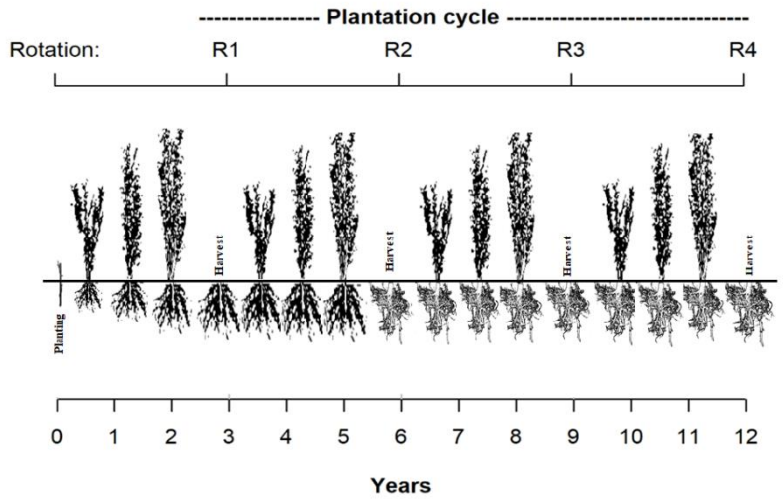


Figure 1.2. Scheme of standard poplar short rotation coppice (SRC) systems with a 12-year plantation cycle, comprising 4 rotations of 3 years each. R: Rotation.

These plantations achieve high productivity in a short period of time (Meyer et al., 2021), storing a large amount of C in the different biomass fractions (Berhongaray et al., 2017; Oliveira et al., 2018). Under Mediterranean conditions in particular, these SRC plantations are notably productive, (Oliveira et al., 2020b). Despite these advantages, the pressure of climate change makes it increasingly important to take water scarcity into consideration. In fact, productivity may be seriously limited by water deficit during

the growing seasons (González-González et al., 2017), making irrigation a necessary requirement for ensuring the survival of poplar plantations, especially in Mediterranean regions (Padrón and Orensanz García, 1987). However, as climate change progresses, water limitation and the need for irrigation is also becoming a concern in climatic zones which are currently not water limited (Coyle and Coleman, 2005; L. Dimitriou et al., 2009; Schweier and Becker, 2013; Yan et al., 2016). In the context of climate change and potential irrigation restrictions, it is crucial to evaluate the impact of water restrictions on the productivity of this land-use system. This study considers the response of these plantations to water scarcity.

1.3. JUSTIFICATION FOR THE THESIS WITHIN THE GENERAL CONTEXT

This thesis is based on a context in which the woody biomass obtained from plantations acquires special importance as a key raw material for the development of the bioeconomy as we move away from our traditional reliance on fossil fuels. Hence, there is also an eminent need for precise, climate-sensitive predictive tools to assess sustainable woody biomass estimates and enhance the sustainable production of lignocellulosic biomass in the face of climate change. Furthermore, this thesis aims to provide clarity on the feasibility, multifunctionality and potential contributions to the bioeconomy of SRC in Mediterranean regions.

1.4. OBJECTIVES

The overall objective of this thesis is to achieve the adaptation of a climate-sensitive biomass model for these particular plantation systems in response to water restrictions while at the same time raising awareness about the economic viability, benefits and the diverse range of advantages associated with ecosystem services offered by poplar SRC systems.

A defined line of progress, outlined in Figure 1.3, has been established. This line of progress is articulated through partial goals:

- A greater understanding of poplar growth under both optimal and limited water conditions by analysing the monthly patterns of biomass acquisition at foliar, root and stem level under Mediterranean conditions.
- Analysis focused on monthly changes in important leaf-level variables, such as leaf count and distribution, foliar biomass, individual and total leaf area index

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

(LAI), specific leaf area (SLA), leaf macronutrients (NPK and C), and foliar gas exchange parameters.

- Adapting 3-PG architecture to deciduous poplar SRC plantations under optimal and restrictive irrigation scenarios.
- Address the parameterization of the 3-PG process-model for short rotation *Populus* spp. cultivation under optimal and restrictive irrigation scenarios.
- Conducting an economic analysis of the agronomic chain for biomass production, incorporating sensitivity analysis to evaluate potential cost reductions.
- The quantification of C sequestration potential in these plantations, along with their economic evaluation for additional payments related to C sequestration.
- Addressing the existing economic and ecological uncertainties and increase awareness of the potential of poplar SRC systems to contribute to a low-carbon bioeconomy.
- Investigating alternative biomass uses in bioproducts to compare their climate mitigation potential, thereby expanding our understanding of the multifaceted benefits offered by poplar SRC systems.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

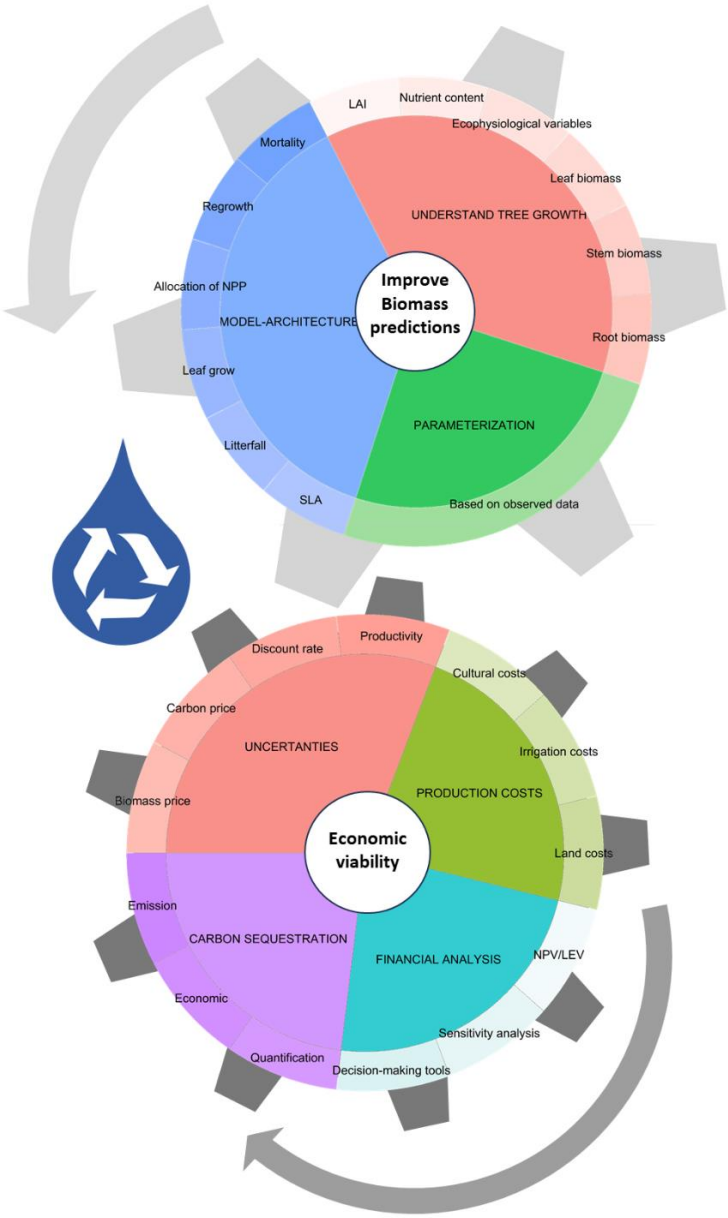


Figure 1.3. Schematic representation of the interconnection between the main objectives of the thesis. The first gear corresponds to objective 1 of the thesis (see 4.1 section) and is linked to the second main objective (see 4.2 section) by the productivity. The raindrop in the figure represents the optimal and restrictive irrigation scenarios studied, which are relevant to both the main objectives. LAI: Leaf Area Index; SLA: Specific Leaf Area; NPV: Net Present Value; LEV: Land Expectation Value.

1.4.1. Process-based models

In order to optimize the management of these systems, to maximise biomass production and meet the demands of the market as well as to develop more accurate predictive management tools, it is crucial to understand tree allometry and growth, as well as have a comprehensive understanding of the various factors that influence the cultivation process. These factors encompass genotype characteristics, site conditions (soil and

climate), and specific cultural practices. Abundant literature is available on each of these topics (Dimitriou et al., 2009; Gielen et al., 2001; Oliveira, 2012; Pellis et al., 2004).

In an ideal case, an improved understanding of the above-mentioned factors and relationships should be synthesized in tools that enable reliable yield predictions. In this regard, allometric studies of SRC plantations have been conducted to evaluate biomass production and C storage potential in fast-growing tree species. The aim of these studies, among others, is to develop predictive models for above-ground biomass production in SRC systems. The models based on tree allometry, which relate the tree diameter or another easily measurable variable to the biomass, are those most commonly used in forest productivity modelling, forest inventories or ecological studies of forest C and nutrient cycling or forest and greenhouse gas inventories, as well as in the validation of process-based models (PBMs) of forest productivity (Oliveira et al., 2020b; Pérez-Cruzado et al., 2011; Vande Walle et al., 2007; Zianis et al., 2005).

Over the last decade, progress has been made as regards empirical modelling to estimate biomass from poplar SRC plantations (Di Matteo et al., 2015; Oliveira, 2019; Pérez-Cruzado et al., 2014; Vanbeveren et al., 2018), as well as other aspects regarding tree architecture, spatial distribution of leaf morphology or leaf area index (LAI). The latter has been identified as an important determinant of biomass production in these plantations (Broeckx et al., 2012; Casella and Sinoquet, 2003; Tripathi et al., 2018).

Under a scenario of changing environmental conditions, an approach to estimating future forest growth and yield is to explicitly consider climate-sensitive forest growth models. In this context, PBMs are considered to be promising tools (Fontes et al., 2011; Nölte et al., 2020; Pretzsch et al., 2014). PBMs are employed in biology to simulate the complex interaction between plant growth mechanisms and the physical environment. These models are based on a theoretical understanding of ecological processes and offer a valuable framework to incorporate specific responses to changes in environmental conditions (Aylott, 2010; Cuddington et al., 2013). PBMs typically simulate biological processes on a daily time step, and in certain cases, hourly steps are used for specific processes, such as carbon assimilation in the Stand to Ecosystem CaRbon and EvapoTranspiration Simulator (SECRETS) (Sampson and Ceulemans, 1999). The choice of time step ultimately depends on the research objectives and the specific biological processes under investigation.

Several such models have already been developed and used to simulate biomass yield from herbaceous and woody crops such as switchgrass, miscanthus, sugarcane, willow or poplar (Surendran Nair et al., 2012). Among some of the PBMs, good predictions for poplar plantations have been achieved for example using SECRETS (Sampson and Ceulemans, 1999), ECOPHYS, developed for poplars in the juvenile phase (Host and Isebrands, 1994), ForestGrowth, adapted and parameterized for both SRC poplar and willow (Tallis et al., 2013) 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 (Amichev et al., 2010; Headlee et al., 2012; Sands and Landsberg, 2002). Although they have great potential, most PBMs are rarely employed as practical tools in forest management, because they are considered too complex. Despite this, PBMs hold significant importance in the field of climate change modelling (Aylott, 2010).

In this regard, the specific 3-PG model, with its monthly time step, offers a more aggregated perspective, focusing on capturing longer-term trends and patterns rather than day-to-day fluctuations (Landsberg and Waring, 1997). The 3-PG model has been constructed in close collaboration with intended end-users, hence has a simple, transparent structure and is therefore easy to use (Esprey et al., 2004). These characteristics increase the likelihood of its use in a management context (Landsberg and Sands, 2011) and make it a powerful tool that allows the user to set up different scenarios (Esprey et al., 2004). One challenge of the 3-PG model is that parameterization should be conducted at species scale.

The 3-PG model, which was originally developed for evergreen species (Landsberg and Waring, 1997), has been adapted for deciduous species. However, it still lacks complete adaptation for predicting the growth of poplar plantations in short rotation. The purpose of this study was to improve biomass predictions from a successfully applied PBM to simulate coppice growth of poplar plantations under Mediterranean conditions. To address this need, the 3-PG model was further adapted and parameterized specifically to accurately predict the growth of poplar plantations in short rotation.

The 3-PG model is based on the physiological processes of photosynthesis, respiration, and growth of trees and requires species-specific parameter values as well as site and climatic data as inputs (Sands and Landsberg, 2002a). See Figure 1.4 to better understand the processes, parameters and variables involved.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

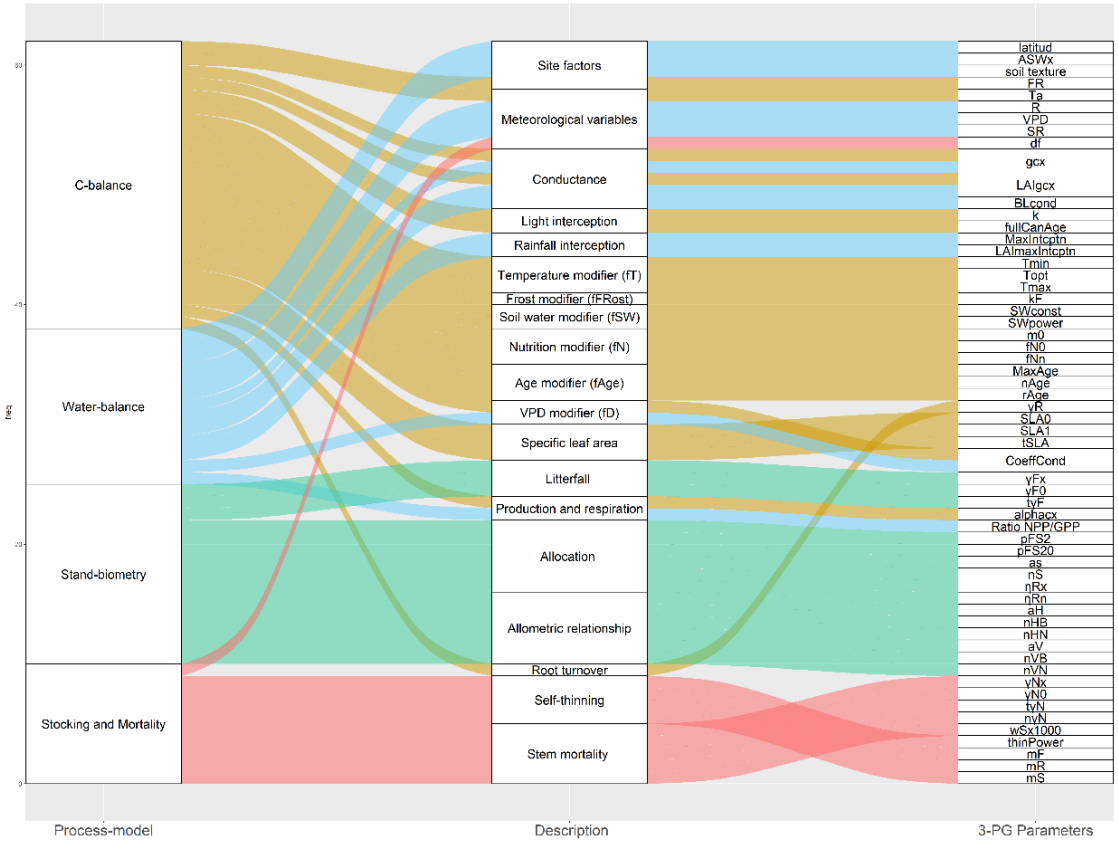


Figure 1.4. The flow diagram shows the process models that comprise the 3-PG model on the left, the description of the variables is shown in the center, and all the required species-specific 3-PG parameters are shown on the right. The description of the variables, the symbols and names used to abbreviate the parameters are based on the data from Sands (2001b).

Few adaptations of the 3-PG model have been developed to simulate growth for deciduous species since they have an annual growth cycle that requires special consideration, with aspects such as dormancy, bud burst, leaf growth in spring from previously accumulated carbohydrates (Forrester and Tang, 2016; Hart et al., 2015; Jégo et al., 2017; Nölte et al., 2020), and aspects related to leaf fall (Forrester and Tang, 2016; Jégo et al., 2017; Potithep and Yasuoka, 2011). Various studies have successfully applied the 3-PG model to assess the production of deciduous trees, including willow plantations (Amichev et al., 2011; Jégo et al., 2017), subtropical mixed-species stands (Forrester and Tang, 2016), deciduous broadleaf forests dominated by white birch (Potithep and Yasuoka, 2011) or sessile oak stands (Nölte et al., 2020). A few studies have also dealt specifically with poplar plantations, incorporating adaptations to the 3-PG model to simulate sprouting and regrowth. In these cases, the species-specific parameters necessary for running the 3-PG model are mostly derived from literature (Amichev et al., 2010; Hart, 2014; Hart et al., 2015; Headlee et al., 2012; Zalesny et al., 2012).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In addition, there are still several challenges associated with predicting SRC productivity accurately using the 3-PG model (Jégo et al., 2017), such us taking into account the allocation of Net Primary Productivity to different biomass components (leaf, stem, root), which changes over the course of the year, or simulate regrowth after harvesting by sprouting from stumps.

In summary, the present study aims to improve 3-PG estimation for poplar SRC systems, not only by determining the required species-specific parameters, mainly from observed data, but also by further adapting the 3-PG model architecture to these specific plantations. The effects of different irrigation regimes on the 3-PG model parameters were also considered to address the response of the poplar plantation to irrigation restriction in the context of climate change.

1.4.2. Economic potential and carbon stocks

From the perspective of promoting the establishment of plantations that contribute to a low-carbon bioeconomy, in addition to reliable biomass production estimates, economic analysis can also serve as a mechanism to bring scientists and decision-makers together with the aim of minimizing economic uncertainties. Plantation owners need to be able to evaluate the impact on the profitability of their investment and the associated C stock potential in order to make informed business decisions.

A comprehensive review by Lindegaard et.al, (2016) examines the impact of policy measures implemented in various EU countries aimed at the development of SRC plantations, using species such as willow (*Salix* spp.), poplar (*Populus* spp.), and eucalypts (*Eucalyptus* spp.). The study reveals a critical need to enhance awareness among farmers and policymakers regarding the multifunctional benefits offered by SRC systems. It identifies a lack of understanding among both farmers and policymakers regarding the diverse advantages associated with these plantations. To address this issue, thorough economic analyses based on well-documented research and experimental field trials should be undertaken and awareness raised about the range of additional benefits of SRC related to biodiversity and ecosystem services.

The ecosystem services associated with the plantations, in addition to the inherent environmental benefits, would provide promising extra revenues. Thus, payments for C sequestration represent a potential additional income when the plantation reaches the minimum required permanence time, and these payments will enhance the economic viability of poplar SRC plantations, possibly increasing their attractiveness to landowners and investors. However, the potential for climate change mitigation is not limited to the actual C sequestered in the plantation and used as a renewable bioenergy source. The conversion of lignocellulosic biomass into bioproducts provides a promising alternative

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

to fossil-based products, thus extending the C sequestration potential of these systems. The EU's Green Deal policies are likely to increase demand for biomass, either in the form of renewable bioenergy or bio-based products to replace fossil products (Herold et al., 2021). The use of C farming practices in agriculture and forestry can enhance C storage sustainably and create a new business model for farmers and foresters (Commission, 2022).

From this perspective, it is important to address critical cost factors associated with plantation management and establishment, as well as economic uncertainties associated with discount rates, biomass and C market prices. Additionally, ecological uncertainties related to possible future climate change, such as water restrictions must also be taken into account.

1.5. DATA BASE

1.5.1. Poplar Plot Network

The data used in this thesis was obtained from a comprehensive Poplar Plot Network (PPN) under SRC management. These plots are strategically distributed throughout the regions of the country with favourable conditions for cultivating such crops. The establishment of this network was initiated in February 2006 and was coordinated through various research and development projects supported by the National Plan for Agricultural Resources and Technology (RTAs), the public-private collaboration (INNPACTO: Decocel and other collaborations through agreements) or backed directly by the Administration (PSE-On Cultivos, Plan E: Lignocrop).

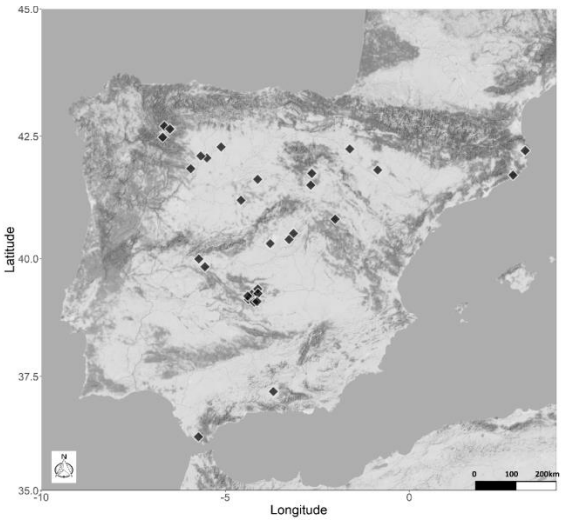


Figure 1.5. Site locations of the Poplar Plot Network (PPN).

The network comprises 350 plots (sampling units within the trials), 98 trials located in 30 different locations, with sizes ranging from less than 1 ha to 8 hectares. The trial densities vary from 5,000-33,333 cuttings ha^{-1}. Around one third (32%) were trials with an area greater than 4 ha (between 4 and 19 ha, specifically) established for both experimental and commercial purposes. All sites provide data for at least the first rotation, with data being available from some sites for the second and third rotations. The data from the trials include 48 genotypes belonging to different hybrid groups of the *Populus* genus (*P. x canadensis* Mönch; *P. x generosa* Henry; *P. deltoides* March. and *P.alba* L.), (Figure 1.5). The set of sites that make up the PPN are all within regions with Mediterranean climate conditions characterized by a marked summer drought. The average temperature (T) in the vegetative period (April-September) ranged from 15.9 to 22.5° C, the average annual T being 14.4° C for the set of plots. Precipitation during the vegetative period ranged from 120 to 308 mm, with a mean yearly value over the study period of 543 mm. Therefore, additional irrigation was required at all sites during the summers. A detailed description of most of the PPN can be found in Sixto et al. (Sixto et al., 2015, 2013).

The network has been monitored since 2006, so dasometric and production data is available and, in most cases, ecophysiological data. Additionally, there is a list of the cultural operations that have been carried out at many of the sites (fertilization schedule and doses, frequency of the cultural operations such as weeding, pest control and irrigation regimes in each rotation of the cycle).

1.5.2. SRC-Trial to obtain monthly parameters

A SRC plantation was specifically established to obtain monthly parameters using the 'AF2' genotype (*Populus* × *canadensis* Mönch) at a density of 10,000 trees ha^{-1} (2m x 0.5m) in central Spain. This genotype is widely planted for the production of chip biomass in the Mediterranean area (Pannacci et al., 2009; Sabatti et al., 2014) due to its high productivity and adaptability to Mediterranean conditions (Sixto et al., 2015). The study site (40° 27' 27'' N; 3° 45' 01'' W) is located at an elevation of 592 m a.s.l, with an annual mean temperature of 14.66°C. The soil has a sandy loam texture with a pH of 8.6 and 0.86% organic matter.

The trial was established manually using hardwood cuttings of 25 cm in length and two irrigation regimes were defined. The first one (T1) was irrigated to field capacity and served as optimum regime. The second (T2) was irrigated to 50% of the field capacity. Each regime (T1 and T2) consisted of five single rows with 295 trees, including inner and outer border rows to minimize border effects. The border effect within the sampling rows was also taken into account, establishing border trees between each sampling group (Figure 1.6). A drip irrigation system was used from May to October every year

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

during the entire rotation. Moisture in both plots was monitored using moisture sensors (SM200 Delta-T). Weed competition was avoided over all three years. Fertilization was not aplied.

Every month, on the 21st ± 3 days, during the 3 growing seasons of the rotation (from April to November), 3 trees (sampling group) per water regime (T1 and T2) were harvested, measured and destructively-sampled to obtain: number of leaves at stool and branch level per harvested tree, leaf area, leaf biomass W_l (kg tree^{-1}, stem biomass W_s (kg tree^{-1}) and root biomass W_r (kg tree^{-1}) per tree and water regime. In total, 138 out of 590 sampled trees were harvested at the end of the first rotation (no sample in April in the first year). All samples were dried in a forced air oven at 60°C to constant dry mass using a balance (EU-C 7500PQ) to an accuracy of 0.1 g. Additionally, monthly C content of all biomass fractions and leaf nutrient concentrations were analysed (LECO; mod CN-2000 and PerkinElmer; mod. Optima 5300 DV). Foliar gas exchange measurements were also recorded using a portable photosynthesis system (LCPro+ with Broad Head, ADC BioScientific Ltd., Hoddesdon, UK).

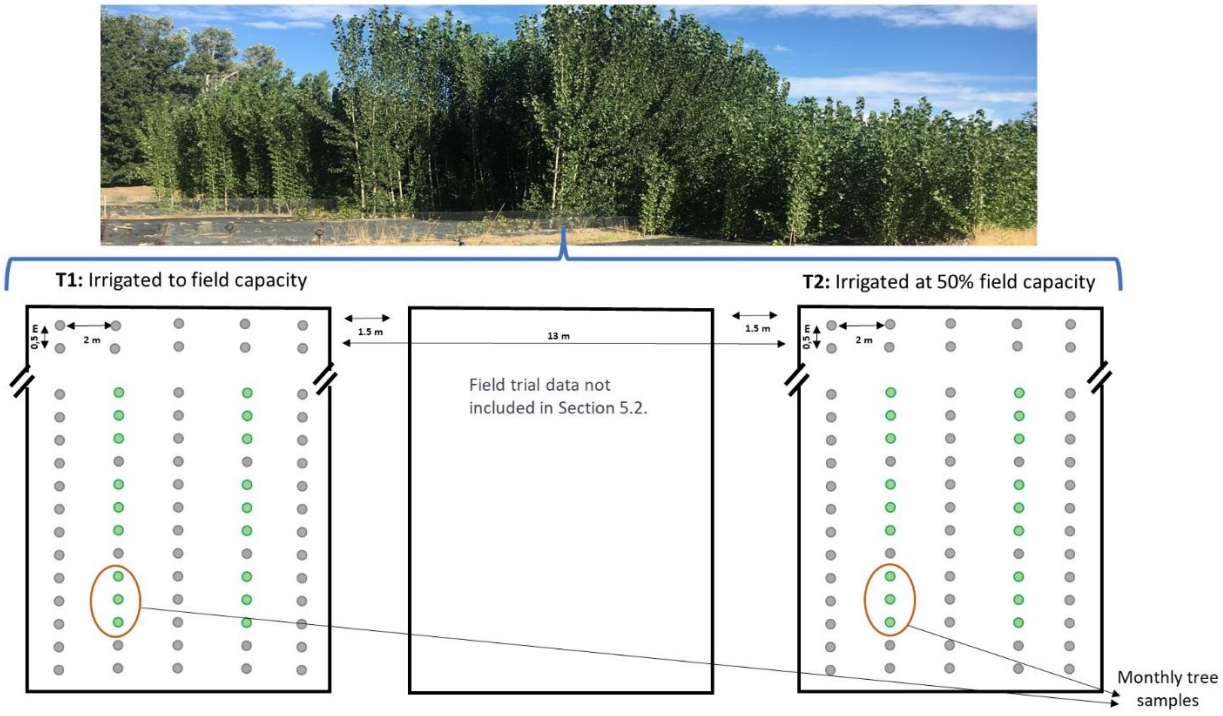


Figure 1.6. Overview of the SRC-trial representing the two irrigation regimes: T1 to field capacity (FC), ensuring optimal moisture conditions for the plants, and T2 in which irrigation is restricted to 50% of FC (T2).

For a more complete understanding of the database used in this thesis, extensive descriptions of the field measurements conducted and the variables employed can be found in the respective chapters.



Chapter 2

TIME-COURSE FOLIAR DYNAMICS OF POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS. RESPONSES TO DIFFERENT WATER SCENARIOS

This chapter under the consent of the publisher was redrafted after: Fuertes, A., Sixto, H., González, I., Pérez-Cruzado, C., Cañellas, I., Rodríguez-Soalleiro, R., Oliveira, N., 2022. Time-course foliar dynamics of poplar short rotation plantations under Mediterranean conditions. Responses to different water scenarios. Biomass and Bioenergy 159, 106391. https://doi.org/10.1016/j.biombioe.2022.106391. More information about this publication can be found in Preface.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 2: TIME-COURSE FOLIAR DYNAMICS OF POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS. RESPONSES TO DIFFERENT WATER SCENARIOS

2.1. INTRODUCTION

The transition to an advanced bio-based economy is a key element to ensure smart green growth in Europe (European Commission (EC), 2012). There is much expectation that biomass plantations will play a key role in the context of promoting the bioeconomy strategy. Commercial plantations of Poplar (*Populus* spp.) grown under Short Rotation Coppice (SRC) systems provide a source of raw material for bioenergy and/or bioproducts, promoting employment in rural areas as well as supplying environmental benefits (McEwan et al., 2020; Scarlat et al., 2015). Furthermore, these plantations make an important contribution towards reaching a low carbon bioeconomy (Oliveira et al., 2020b; Pawson et al., 2013).

Hybrid poplars under this management system are characterized by their high productivity over a short time period. Moreover, they are managed in a sustainable way (Dickmann et al., 2001) without competing with biomass resources from forests (Maletta and Díaz-Ambrona, 2020). However, productivity may be seriously limited by water deficit during the growing season (Cañete-Salinas et al., 2019). Irrigation is an indispensable operation not only to ensure their survival under Mediterranean conditions (Garavilla, 2004) but also to achieve high productivity in other areas of Europe (L. Dimitriou et al., 2009; Schweier and Becker, 2013; Vande Walle et al., 2007) and around the world (Coyle and Coleman, 2005; Yan et al., 2016).

In order to optimise the management of these systems to maximise biomass production and meet the demands of the market as well as to develop more accurate predictive management tools, it is crucial to understand tree allometry and growth. In recent years, considerable progress has been made in this regard (Oliveira et al., 2017a), especially in the development of specific predictive models for SRC plantations under Mediterranean conditions (Barrio-Anta et al., 2008; Oliveira et al., 2017b; Sánchez-González et al., 2017). However, more reliable predictive models based on ecophysiological processes could further contribute to our understanding of crop development and therefore help to promote this type of plantation. The precision of the model estimates would be improved by taking into account changes in allometry and physiology as a result of limited water availability, not only in Mediterranean environments but also in other areas where reduced water availability is likely in the foreseeable future. These enhanced models would also enable us to simulate different climate change scenarios under which limited water availability will increasingly become a reality. Hence, it is necessary to further our understanding of the behaviour of each fraction and the role

they play in the growth of the tree. The foliage fraction is an essential component in this regard, because it constitutes the primary interface between the trees and their atmospheric environment, therefore being key to the ecophysiological relationships (Landsberg and Sands, 2011).

Poplar foliage biomass and therefore the Leaf Area Index (LAI) is never static. It changes continuously, producing the full complement of leaves each season (Landsberg and Sands, 2011). These changes are even more pronounced in short rotation crops, where frequent cuttings occur, usually every 3 years (Tripathi et al., 2018b). There is a strong correlation between biomass production and LAI over time (Pellis et al., 2004a; Ridge et al., 1986), this correlation being very high (r^2 = 0.96) at least until LAI reaches values of 6 (Heilman and Xie Fu Guang, 1994). In this regard, Scarascia-Mugnozza et al. (1986) showed that the clonal ranking of biomass production and the LAI was highly coincident. The limitations on plant production caused by water stress can affect foliar traits at morphological, physiological and biochemical scales (Hennig et al., 2015; Hinckley et al., 1991; Liang et al., 2006). Monclus et al. (2009; 2005) studied 33 poplar genotypes under water deficit conditions and found significant reductions in foliar biomass as well as a decrease in maximal individual leaf area and SLA in response to drought.

Another parameter of special interest in the leaf fraction is the leaf nutrient content given the important role it plays in physiological processes such as photosynthesis, the plant-water relationship (Aerts and Chapin, 2000; Fernàndez-Martínez et al., 2017) and nutrient recirculation via leaf turnover. Identifying the concentrations of elements in plant tissues in terms of macro and micronutrients is highly important in order to optimize crop production and evaluate fertilizer requirements (Farago and Margaret, 2008). According to the literature the optimal range of NPK for *Populus* species is 17-30 g kg^{-1} for N, 1-4.4 g kg^{-1} for P and 7-20 g kg^{-1} for K (González et al., 2020). Inadequate supply of any nutrient will affect canopy photosynthesis and in turn the biomass production (Landsberg and Sands, 2011). Identifying nutrient dynamics is essential to understanding and predicting the effects of nutrition on tree growth (Landsberg and Sands, 2011). C and NPK stoichiometry provides a powerful indicator of diverse ecological and physiological processes, revealing evident responses to environmental condition such as water stress during growth (Tripathi et al., 2018a).

Gas exchange measurements can also provide important indications of water stress at leaf level. Stomatal conductance (g_s) for instance is used to characterize the plant water status because of its relationship with stomatal behavior and osmotic adjustments (Marron et al., 2002). The relationship between the photosynthesis rate and the transpiration or stomatal conductance provides an instantaneous estimate at leaf level of the water use efficiency (WUE) or the intrinsic water use efficiency (IWUE), respectively, more or less dependent on the environmental factors (Ehleringer, 1993).

Furthermore, at biochemical level, parameters such as soluble sugar content, proline levels, malondialdehyde (MDA) and in general the activity of antioxidant enzymes are affected by water restrictions (Popović et al., 2017).

Our research provides information on the monthly evolution of relevant variables at foliar level throughout the entire first rotation of a poplar short rotation plantation under different water scenarios. The aim of this study is to contribute towards more reliable predictions by process-based models in which specific parameterization of water deficit scenarios may be of interest. Monthly estimates could also be produced by considering specific leaf dynamics. A greater understanding of the behavior of these variables under conditions of limited water availability by analysing the monthly patterns may also be of particular interest, not only for modelling purposes, but also to identify the variables which most affect production, thus contributing to the development of improved breeding programs.

In summary, the aim of this research is to further our knowledge of foliar dynamics during the entire first rotation of a SRC plantation in which optimal irrigation was applied under a scenario of restricted water availability, focusing on:

i) analysing the monthly foliage biomass production and distribution
ii) comparing the monthly progression of Leaf Area Index (LAI) and Specific Leaf Area (SLA)
iii) evaluating monthly nutrients - C, N, P and K leaf content, the Nitrogen Use Efficiency (NUE), and the Photosynthetic Nitrogen Use Efficiency (PNUE)
iv) evaluating the most important ecophysiological variables - stomatal conductance (g_s), photosynthetic assimilation rate (A), transpiration rate (E), Water Use Efficiency (WUE), and the Intrinsic Water Use Efficiency (IWUE).

It is important to emphasize that this study isolates the effect of the genotype, which presents a pure signal that changes over the growing seasons. The poplar clone used in the experiment was 'AF2', selected specifically for biomass production (Sixto et al., 2014).

2.2. MATERIAL AND METHODS

2.2.1. Data source

Data for this work was collected from a poplar SRC plantation established in early spring 2018 for a rotation length of three years and a planting density of 10,000 trees ha^{-1} (spacing 2m x 0.5m). The study site was located in central Spain (40° 27' 27'' N; 3° 45' 01'' W) at an elevation of 592 m a.s.l. The annual mean temperature was 14.66°C, the

annual mean precipitation was 425.5 mm and the soil has a sandy loam texture with a pH of 8.59.

The genotype used was 'AF2' (*Populus* × *canadensis* Mönch), which is widely used for the production of chip biomass in the Mediterranean area (Pannacci et al., 2009; Sabatti et al., 2014; Sixto et al., 2014) and was specifically selected as a high biomass productivity clone for biomass production by the private forest nursery company Alasia Franco Vivai (Savigliano, Italy). The plantation was established manually using hardwood cuttings of 25 cm in length. Two different watering scenarios were applied (T1 and T2). The experimental plantation T1 was irrigated to field capacity (FC) and the adjoining plantation T2 consisted of half that dose (50% of FC). A drip irrigation system was used during the growing seasons (from May to October every year). Moisture in both trials was monitored using moisture sensors (SM200 Delta-T). A weed control fabric was spread over the whole area in order to avoid weed competition. Fertilization was not aplied.

A total of 590 trees were planted. Each scenario (T1 and T2) consisted of five single rows with a total of 295 trees per water scenario, including inner and outer border rows to minimize these effects. Every month, on the 21st ± 3 days, during the 3 growing seasons of the rotation cycle (from April to November), 3 trees (sampling group) per scenario were harvested and inventoried, being in summary 6 harvested trees per month considering both water scenarios (T1 and T2). The data set is collected from 138 measured trees out of 590 at the end of the first rotation (no sample in April in the first year). The border effect within the sampling rows was also taken into account, establishing border trees between each sampling group.

Given the notable intra-annual variability with regard to the entire foliar phenology, only the months with active tree growth (June-September) were considered for comparison of some variables. This period is defined as the mid-growing season. Hence, although all the months of the growing seasons are shown, henceforth the mean values for each year and scenario refer to the mid-growing season.

2.2.2. Foliage fraction measurements

To monitor monthly changes in the foliage fraction in plantations T1 and T2 for all the years of the rotation, all leaves were measured for all destructively sampled trees. We counted all the leaves, per water scenario, from the bottom to the top of all stools and separated them into two categories, branch leaves and stools leaves, obtaining the total amount of different leaves at stool and branch level per harvested tree. All collected leaves per category were then dried at 60°C in a forced air oven to constant dry mass and weighed using a balance (EU-C 7500PQ) with an accuracy of 0.1 g to calculate the total dry foliar biomass per tree W_f (kg tree^{-1}).

2.2.3. Leaf area estimation

Each month from May to November during the first growing season, all the leaves present per sampling group (three trees) and scenario (T1 and T2) were fresh scanned in order to determine the leaf area per tree.

As leaf area determination by scanning all leaves on a tree was expected to be far more complex in the second and third years due to tree size, the required sample size to achieve a target sampling error of 5% was estimated for the second and third year by using the data from the first year as a reference. The simple random sampling estimators (Gregoire and Valentine, 2007) were used to estimate sample size by considering the population variance observed in the first year as proxy of same parameter for the second and third years. A total of 2,390 leaves were fresh scanned during the first year to calculate their individual green leaf area, in cm^2, using the ImageJ software (Abràmoff et al., 2004). The leaves were then dried at 60°C in a forced air oven to constant dry mass to obtain their individual dry weight using a balance (EU-C 7500PQ) with an accuracy of 0.1 g. Different sample sizes of randomly collected leaves were compared in order to achieve this target. Finally, a subsample of 50 random leaves (ss_{50}) per tree was determined to be the minimum sample size, assuming a standard error of 4.33% in leaf area prediction.

2.2.4. Specific Leaf Area (SLA) and Leaf Area Index (LAI)

The total leaf area measured for the design-based sampling of 50 random leaves per tree linked to its dry mass is the Specific Leaf Area, SLA ($m^2\ kg^{-1}$), according to Eq.1.

$$SLA = \frac{Leaf\ area_{ss50}}{W_{fss50}}$$

Eq.1

where SLA is the Specific Leaf Area ($m^2\ kg^{-1}$), Leaf $area_{ss50}$ is the leaf area of the sub-sample of 50 leaves per tree ($m^2\ tree^{-1}$) and W_{fss50} is the dry leaf biomass of the sub-sample per tree ($kg\ tree^{-1}$).

The total LAI was defined as the leaf area per unit ground surface area, following Eq.2.

$$LAI = \frac{SLA \times W_f}{ground\ area}$$

Eq.2

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

where LAI is the Leaf Area Index (m^2 m^{-2}), SLA is the Specific Leaf Area (m^2 kg^{-1}), W_f is the total dry leaf biomass per tree (kg $tree^{-1}$) and the ground area (m).

The Maximum Leaf Area (LAI_{max}) was calculated with the highest monthly mean LAI value for each growing season.

The individual mean leaf area was calculated as the mean value of leaf area per leaf.

2.2.5. Leaf nutrient analysis

To evaluate monthly C, N, P and K leaf nutrient concentrations, a sub-sample was randomly selected for each scenario (T1 and T2) from the total leaves (branch and stool leaves) collected per harvested tree and month and dried at 60°C. The random leaf sample was ground to fine powder to analyse leaf nutrient concentrations.

C and N were determined through dry combustion analysis using an automated analyser *(LECO; mod CN-2000)* and P and K by emission spectroscopy using ICP-OES (Perkin Elmer, mod. Optima 5300 DV) after acid digestion of the sample in a closed microwave system (Ethos plus). The concentrations of the different elements were calculated on a dry mass basis and expressed as mg g^{-1} of dry mass.
The Nitrogen Use Efficiency (NUE), defined as the total biomass produced per unit of nutrient absorbed, equivalent to the nutrient concentration in the biomass produced (Gourley et al., 1994) along with the Photosynthetic Nitrogen Use Efficiency (PNUE) were calculated as the ratio of the maximum photosynthetic assimilation to foliar N content.

2.2.6. Foliar gas exchange measurements

In addition, every month throughout the growing season during the 3 years of the rotation, gas exchange measurements were recorded in both irrigation scenarios (T1 and T2) on two fully expanded mature leaves per tree (three per water scenario) from the top of the canopy between 9 and 11 a.m. A portable photosynthesis system (LCPro+ with Broad Head, ADC BioScientific Ltd., Hoddesdon, UK) was used with a light saturation of 1500 mol m^{-2} s^{-1} obtained using a LED lamp.

We performed stomatal conductance (g_s, mol m^{-2} s^{-1}), photosynthetic assimilation rate (A, µmol CO_2 m^{-2} s^{-1}) and instantaneous transpiration rate (E, mmol H_2O m^{-2} s^{-1}) measurements. Leaf gas exchange measurements were therefore used to calculate the Water Use Efficiency as the ratio between A and E (WUE, in µmol CO_2 mol^{-1} H_2O) and Intrinsic Water Use Efficiency as the ratio between A and g_s (IWUE, in µmol CO_2 mol^{-1} H_2O).

USC
DE SANTIAGO
DE COMPOSTELA

2.2.7. Statistical analysis

The effect of scenarios T1 and T2 on the different variables over the three growing seasons was analyzed using analysis of variance ANOVA (Generalized Linear Model procedure, GLM). Prior to the ANOVA, when normality was not fulfilled, data were transformed using the Box-Cox procedure. Non-parametric local polynomial regression (LOESS) with a smoothing parameter (a) of 0.75 and confidence intervals of 95% was used as a complementary analysis to GLM to analyse differences in the temporal pattern across years as well for variables with non-stable values across the studied period.

All the analyses were performed using the R program (R Core Team, 2019) and the level of significance was set to p-value < 0.05 for all the analyses. Means were tested using Tukey's test.

2.3. RESULTS AND DISCUSSION

2.3.1. Monthly foliage productivity, distribution and individual leaf area

Many of the traits of the leaves, including the crown architecture, are marked by strong genotypic control (Ceulemans et al., 1990; Nelson et al., 1981; Weber et al., 1985; Wilcox and Farmer, 1967). However, in the case of the genus *Populus* some morphological plasticities have been demonstrated in response to certain cultural management (Loomis RS, Williams WA, 1971; Nelson et al., 1981). According to Isebrands and Nelson (1982), most agronomic practices, including irrigation, have an impact on the number of leaves, leaf area and leaf display.

Regarding the number of leaves produced during the first year, a clear upward trend over the growing season can be seen in both scenarios, while in years 2 and 3, the number of leaves stabilizes from the second month after leaf emergence (May) as a result of bud flushing on the preformed branches (Figure 2.1). The total number of leaves increased 13.6 times from year 1 to the end of the rotation in the optimal scenario. That increase was, however, 10.5 times in the restricted scenario (Figure 2.1). The average values for number of leaves over the years of the study are in line with the values obtained by other authors (Broeckx et al., 2012) (Table 2.1). In years 2 and 3 a significant decrease in the number of leaves was observed in the restrictive scenario with respect to the optimal scenario, (p-value=0.023 and p-value=0.015 respectively). This reduction was clearly observed in terms of foliar biomass, even in year 1 when there was no reduction in the number of leaves (p-value=0.667), the W_f reduction between scenarios being 38%, 43% and 30% in years 1, 2 and 3, respectively (Figure 2.2). Significant differences were found between both scenarios as regards foliar biomass in

years 2 and 3 (*p*-value=0.005 and *p*-value=0.003), evaluated in the mid-growing season period, LOESS analyses confirming these differences to be significant with a *p*-value=0.05.

The spatial distribution of leaves within the tree varies over the growing years. In the establishment year, the leaves grew mostly at stool level in both water scenarios, in contrast to growth in subsequent years once the plantation was established. Furthermore, the leaves were mostly produced at branch level (93% of the leaves come from branches in year 2 and 96.5% in the year 3) (Figure 2.1). However, in the first year, the leaf distribution percentages differed between water scenarios. In the optimal scenario (T1) 92% of the leaves were stool leaves, while in the restrictive scenario (T2) that percentage was 82%. Although these differences were not significant (*p*-value= 0.07), it seems that the category of the leaves differed slightly in this first year. This may have been a consequence of greater branch production under conditions of water restriction (47% more branches under T2 than T1 in the first year). This increase in branch production, all of which were sileptic in this first year, may have contributed to the success of the establishment in the water restricted plantation. The importance of the sileptic branches in the success of implementation and biomass production has been referred to by Broeckx et al. (2012) among others. Smaller leaves as well as a greater number of branches in plantations grown under more severe xericity has previously been reported (Dunlap et al., 1995).

In years 2 and 3, the number of leaves at stool level decreased dramatically. The leaves mostly corresponded, in both scenarios, to branch leaves (without differentiating between sileptic and prolectic branches), the proportions being 95% and 98% in T1 for years 2 and 3 respectively and 95% and 97% in T2 for the same years. Broeckx et al (2012) reported similarly very small percentages of stool leaves in a 2-year plantation in northern Europe. Under the restrictive water scenario no changes in the spatial distribution of the leaves between stool and branch-level were found beyond the establishment year. Furthermore, it must be borne in mind that individual leaf area is much smaller for branch leaves than for stool leaves (Al Afas et al., 2005; Broeckx et al., 2012; Pellis et al., 2004a). However, during years 2 and 3, the greater number of leaves at branch-level (more than 95% of the total) means that in general terms, their contribution to the total leaf area of the tree was much greater than that of the stool leaves. Broeckx et al. (2012) pointed out that despite stool leaves being less important, both in terms of the number of leaves and the contribution to foliar area, these leaves can be of significant physiological importance due to their high specific leaf area (Casella and Ceulemans, 2002), optimal leaf exposition and leaf properties such as lower leaf osmotic potentials to improve water extraction from drying soil (Niinemets et al., 2004; Peltoniemi et al., 2012) and seasonal longevity, since these are the last ones abscised (Scarascia-Mugnozza et al., 1999).

USC DE COMPOSTELA

If we focus on the individual mean leaf area in each of the scenarios over the years, significant differences are observed between years (*p*-value <0.0001), the individual leaf area in first year being 56% and 66% higher than the second and third years respectively, probably due to the predominance of leaves at shoot-level (Figure 2.3). Although the number of leaves during this first year was basically the same for both scenarios, a reduction in the individual leaf area was observed between the two scenarios, with significant differences being observed in year 2 (*p*-value = 0.007), although this was not the case for years 1 and 3 (*p*-value = 0.228 and *p*-value = 0.123 respectively). The individual leaf area in year 1 was notably lower in the restricted scenario due to the greater presence of branch leaves (104 cm^2 in the optimal scenario in comparison with 71 cm^2 in the restrictive scenario, Figure 2.2). Numerous studies have documented this reduction in leaf size and weight as a result of water stress (Kira, 1975; Pellis et al., 2004b). In years 2 and 3, the mean individual leaf area is considerably reduced due to the greater presence of branch leaves, which are associated with lower individual leaf area in comparison to leaves located at shoot-level (Figure 2.3). This same trend for different *Populus* clones was observed by Al Afas et al. (Al Afas et al., 2008), concluding that leaves in the upper canopy layer were larger and heavier, but differed significantly among clones, the mean individual leaf area ranging from 46.37 to 127.67 cm^2 for the first growing season.

Therefore, although no significant differences in yearly mean leaf area between the two scenarios were detected, these differences were present in the global computation, being visible not only in the change in the spatial distribution pattern of the leaves during the first year, but also the clear reduction in the number of leaves during years 2 and 3, as well as a reduction in their individual leaf area and weight in all the years of the study as a result of water stress. Many authors consider that water availability is one of the core factors affecting poplar foliage production (Anjum et al., 2011; Gao et al., 2017; Gaudillere, 1989; Taiz and Zeiger, 1991). Leaf modifications, such as smaller leaves, were considered adaptive responses under conditions of water stress. Similar observations have been reported by other authors, who point to Mediterranean genotypes of *Populus* developing smaller leaves as an adaptation to drought as well as reduction in leaf biomass production (Cocozza et al., 2010; Viger et al., 2016).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 2.1

Foliar biomass (kg tree $^{-1}$ yr^{-1}) and Number of leaves (leaves tree^{-1} yr^{-1}) during the first rotation: optimal (T1) and restrictive (T2) water scenarios.

		Growing season			Mean values for the whole rotation (mid-growing season)
	Scenario	1st	2nd	3rd	
W_f (kg tree $^{-1}$ yr^{-1})	T1	0.11 ± 0.10 c	0.60 ± 0.26 b*	0.83 ± 0.21 a*	0.49 ± 0.4 *
	T2	0.07 ± 0.06 c	0.35 ± 0.14 b**	0.58 ± 0.13 a**	0.31 ± 0.2**
n_l (leaves tree^{-1} yr^{-1})	T1	98.75 ± 65.68 c	1385.33 ± 404.38 b *	2518.50 ± 901.43 a*	1264.5 ± 1085.3
	T2	91.42 ± 59.09 c	1017.00 ± 327.45 b**	1796.78 ± 537.45 a**	893.39 ± 766.1

W_f: Foliar biomass in oven-dry matter; n_l: Number of leaves; T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC.

Different number of * show significant differences between water scenarios for the same year.

Different letters indicate significant differences between years in the rotation for the same water scenario according to Tukey's test (p-value < 0.05).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

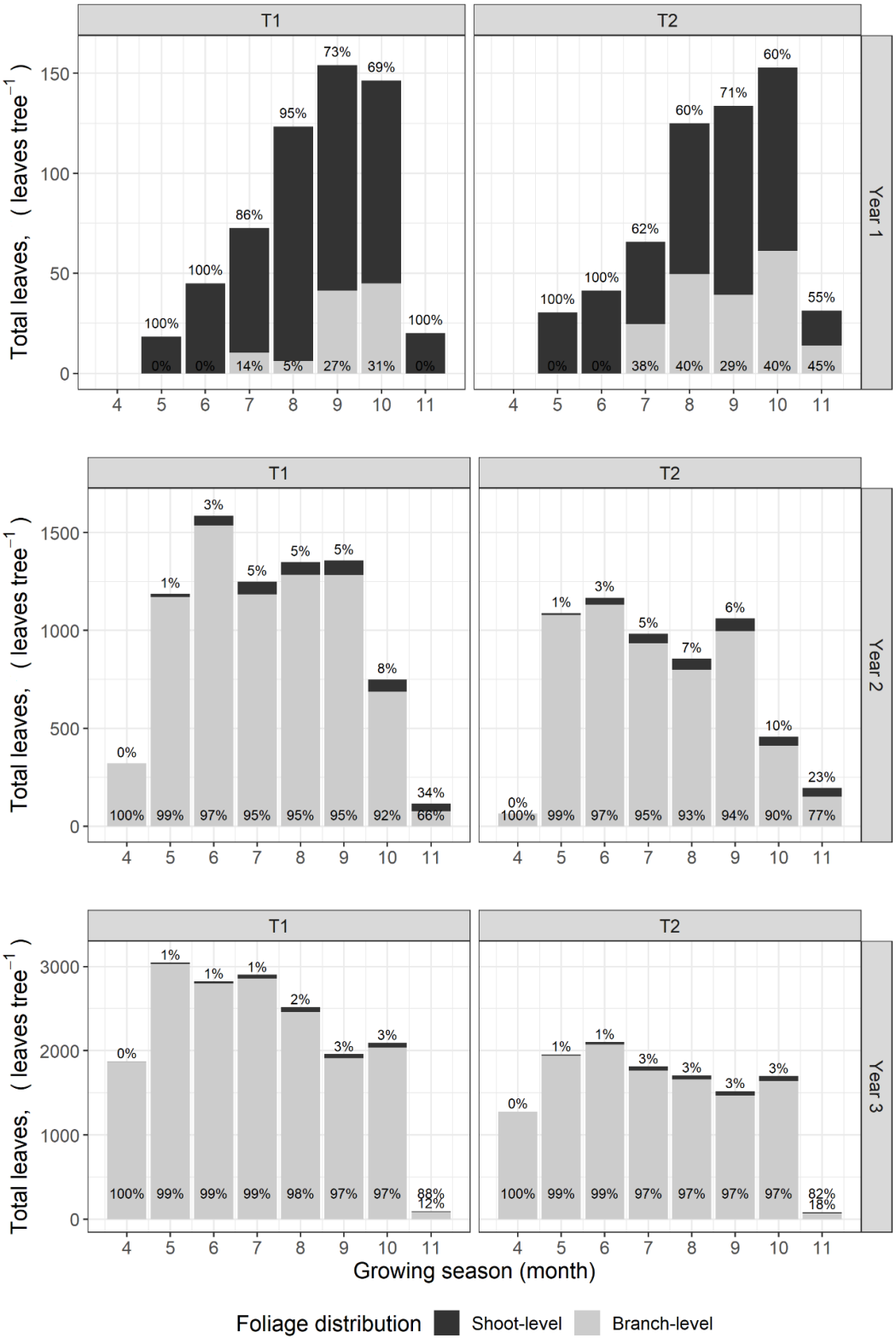


Figure 2.1. Monthly leaf distribution and productivity during the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively.

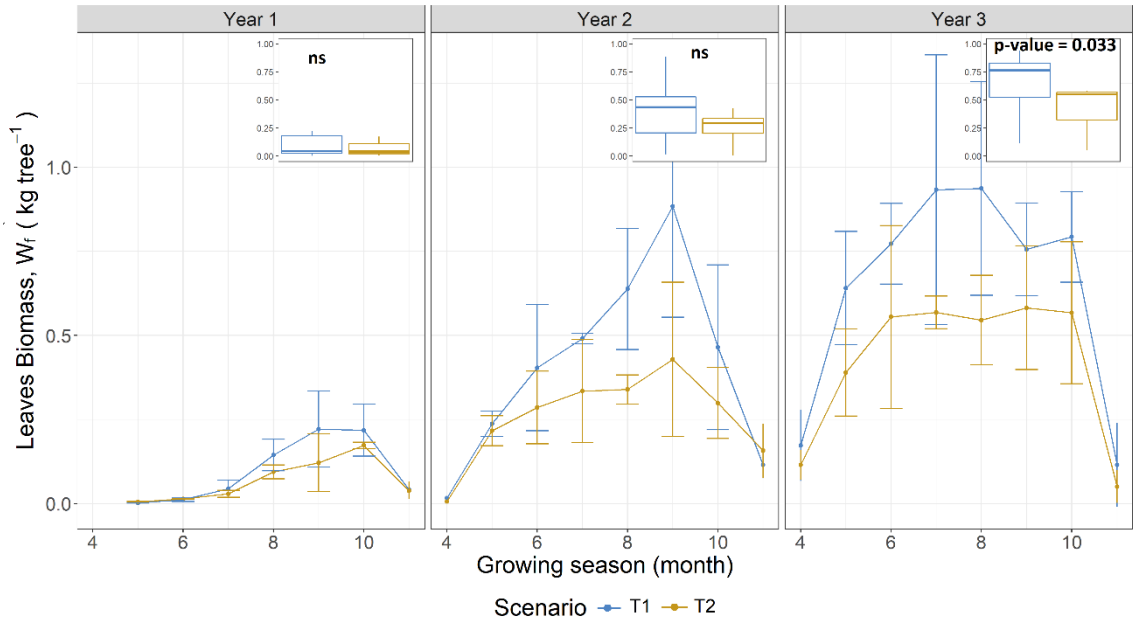


Figure 2.2. Monthly dynamics of W_f during the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively. Inset boxplot for the whole growing season, denoting no significant differences as ns.

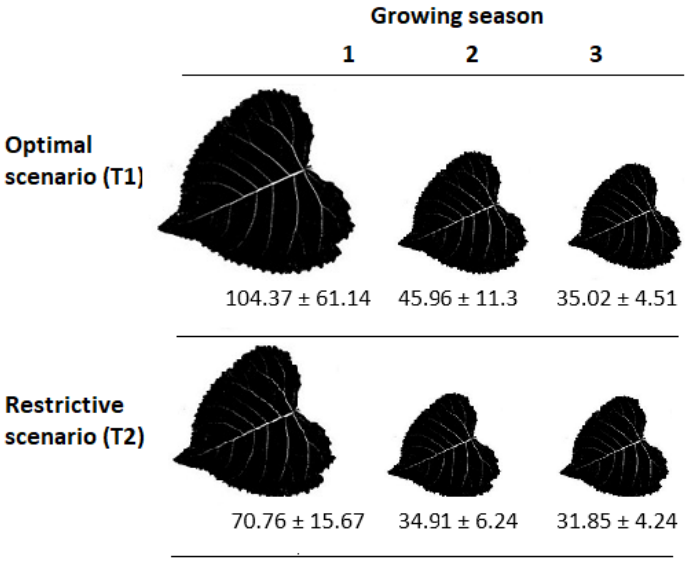


Figure 2.3. Evolution of individual leaf area (cm^2 ± sd) yearly average during the mid-growing season in the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively. The leaf sizes in the figure are to scale.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

2.3.2. Monthly LAI and SLA analysis

Since differences in the amount and the distribution of the leaf area as well as in the branching patterns have been addressed above, it is also evident that considerable differences in LAI can be found not only over the years, but also between the different water scenarios analyzed in this study.

In the establishment year, the LAI value increased gradually, reaching a maximum (2.39) in late September (Figure 2.4). This value is lower than that reported by Tripathi et al. (2016) in a Central European plantation (3.6), although it is within the range of the values reported by Al Afas et al. (2005) , from 2.1 to 5.8, for a variety of genotypes, and is above that reported by Broeckx et al. (2015) in a multiclonal plantation in Northern Europe (0.97).

In the restrictive scenario, the LAI pattern was similar to that of the optimal scenario. However, while the same progressive increase was seen over the months, in the restrictive scenario the maximum was reached at the end of October (2.04), one month later than in the case of the optimal scenario, where the maximum value was slightly lower (Figure 2.4). However, no significant differences were observed between the different months (*p*-value=0.152). The delay in reaching the maximum value under water constraint conditions in this first year is also observed both in the number and weight of leaves (Figure 2.1 and 2.2). This was probably due to the different branch patterns, which as mentioned above was 47% higher in this first year in the case of the restrictive scenario. According to Monclus et al. (2009) the LAI_{max} and the magnitude of leaf area reduction were tightly associated with productivity and drought tolerance, these being good indicators of the drought susceptibility of the genotype. This genetic effect along with others associated with the site and management conditions complicate comparison with other studies (Al Afas et al., 2005; Broeckx et al., 2015; Monclus et al., 2009). In our study, LAI_{max} values were always lower in the restrictive scenario, although more notable in the 2nd and 3rd growing seasons.

During year 2, the LAI increased rapidly in the first month of the growing season as a result of the flushing of preformed buds. From then on, it continued to increase to its peak at the end of September with values of 7.47. In the last year of the rotation the LAI increased sharply to a peak in the first month of growth, displaying a sustained trend from then until leaf fall. This is probably due to the closure of the canopy, given the high density of plantation. This has also been suggested by other authors, who observed similar trends after canopy closure explained by increasing self-shading and leaf shedding (Broeckx et al., 2015). In year 2, the LAI_{max} value in T1 was reached in late July at 9.34. There are several studies in which the evolution of the leaf area index over the years has been studied (Le Dantec et al., 2000; Tschaplinski and Blake, 1989; Vanbeveren et al., 2013). For example, a study conducted in a SRC plantation in Central Europe with

similar density reported LAI_{max} values of 3.6, 5.5 and 6.8 during three growing seasons (Tripathi et al., 2016), which are lower than those reported in our study for T1. However, another poplar experimental plantation in the USA with a similar density presented higher values during the three years of the rotation of two different poplar clones (2.9, 10, 11 and 1.5, 5.7, 11.6) (Ceulemans, 1990).

In the case of the restrictive scenario (T2), the LAI dynamic was similar, although with significantly lower values (*p*-value=0.0002 and *p*-value=0.0007 for the years 2 and 3 respectively, these differences being significant as confirmed by the LOESS analyses, with *p*-value=0.05). The reduction in irrigation (50% of FC) led to a decrease in LAI_{max} of 50.13% and 34.26%, respectively, for the 2nd and 3rd growing seasons. The LAI_{max} for the restrictive scenario was reached in late September in the 2nd year, as in the optimal scenario. In the 3rd year, the LAI_{max} value was reached earlier than in the optimal scenario, this maximum being in late June (6.14). These findings are in line with those of other studies pointing to the LAI_{max} being severely limited by reduced water availability and development of the canopy, which reduce growth and yield (Monclus et al., 2009; Tripathi et al., 2018b).

LAI is a key component of biochemical cycles in ecosystems (Bréda, 2003) and has an important influence on the exchange of energy, gas and water in trees (Johansson and Karačić, 2011). The LAI development response under water stress scenarios can be potentially used to better understand the evolution of these plantations under current climate change conditions where water availability may decrease, affecting biomass production. Some authors (Barigah et al., 1994; Ceulemans et al., 1990; Verlinden et al., 2013) have suggested that LAI rather than individual leaf area could be a more reliable indicator of biomass productivity, although both leaf characteristics have frequently been found to be positively correlated with biomass production (Marron et al., 2005; Monclus et al., 2009, 2005; Rae et al., 2004).

SLA, as well as LAI, is an important structural parameter of forest ecosystems (Johansson and Karačić, 2011) since it is positively related to net assimilation rate (Korner, 1991). Figure 2.4 shows a decreasing SLA trend over the years, the SLA values being slightly lower in the restrictive scenario although no significant differences were observed in any of the years of the rotation (*p*-value=0.805, *p*-value=0.57 and *p*-value=0.271 for years 1, 2 and 3 respectively, these differences being non-significant, as confirmed by the LOESS analyses with *p*-value=0.05). Higher initial SLA values (1st month) were observed in both scenarios in comparison to the rest of the months of the growing season (Figure 2.4). This could be due to the reported seasonal heterophilia of the genus (Eckenwalder, 1996). Preformed leaves have a different texture and shape to neoformed leaves, the former being harder so as to better withstand spring frosts. The greater SLA detected during the first month of each growing season was probably an

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

indicator that highlights greater foliar surface development in relation to volume (Stettler et al., 1996). The slight rise in SLA values at the end of the growing season for years 1 and 2 can be explained by the different sample trees considered for the analyses or as a result of a loss of leaf biomass due to nutrient retranslocation (Figure 2.4).

The average SLA value during the mid-growing season in the optimal scenario was 12.25 m^2 kg^{-1} in the establishment year, 10.82 m^2 kg^{-1} in the second year and 10.47 m^2 kg^{-1} in the third year. These values were lower than those reported by Al Afas et al. (2005) but in line with those reported by Verlinden et al. (2013), an overall decrease in SLA with stand aging being identified in both cases.

Although there were no significant differences, the restrictive scenario (T2) showed lower values than the optimal scenario (T1), which is common in plants under water stress (González-González et al., 2017; Marron et al., 2002; Monclus et al., 2009; Semerci et al., 2017), with an average value of 11.98 m^2 kg^{-1} in the establishment year, 10.49 m^2 kg^{-1} in the second year and 9.91 m^2 kg^{-1} in the last year of the rotation, presenting the same decreasing trend.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

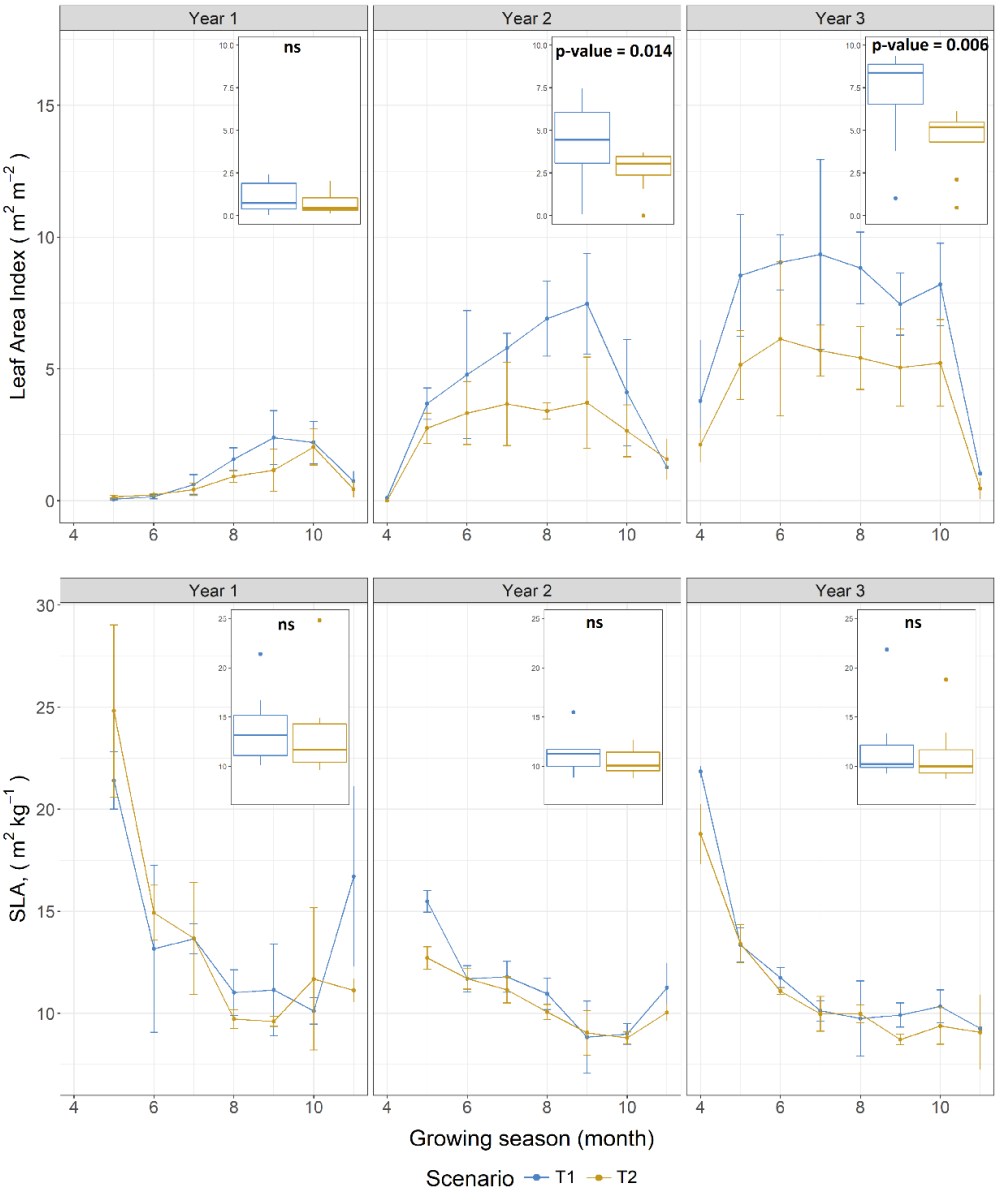


Figure 2.4. Monthly dynamics of LAI and SLA during the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively. Inset boxplot for the whole growing season, denoting no significant differences as ns.

2.3.3. Monthly dynamics of foliar nutrient concentrations: carbon, nitrogen, phosphorus and potassium

A decrease in nutrient concentration was observed between the initial and senescent leaves (Figure 2.5) of around 56% for N, 75% for P and 54% for K, with an average percentage for the three years. Therefore, foliar nutrient concentrations change dynamically with canopy growth, an expected, strong seasonal variation with decreasing trends being observed over the different growing seasons. The magnitude of these

variations leads us to rethink leaf nutrient characterisation protocols and the effect of leaf age on the variability observed in some species (Rodríguez-Soalleiro et al., 2018).

The lower foliar concentrations of N and P at the end of each growing season would indicate high efficiency in the reabsorption of those nutrients prior to leaf abscission. Nutrient mobility, however, may sometimes be masked by dilution effects due to increased carbohydrates in the leaf, resulting from very strong photosynthetic activity (Schlesinger, 1997).

However, this trend was not observed in K, perhaps due to lower requirements for this nutrient or less limitation in the ground, which would imply less need for retranslocation.

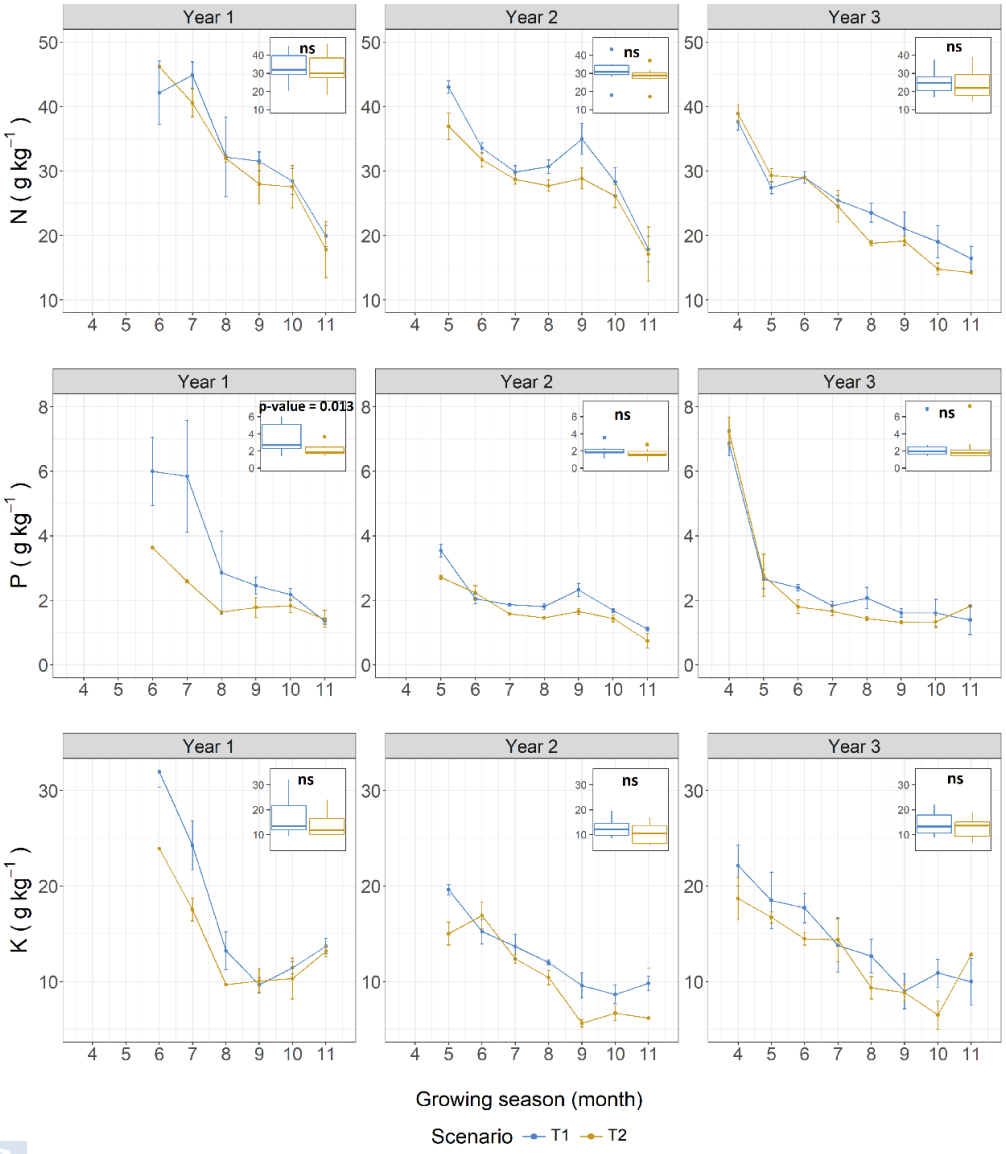


Figure 2.5. Monthly dynamics of N, P and K leaf concentration during the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively. Inset boxplot for the whole growing season, denoting no significant differences as ns.

The gradual decrease in NPK observed over the whole growing season has often been described as the translocation of these highly mobile nutrients from the more mature leaves to the woody above and belowground biomass of the tree (Chapin et al., 2002).

However, as in the case of this study, reabsorption can also occur from the first leaves during the growing season (Nambiar and Fife, 1991). This translocation is especially intense in highly productive deciduous species such as poplar (Pregitzer et al., 1990). The greater translocation observed for P could also suggest a greater limitation of this element as observed by Ozbucak et al. (2008) in *Corylus avellana*. L plantations. Our study area presents very poor initial values of assimilable P in the soil (9.35 mg kg^{-1}). Wu et al. (2020) identified an adequate P level as being between 10 and 40 mg kg^{-1}. The basic pH of the study area leading to the formation of calcium phosphate precipitates results in low P solubility, which may add to the increased translocation (Gueçaimburu et al., 2019).

Harvey and Van de Driessched (1999) also observed an important decrease in hybrid poplar NPK concentrations between mature leaves (August) and senescent leaves (November) of around of 60% for N, 12% in the case of P and 16% for K. In riparian ecosystems, González et al. (2010) also found gradual decreases in foliar concentrations of N and P in the *Populus* genus throughout the entire growing season.

Under the restrictive scenario (T2), a similar dynamic was observed, with a decrease of 59.5% for N, 69.5% for P and 45.1% for K. The retranslocation observed in P and K was therefore slightly lower. This could be due to the greater susceptibility of the species to drought conditions, which affects the restranslocation of nutrients (Fichot et al., 2015; Pugnaire and Chapin, 1992). This behaviour has been considered a mechanism to increase osmotic regulation (Harvey and van den Driessche, 1999), especially in the case of P and K given the important role of these nutrients in osmotic regulation, stomatal control and water use efficiency (Bergmann, 1992).

The foliar C concentrations, both in the optimal and restricted scenarios, showed a less marked decrease between the initial and final growing season, due to the low mobility of this element. The average percentage decline over the three years was slightly higher in the restricted water scenario (7.9%) compared to the optimal water scenario (6.0%).

In mature leaves (mid-growing season), a gradual and significant inter-annual decrease in the concentrations of N and P were observed for both water scenarios mostly as a result of the higher demand derived from tree growth. In the case of K concentration, however, a gradual decrease was not observed over the rotation period, a slight increase in K concentration being observed in the third year compared to the second year of the rotation (Table 2.2).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The high mean concentrations of nutrients during the mid-growing season, especially K, detected in the initial year of our study in mature leaves compared to the following two years of rotation, are due to the high concentrations obtained in June and July of the establishment year (Table 2.2). In that period, absorption from the soil and the retranslocation of nutrients from the root and stem to developing leaves occur, this retranslocation being especially notable in the case of K, since it is a very mobile element (Bergmann, 1992).

Table 2.2

Mean values ± sd of C, N, P and K concentration in mature leaves (mid-growing season) during the first rotation (3 years) in optimal (Field Capacity T1) and restrictive (T2) water scenarios.

		Growing season			Mean values for
	Scenario	1st	2nd	3rd	the whole rotation
C (%)	T1	44.08 ± 1.19	44.29 ± 1.12	44.07 ± 0.96	**44.15 ± 1.06**
	T2	44.66 ± 8.25	44.29 ± 1.32	44.32 ± 12.71	**44.41 ± 1.21**
N (g kg^{-1})	T1	37.69 ± 7.11a	32.27 ± 2.50a*	24.77 ± 3.32b	**31.57 ± 7.09**
	T2	34.77 ± 6.83a	29.26 ±1.84a**	22.87 ± 4.50b	**28.63 ± 6.65**
P (g kg^{-1})	T1	4.29± 2.00 a*	2.01 ±0.24 b*	1.97 ± 0.35 b*	**2.76 ± 1.59***
	T2	2.16 ± 0.68**	1.73 ±0.33**	1.55 ± 0.23**	**1.79 ± 0.49****
K (g kg^{-1})	T1	19.77 ± 9.38	12.63 ±2.39	13.29 ± 3.68	**15.23 ± 6.66***
	T2	13.58 ± 5.20	11.34 ±4.29	11.77 ± 3.03	**12.15 ± 4.18****

Different number of * show significant differences between water scenarios for the same year.

Different letters indicate significant differences between years in the rotation for the same water scenario according to Tukey's test (*p*-value < 0.05).

The foliar concentrations of C in mature leaves hardly varied over the whole rotation cycle for both water scenarios (Table 2.2). Similar results were obtained by Tripathi et al. (2018a) and Kanwal et al. (2019) under controlled greenhouse conditions. The accumulation of C in the leaf was a consequence of the photosynthetic balance and leaf respiration. Drought conditions lead to a decrease in gas exchange, which causes a decrease in the net gain of C and a reduction in growth, associated in turn with a lower C investment (Liu et al., 2017), so that C will remain in equilibrium regardless of water availability (Xu et al., 2020).

In the restrictive scenario (T2), throughout the years of the rotation, the mean concentrations of NPK in mature leaves (mid-growing season) were lower than those obtained in T1, these differences only being significant in the case of P, and of N in the intermediate year (Table 2.2). This decrease was more pronounced for P (28.3%) and K (17.7%) than for N (8.3%), probably due to the lower mobility of P and K under restricted water conditions (Sardans et al., 2008) and the lower root absorption due to reduced

USC DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

soil water availability, as suggested by Díaz and Roldan (2000) and Meng et al. (2016). This would also imply a reduction in soluble forms of P and K in the soil (Sardans and Peñuelas, 2005). Similar results between different water scenarios in poplar SRC plantations have been obtained by Tripathi et al. (2018a), who reported decreases in NPK foliar concentrations under drought conditions of around 8%, 21% and 17%, respectively.

Nitrogen Use Efficiency (NUE) showed a progressive and significant increase throughout the whole rotation in both water scenarios (Table 2.3). NUE tended to increase as nitrogen availability decreased (Karim and Hawkins, 1999; Li et al., 2012), as observed in this study, where soil N contents were low, and fertilization was not applied during the rotation.

NUE, however, decreased under water restriction, this decrease being especially notable in years 2 and 3 when the effect of stress was more evident. This decrease is in line with that previously reported by Liang et al. (2018). In all cases, the nitrogen use efficiency values were highly dependent on the site conditions and the genotype (Berthelot et al., 2000; Jug et al., 1999).

Table 2.3

Mean value ± sd of NUE and PNUE in the mid growing season during the first rotation (3 years) in optimal (Field Capacity T1) and restrictive (T2) water scenarios.

		Growing season			Mean values for
	Scenario	1st	2nd	3rd	the whole rotation
NUE ($g\ g^{-1}$)	T1	73.90 ± 29.42c	139.60 ± 17.00b*	314.61 ± 75.10a*	**167.89 ± 109.32**
	T2	75.16 ± 27.20c	117.55 ± 19.86b**	240.08 ± 46.19a**	**139.45 ± 74.45**
PNUE ($\mu mol\ g^{-1}s^{-1}$)	T1	3.76 ± 1.53c	5.60 ± 1.24b	7.06 ± 1.77a	**5.38 ± 1.99**
	T2	3.16 ± 2.23	5.24 ± 1.25	5.65 ± 2.68	**4.69 ± 2.27**

Different number of * indicate significant differences between scenario in the same year and different letters indicate significant differences between years in the same scenario according to Tukey's test (p-value < 0.05).

The Photosynthetic Nitrogen Use Efficiency (PNUE) increases significantly in the optimal irrigation scenario throughout the rotation (Table 2.3), which would indicate a greater amount of N invested in the photosynthetic activity for the production of greater biomass (Poorter et al., 2019). In the restricted irrigation scenario, however, the increase was not significant, with the PNUE values being lower in the initial year compared to the 2nd and 3rd, in which similar mean values were found. This may indicate an optimization of foliar N invested in photosynthesis in the last year of the rotation when the water stress is more pronounced.

No significant differences in PNUE were found between the two water scenarios, although in the 3rd year of rotation the mean values were notably lower in the restrictive irrigation scenario compared to the optimal scenario. Under drought conditions, NUE and WUE were closely linked to stomatal closure, which will lead to an increase in IWUE and a decrease in PNUE (Chaves, 1991; Fernández-De-Uña et al., 2017). In the restrictive irrigation scenario, IWUE was significantly higher than in the optimal scenario (Table 2.4), which should therefore mean lower PNUE values. However, this only occurred in the last year of the rotation, indicating that in the first two years of water restriction, higher IWUE would not entail a cost at photosynthetic level as a consequence of a greater mobilization of N to the photosynthetic apparatus, this being characteristic of deciduous species with short leaf life (Takashima et al., 2004). According to our results, high PNUE values could therefore be associated with a greater tolerance to situations of water deficit, indicating that N use efficiency could mean an important functional advantage under restrictive conditions, as previously reported by (Sánchez-Gómez et al., 2013).

2.3.4. Monthly dynamic responses of leaf gas exchanges

The photosynthetic rate (A) recorded throughout the growing season under optimal irrigation was highly variable (Figure 2.6). This might be expected when dealing with instantaneous measurements over a long period of time with environmental fluctuations in temperature, irradiance or humidity (Kaiser et al., 2015). In any case, instantaneous measurements of photosynthesis should be seen as general trends, otherwise they can be misleading (Blake and Tschaplinski, 1992). Values higher than 15 µ mol m^{-2} s^{-1} were recorded in most months with peaks of 22 µ mol m^{-2} s^{-1}, which is comparable to rates previously reported for this genotype in similar environments (González-González et al., 2017). Among woody plants, poplar trees are known to show high photosynthetic capacity although they also exhibit high genotypic variation within the genus (Ceulemans and Isebrands, 1996). The A values range, for example, from 5-10 µ mol m^{-2} s^{-1} reported by Luukkanen and Kozlowski (1972) in *Populus nigra* L.to 20-22 µ mol m^{-2} s^{-1} in *Populus trichocarpa* Torr. & A.Gray ex. Hook. cited by Wiard (1987).

In the mid-growing season, when the maximum vegetative activity occurs, higher mean A values under optimal water conditions were detected in years 2 and 3 of the rotation (16.5 µ mol m^{-2} s^{-1}) in comparison to those observed in year 1 (11.1 µ mol m^{-2} s^{-1}). This is probably due to the temperature and humidity conditions recorded in year 1, which led to a greater deficit in CO_2 concentration (ci). The g_s values in this scenario dropped sharply in relation to the remaining months of the following years of the rotation (to around 0.36 mol m^{-2} s^{-1}), coinciding with the higher temperatures that characterize this climate during these months (35ºC maximum mean temperature and 76651 Kj m^2 global radiation at the plantation site). In fact, this stomatal conductance was similar to that

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

observed under Mediterranean conditions in the absence of irrigation (Di Matteo et al., 2015).

The monthly oscillations of A and g_s in the two water scenarios (T1 and T2) often ran in parallel, although the values were always lower in the restricted water scenario. Thus, mean g_s values were significantly lower in T2 during the three growing seasons (Figure 2.6) and especially in the mid-growing season, indicating that stomatal closure occurred. The A values also declined, although less notably. The greater decrease in g_s compared to that of A in the restricted water scenario points to the possibility of applying less water through strategies aimed at increasing efficiency. This possibility has previously been explored in poplar plantations including this genotype by Gonzalez-Gonzalez et al. (2017).

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

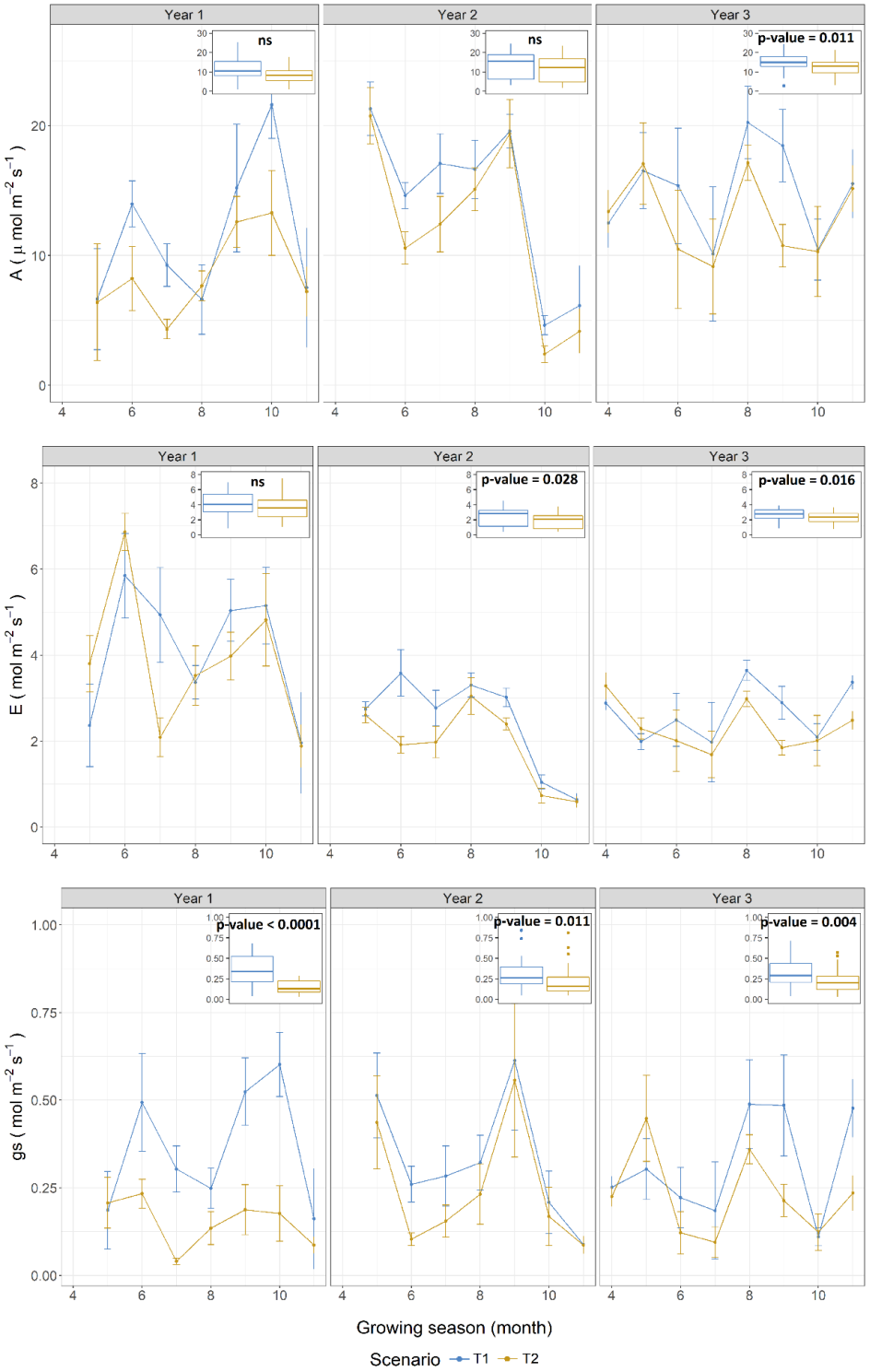


Figure 2.6. Monthly dynamics of A, E, g_s during the first rotation: optimal (Field Capacity (FC)) and restrictive (50% of FC) irrigation scenarios T1 and T2 respectively. Inset boxplot for the whole growing season, denoting no significant differences as ns.

In the months of maximum growth, intrinsic water use efficiency (IWUE) as well as transpiration efficiency (WUE) were significantly higher in years 2 and 3 of the rotation compared to the establishment year under both water scenarios (Table 2.4). These differences are attributable to significantly lower A in the initial year (*p*-value= 0.001 and

< 0.00001 in T1 and T2 respectively, these differences being significant as confirmed by the LOESS analyses at p=0.05) rather than to differences in stomatal conductance (p-value 0.5729 and 0.1566), which was similar in the three periods of each water scenario. Photosynthesis is a combination of diffusive and biochemical process and is limited by both stomatal as well as non-stomatal factors such as mesophyll conductance, carboxylation and photochemistry (Nadal et al., 2018). Furthermore, the density-driven change in photosynthetic photon flux and the changes in stomatal conductance can occur at different time scales, the former being much faster (Lawson and Ere Vialet-Chabrand, 2019).

Table 2.4

Mean value and standard deviation of intrinsic Water Use Efficiency (IWUE) and Water Use Efficiency (WUE) during the first rotation (3 years) in optimal (Field Capacity T1) and restrictive (T2) water scenarios.

		Mid-growing season		
	Scenario	**1st**	**2nd**	**3rd**
IWUE	T1	29.71 ± 9.87b*	54.59 ± 24.1a*	55.72 ± 20.05a*
(µmol CO_2 mol^{-1} H_2O)	T2	69.73 ± 30.96**	78.88 ± 25.65**	71.71 ± 24.44**
WUE	T1	2.08± 0.74 b	5.96± 1.03 a	5.47± 0.94 a
(µmol CO_2 mol^{-1} H_2O)	T2	2.31± 0.86 b	5.38± 1.13 a	5.77± 0.61 a

Different number of * show significant differences between water scenarios for the same year.

Different letters indicate significant differences between years of the rotation for the same water scenario according to Tukey's test (p-value < 0.05).

Under restrictive water conditions, IWUE was always significantly higher than under optimal irrigation in any of the years of the rotation (p-value <0.0001), denoting greater instantaneous gain of carbon in relation to water loss. The observed decreases in conductance were always far greater (about double the percentage) than those observed in the rate of A. In any case, the mean photosynthesis values under this restrictive scenario remained high in the maximum period of tree activity (11.1 µ mol m^{-2} s^{-1}). The values obtained in relation to IWUE were indicative of the capacity of the leaf to regulate photosynthesis and stomatal conductance and therefore the suitability of the genotype for adaptation to restrictive water conditions endured over time. This strategy to increase efficiency therefore avoids dehydration and could constitute long-term acclimatization, contributing to prioritizing carbon gain.

Even though the transpiration rate was significantly lower in the restrictive scenario (Figure 2.6), WUE values did not, however, show significant differences between water scenarios, revealing that for a given stomatal opening, the transpiration rate can be

highly variable, depending on the set of environmental factors such as humidity, temperature, radiation and wind speed (Medrano et al., 2007).

Based on these findings, the genotype 'AF2', identified as highly productive in different scenarios (González-González et al., 2017; Lazdiņa et al., 2014; Sabatti et al., 2014), showed tight stomatal control over water restriction, maintaining high photosynthetic levels, which is associated with some degree of isohydricity. The isohydric or anisohydric behavior of different poplar genotypes and therefore of different strategies to tackle water scarcity has previously been reported (Silim et al., 2009; Zhang et al., 2020). Regulation of water status may be critical in terms of survival or mortality under drought events (McDowell et al., 2008). In this regard, the survival rates under the restrictive water scenario were very high (100%) with no symptoms of defoliation, which highlights the ability of 'AF2' to survive in these environments, as previously reported in other studies conducted under Mediterranean conditions (González-González et al., 2017).

2.4. CONCLUSIONS

Detailed monthly foliar analyses under different water scenarios could help to better understand poplar plantations, contributing to improve biomass models, future breeding programs and promote these plantations under Mediterranean conditions where irrigation could be restricted in the context of climate change.

The findings of this study point to different behavioural patterns of variables in foliar dynamics of a poplar short rotation plantation under different water scenarios (an optimal scenario with irrigation to field capacity and a restrictive scenario with irrigation to 50% of the field capacity), as along with differing dynamics of the plantation over the three years of the rotation cycle.

The spatial distribution of leaves varies over the growth years studied, with most leaves appearing at stool level in the first year whereas in years 2 and 3 leaf production occurs at branch level. This behavior is explicitly reflected in the individual mean leaf area for the three years of the rotation cycle, this variable being clearly greater in the first year (104 cm^2) and then stabilizing in subsequent years at 35 cm^2.

Under conditions of water restriction, clone 'AF2' adopted a strategy of producing 47% more branches in the establishment year, displaying a different behavior in the distribution of leaves with a lower percentage of stool leaves. Water restriction led to a decrease in leaf biomass, even in year 1, where leaf production (number of leaves) was exactly the same in both scenarios.

The LAI dynamic observed is similar for the three years of the rotation cycle, the LAI_{max} being 2.39, 7.47 and 9.34, respectively. The LAI response under water stress scenarios can potentially be used to better understand these plantations, the results of our study

pointing to significantly lower values after the establishment year in the restrictive scenario, that is, a decrease in LAI_{max} of 50.13% and 34.26% in the restrictive scenario for the 2nd and 3rd growing seasons.

A downward trend in the SLA is observed throughout the years of the rotation, although no significant differences are detected between water scenarios despite the fact that the average is lower in the restrictive scenario. A decrease is observed for NPK foliar concentrations and PNUE values over the three years of the rotation, lower values being observed under water restriction. In contrast, IWUE values are significantly greater under water restriction, these being indicative of the suitability of the genotype for adaptation to longer term restrictive water conditions.

Gas exchange results, considered representative of what may occur at plant level, suggest that the selected genotype 'AF2' has tight stomatal control under conditions of water stress, maintaining high photosynthetic levels, which is associated with some degree of isohydricity. This genotype adopts strategies which mitigate losses in production under climate change scenarios. Hence, besides being of interest for breeding programs, this behavior makes it a good candidate for use in modeling behavior for biomass production in poplar short rotation plantations given its positive response under different water restriction scenarios.

The information provided corresponds to a specific clone 'AF2'. Further studies including other genotypes would be of interest to compare different clone responses.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA


IN VITRO

Chapter 3

ADAPTING 3-PG TO DECIDUOUS TREES IN RESPONSE TO WATER RESTRICTION: POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS

This chapter under the consent of the publisher was based on: Fuertes, A., Oliveira, N., Pérez-Cruzado, C., Cañellas, I., Sixto, H., & Rodríguez-Soalleiro, R. (2023). Adapting 3-PG foliar variables to deciduous trees in response to water restriction: poplar short rotation plantations under Mediterranean conditions. Forestry: An International Journal of Forest Research, 1–13. https://doi.org/10.1093/forestry/cpad022. More information about this publication can be found in Preface.

This chapter includes unpublished material.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 3: ADAPTING 3-PG TO DECIDUOUS TREES IN RESPONSE TO WATER RESTRICTION: POPLAR SHORT ROTATION PLANTATIONS UNDER MEDITERRANEAN CONDITIONS

3.1. INTRODUCTION

The Sustainable Development Goals (Baeyens and Goffin, 2015), the Paris Climate Agreement (Delbeke et al., 2019) and The Land Use and Forestry Regulation (European Commission, 2018) establish new requirements for European forests, underlining the need to mitigate climate change, commitment to deliver goods and services, create jobs, and provide sustainable fuels and materials (Freer-Smith et al., 2019). Additionally, they highlight the need to support foresters by increasing awareness of the benefits to the climate of wood products, which can store carbon sequestered from the atmosphere and provide substitutes for emission-intensive materials. These different elements form part of a sustainable bio-based economy which is key to ensuring smart, green growth in Europe (European Commission (EC), 2012). In this regard, biomass plantations are expected to be a key ingredient in advancing the bioeconomy strategy (Scarlat et al., 2015).

The genus *Populus* possesses traits (abundant supply of improved genetic material largely as a result of their ease of hybridization, fast growth rates, facility for vegetative multiplication) that make it suitable for the production of biomass under short rotation coppice (SRC) systems (Dickmann et al., 2002). Such SRC system can provide a source of raw material for bioenergy and/or bioproducts, promote employment in rural areas as well as supply environmental benefits (McEwan et al., 2020; Scarlat et al., 2015). Furthermore, these plantations make an important contribution towards achieving a low carbon bioeconomy (Oliveira et al., 2020; Pawson et al., 2013).

However, if the desired production and associated benefits are to be achieved, short rotation poplar cultivation requires a sound understanding of numerous factors influencing the cultivation. These include for example clonal characteristics, site conditions, change in climate, and specific cultural practices (Dimitriou et al., 2009; Gielen et al., 2001; Oliveira, 2012; Pellis et al., 2004).

In ideal case, an improved understanding of the above-mentioned factors and relationships should be summarized in tools that enable reliable yield predictions. Over the last decade, progress has been made as regards empirical modelling to estimate biomass from poplar SRC plantations (Di Matteo et al., 2015; Oliveira, 2019; Pérez-Cruzado et al., 2014; Vanbeveren et al., 2018), as well as other aspects regarding tree architecture, spatial distribution of leaf morphology or leaf area index (LAI). The latter is an important determinant of biomass production in these plantations (Broeckx et al., 2012; Casella and Sinoquet, 2003; Tripathi et al., 2018). Under a scenario of changing

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

environmental conditions, an approach to calculate future estimates of forest growth and yield is to explicitly consider climate-sensitive forest growth models. In this context, process-based models are regarded as promising tools (Fontes et al., 2011; Nölte et al., 2020; Pretzsch et al., 2014). In recent years, progress has been made in the development of these type of models specifically adapted for SRC poplar plantations. Notable examples include ForestGrowt (Tallis et al., 2013), SECRETS (Sampson and Ceulemans, 1999), and the 3-PG model, which will be the primary focus of this study.

The model 3-PG (Physiological Principles Predicting Growth), developed by Landsberg and Waring (1997), is a simple, process-based, stand-level model of forest growth (Sands and Landsberg, 2002a). The 3-PG model has been constructed in close collaboration with intended end-users, and has hence a simple, transparent structure and is therefore easy to use (Esprey et al., 2004). These characteristics increase the likelihood of its use in a management context (Landsberg and Sands, 2011) and makes it a powerful tool that allows the user to set up different scenarios (Esprey et al., 2004). One challenge of the 3-PG model is that parameterization should be conducted at species scale. 3-PG was originally developed for evergreen trees, with a monthly increment output at stand level (Landsberg and Waring, 1997). To date, few adaptations of the 3-PG model for deciduous trees have been developed, since it is necessary to consider processes specific to deciduous species that must inevitably occur, such as the fact that all the leaves must fall every year, or the monthly variations of the LAI throughout the growing season (rather than throughout the life of the plantation).

As part of estimating SRC willow productivity, Jégo et al. (2017) modified the 3-PG model to simulate annual leaf growth and fall, as well as to take litterfall into account as a function of the month, highlighting several challenges associated with predicting SRC willow productivity accurately. The challenges associated with adapting 3-PG to deciduous trees are summarized in Figure 3.1.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

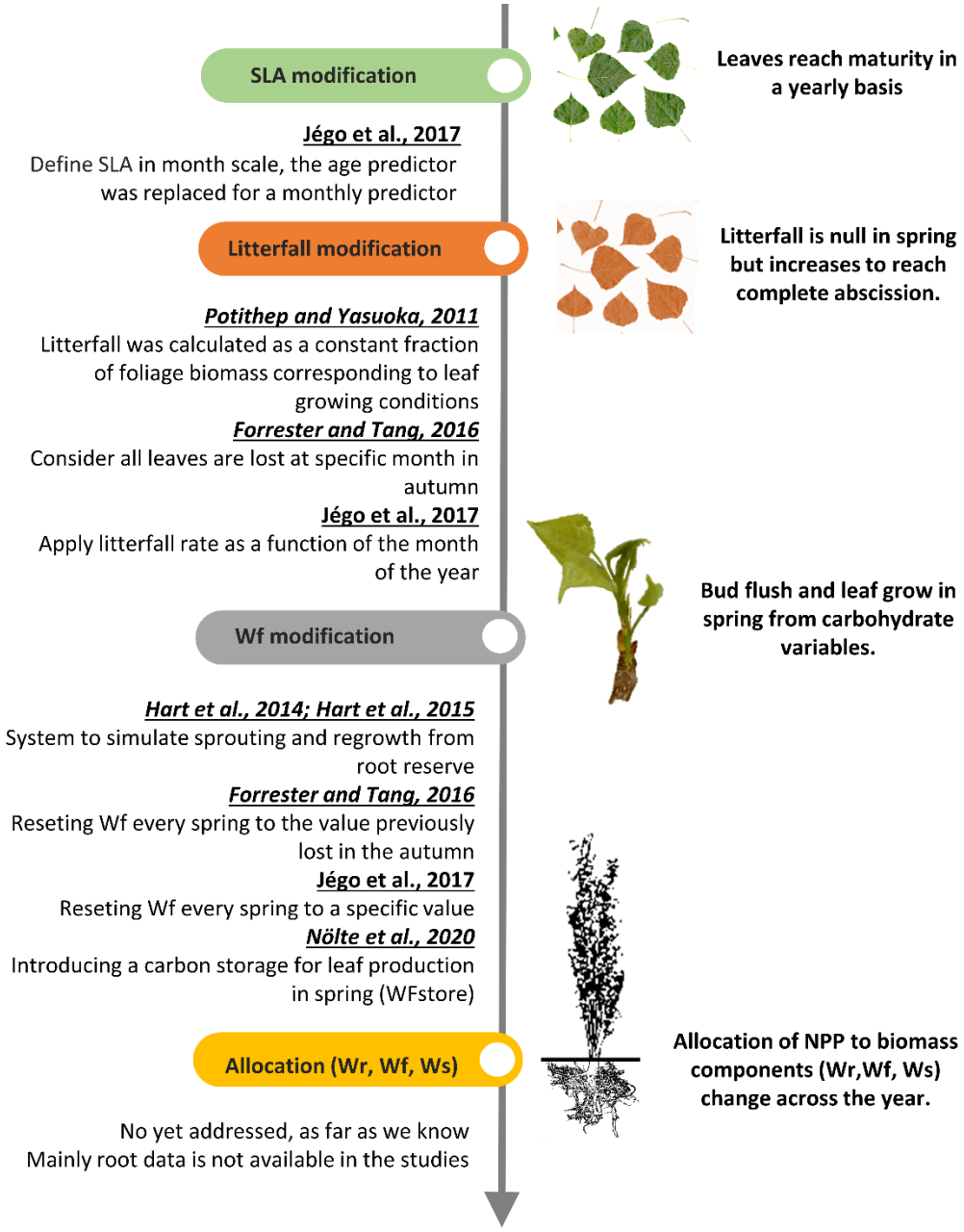


Figure 3.1. Description of the challenges associated with adapting 3-PG to deciduous trees and the solutions that have been proposed by different authors (Forrester and Tang, 2016; Hart et al., 2015; Jégo et al., 2017; Nölte et al., 2020; Potithep and Yasuoka, 2011). NPP: Net Primary Productivity; W_R: root biomass; W_F: leaf biomass and W_S: stem biomass.

In addition to the challenges described in Figure 3.1, it would be of particular interest for biomass prediction in the context of global warming to introduce a modification of the 3-PG model to improve leaf cycle processes by representing changes in leaf unfolding and leaf senescence dates in relation to monthly average temperatures (Nölte et al., 2020).

There are several studies in which 3-PG is applied to deciduous trees such as willow plantations (Amichev et al., 2011; Jégo et al., 2017), subtropical mixed-species stands (Forrester and Tang, 2016), deciduous broadleaf forests dominated by the Asian white birch (Potithep and Yasuoka, 2011) or sessile oak stands (Nölte et al., 2020). A few studies have also dealt specifically with poplar plantations (Amichev et al., 2010; Hart, 2014; Hart et al., 2015; Headlee et al., 2012; Zalesny et al., 2012). The species-specific parameters required to run the 3-PG model are often derived from literature and include the Specific Leaf Area (SLA) and LAI related parameters as well as the allocation parameters, which do not consider the effects of site condition on the response.

Some authors have conducted a detailed sensitivity analysis of the 3-PG model parameters to better understand them and identify those that need to be accurately determined (Esprey et al., 2004; Pérez-Cruzado et al., 2011). Parameters such as canopy quantum efficiency, maximum canopy conductance, LAI, litterfall or SLA of mature trees were identified as being highly sensitive, but information on their temporal variability is still scarce (Esprey et al., 2004; Nouvellon et al., 2010).

Detailed species-specific parameters based on observed data are key to obtaining the most accurate values for the mentioned variables and therefore achieving the full potential of the 3-PG model. In chapter 2, a detailed analysis was carried out of the monthly change of important leaf-level variables such as the number and distribution of leaves, foliar biomass, individual and total LAI, SLA, leaf macronutrients (NPK and C) and foliar gas exchange parameters. These variables are of particular interest in the 3-PG parametrization (Fuertes et al., 2022).

The present chapter aims on adapting 3-PG variables to deciduous poplar plantations over the course of the first rotation of three years of a poplar SRC plantation under two contrasting irrigation scenarios: optimal and restricted water availability. Furthermore, we propose parameters for poplar short rotation plantations, which also take into consideration their differing response under a water restriction scenario. More specifically, we i) model the change of SLA, ii) calculate the litterfall rate (γ_F), iii) determine the maximum canopy quantum efficiency (α_{Cx}) of poplar stands growing in a SRC plantation and, iv) we implement the observed monthly variation pattern in the NPP allocation parameters to the different biomass components (W_F, W_S, and W_R).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

3.2. 3.2. MATERIAL AND METHODS

3.2.1. Model description

The model 3-PG (Landsberg and Waring, 1997), is a simple, process-based, stand-level model of forest growth consisting of different sub-models: the assimilation of carbohydrates, the distribution of biomass among foliage, roots and stems, the determination of stem number, soil water balance, and conversion of biomass values into variables of interest to forest managers. It requires species-specific parameter values as well as site and climatic data as inputs (Sands and Landsberg, 2002a). An overview of all the process models that comprise the 3-PG model and all the required species-specific parameters and their interactions within the 3-PG models is provided (Figure 3.2). A detailed explanation of the sub-models is included below:

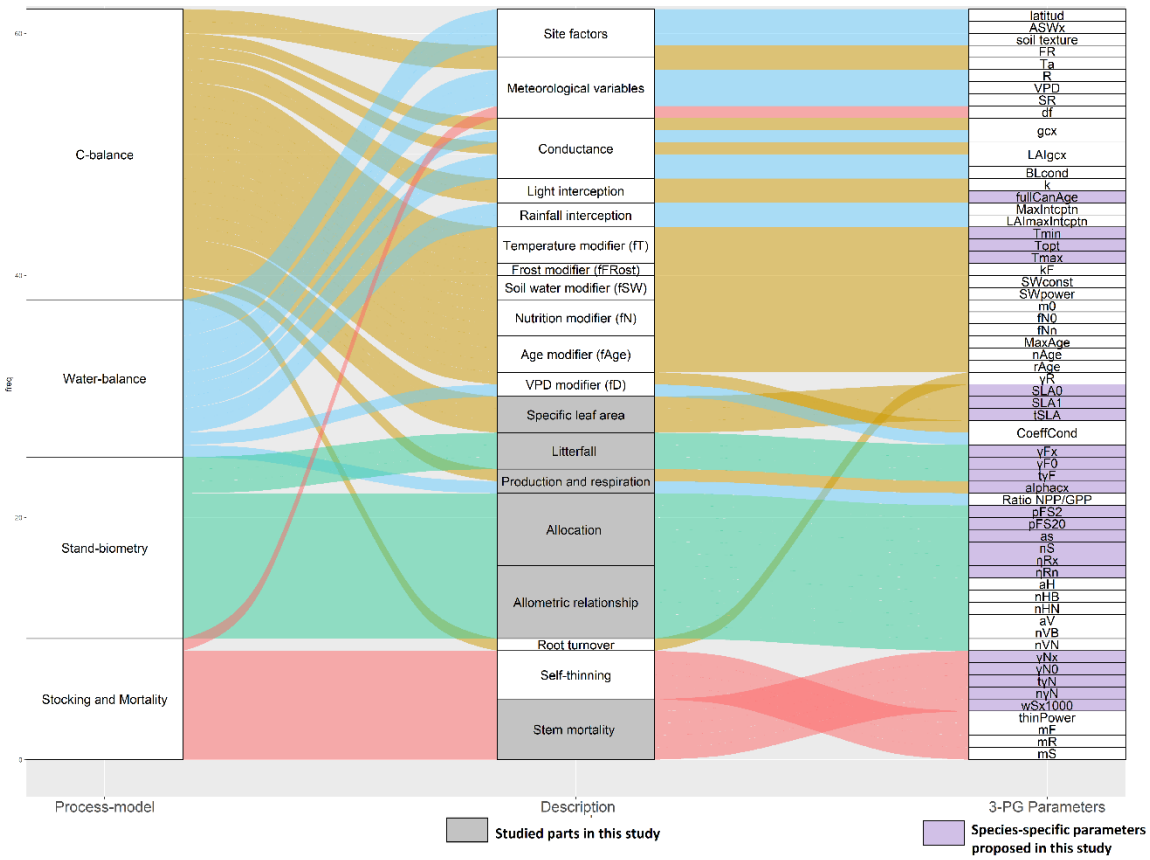


Figure 3.2. The flow diagram shows the process models that comprise the 3-PG model on the left, the description of the variables is shown in the center, and all the required species-specific 3-PG parameters are shown on the right. The description of the variables, the symbols and names used to abbreviate the parameters are based on the data from Sands (2001b).

Assimilation of carbohydrates

We have followed the approach of Forrester (2014) and considered the proportion of ground covered by canopy to estimate the intercepted radiation by Eq. (1):

$$Q_{int} = \left(1 - e^{\frac{-kL}{\zeta}}\right) \zeta \, \mathrm{SR} \qquad (1)$$

Eq. 1

Where Q_{int} is the radiation intercepted by the crown (MJ m^{-2} $month^{-1}$), k is the light extinction coefficient (species-specific parameter, %), L is the LAI (m^2 m^{-2}), ζ is the proportion of ground covered by canopy (%) and SR is the radiation (MJ m^{-2} $month^{-1}$, observed meteorological variable).

The LAI should be obtained along the plantation age (t, months) by multiplying the observed foliage biomass (W_F, t ha^{-1}) by the specific leaf area (σ or SLA, m^2 kg^{-1}, which for evergreen species varies along the plantation age). ζ is obtained before canopy closure as t (months) divided by the full canopy age (t_c, months), a parameter which takes into consideration the speed of canopy closure. ζ =1 if the plantation age is ≥ than the full canopy age.

A second important equation in the C-balance process of the 3-PG is the one used to estimate the Net Primary Production (NPP, t ha^{-1} $month^{-1}$):

$$NPP = 0.47 \; \alpha_c \; 2.3 \; 24 \; 10^{-2} \; Q_{int} \qquad (2)$$

Eq. 2

Where a constant factor of 0.47 (%) is used to consider respiration losses, α_c is the crown quantum photosynthetic efficiency (molC $molPAR^{-1}$), PAR is photosyntetically active radiation and Qint is the total radiation intercepted by the crown. Several unit conversion factors should be used in Eq. (2): 2.3 molPAR MJ^{-1}, 24 g dry matter $molC^{-1}$, 10,000 m^2 ha^{-1} and 1 t 10^{-6}g).

A set of growth modifiers are used in 3-PG to determine the rate of assimilation of carbohydrates (α_c) from the maximum value of the canopy quantum efficiency that could be expected (α_{cx}), which is a species-specific parameter:

$$\alpha_c = f_T \, f_F \, f_N \; min\{f_D, f_\theta\} \, f_{age} \, \alpha_{cx} \qquad (3)$$

Eq. 3

Where f_T, f_F, f_N, f_D, f_θ and f_{age} are the temperature, frost, nutrition, vapour pressure deficit, soil moisture and age modifiers, respectively (all of them as %). These six modifiers have to be modelled through equations that take into consideration site factors, observed monthly meteorological variables, parameters and biomass and water balance variables.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Model	Eq.	Site factors	Met variables
$f_T = \frac{T - T_{min}}{T_{opt} - T_{min}} \left(\frac{T_{max} - T}{T_{max} - T_{opt}} \right)^{\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}}$	(4)	-	T (mean monthly temperature)
$f_F = 1 - K_F \frac{d_F}{30}$	(5)	-	d_F, numer of frost days per month
$f_N = 1 - (1 - f_{N0})(1 - FR)^{f_{Nn}}$	(6)	FR, fertility rate	-
$f_D = e^{-k_d VPD}$	(7)		VPD (vapour pressure deficit)
$f_\theta = \frac{1}{\left[\frac{\left(1 - \theta / \theta_x\right)}{c_\theta} \right]^{n_\theta}}$	(8)	Soil texture (SW constant cθ and SW power nθ) and θ_x (maximum ASW)	-
$f_{age} = \frac{1}{1 + \left(\frac{t}{r_{age}\, t_{max}} \right)^{n_{age}}}$	(9)	-	-

The parameters associated to equations (4) to (9) are: T_{max} (maximum monthly temperature for growth), T_{min} (maximum monthly temperature for growth), T_{opt} (optimum monthly temperature for growth), K_F (number of days of production loss per frost day), f_{N0} (value of f_N when FR=0), f_{Nn} (shape of the response of f_N to FR), k_d (coefficient of conductance, which defines stomatal response to VPD), r_{age} (relative age at which f_{age}=0.5), n_{age} (power or shape response to relative age) and t_{max} (maximum age of the stand).

Eq. (8) considers a balance variable (θ), which is the available soil water (mm m^{-2}) that derives from the monthly water balance with the bounds of the maximum and minimum soil water values (ASW_x and ASW_{min}). These values are site-specific parameters.

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 are:

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

	Eq.
$\Delta W_F = \eta_F NPP - \gamma_F W_F$	(10)
$\Delta W_R = \eta_R NPP - \gamma_R W_R$	(11)
$\Delta W_S = \eta_S NPP$	(12)

Where ΔW_F, ΔW_R and ΔW_S are the monthly variation of foliar, root and stem biomass, respectively (t ha^{-1}), η_F, η_R and η_S are the allocation rates of NPP to leaves, roots and stem, respectively (%, note the sum should be equal to 1), γ_f is the leaf fall rate (%), γ_R the monthly root turnover (%) and W_F, W_R and W_S are the foliar, root and stem biomass, respectively (thus the three biomass balance variables).

The leaf fall ratio γ_F should also be modelled to predict the monthly rate of leaf biomass that is loss through litterfall. As the 3-PG was originally devised for evergreen species, γ_F was modelled along t using equation (12), without considering changes in litterfall rates along the growing season.

$$\gamma_F = \frac{\gamma_{Fx}\,\gamma_{F0}}{\gamma_{F0} + (\gamma_{Fx} - \gamma_{F0})\,e^{-kt}} \text{ with } k = \frac{1}{t_{\gamma F}} \ln\left(1 + \frac{\gamma_{Fx}}{\gamma_{F0}}\right) \quad (13)$$

Eq. 13

Where γ_{Fx} is the maximum litterfall rate for old stands, γ_{F0} is the litterfall rate at age 0 and $t_{\gamma f}$ is the age at which the litterfall rate is $\frac{1}{2}(\gamma_{Fx} + \gamma_{F0})$.

The specific leaf area is modelled in a similar way using plantation age (t) as the dependent variable and considering three parameters: the SLA at age 0 (σ_0), the SLA of mature leaves (σ_1) and the age at which the SLA has a intermediate value (t_σ).

The monthly root turnover in Eq (11) is considered a species-specific parameter.

The procedure to provide the monthly values of the allocation ratios of NPP (η_F, η_R and η_S) involves the initial calculation of η_R based on the growth conditions and bound by a maximum and a minimum rate:

$$\eta_R = \frac{\eta_{Rx}\,\eta_{Rn}}{\eta_{Rn} + (\eta_{Rx} - \eta_{Rn})}\, m\, \varphi \quad (14)$$

Eq. 14

Where η_{Rx} and η_{Rn} are the maximum and minimum allocation rate to roots, respectively, and m ϕ is representative of the growing conditions. m is calculated as $m=m_0+(1-m_0)$ FR, with m_0 as th value of m when FR = 0. ϕ is the Physmod and can be calculated as $\phi=f_{age}$ min (f_D, f_θ).

Once the value of η_R is obtained, the monthly calculation of η_F and η_S takes into consideration that the sum of three allocation rates should be 1 and the dependence of the foliage/stem partitioning (pFS) on the tree size (considered as the average stand breast height diameter, B). The classic procedure sets the values of pFS for two values of B (2 and 20 cm: pFS2 and pFS20, which are species-specific parameters). The pFS for any vale of B is then modelled through:

$$pFS = {}^{\eta_F}/_{\eta_S} = a_p B^{n_p} \quad (15)$$

Eq. 15

Where a_p and n_p are parameters depending directly from the pFS_2 and pFS_{20} values indicated above. The proposal of the last two parameters allow then the monthly calculation of η_F and η_S after the determination of η_R.

Water balance

The 3-PG performs a monthly balance among 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}). The balance determines the soil water availability (θ, mm), being the excess over maximum storage (ASWx) lost as runoff or drainage.

The interception is modelled through the equation:

$$I = I_{cx} \frac{LAI}{L_{IC}} R \text{ for LAI<}L_{IC}\text{, I=}I_{cx}\text{ R if LAI}\geq L_{IC} \quad (16)$$

Eq. 16

Being I_{cx} the maximum interception rate (also denoted MaxIntctn, %) and L_{Ic} the LAI providing the maximum interception (also denoted LAImaxIntctn, m^2 m^{-2}), both of them species-specific parameters.

The evapotranspiration is determined from the Penman-Monteith equation and thus driven by solar radiation (SR) and by LAI through canopy conductance.

$$\lambda_v E_T = \frac{\Delta\, SR + \rho_a c_p\, VPD\, g_b}{\Delta + \gamma\left(1 + {}^{g_b}/_{g_c}\right)} \quad (17)$$

Eq. 17

Being λ_v the volumetric latent heat of vaporization (constant, 2454000 J kg^{-1}), Δ(Pa K^{-1}) the slope of saturation water pressure versus T (Δ=47.117 $e^{0.0553T}$), ρ_a the density of dry air (1.204 kg m^{-3}), c_p the specific heat of dry air (1004 J kg^{-1} K^{-1}), γ the psycrometric

constant (66.1 Pa K^{-1}), g_b the canopy boundary layer conductance (m s^{-1}, species-specific parameter) and gc the canopy conductance (m s^{-1}).

The canopy conductance is affected by site and environmental factors through growth modifiers (ϕ) and depends on LAI up to a maximum g_{sx}:

$$g_c = g_{sx}\ \varphi\ LAI \text{ for LAI<}L_{gcx}\text{, } g_c=g_{sx}\ \phi \text{ if LAI}\geq L_{gcx} \quad (18)$$

Eq. 18

Thus, L_{gcx} is a species-specific parameter (LAI for maximum canopy conductance), along with gsx (maximum canopy conductance (m s^{-1}).

As E_T is obtained from Eq. (18) as mm s^{-1}, its transformation to a monthly based unit needs the calculation of the day length, for which the latitude of the site is required by 3-PG.

Stand biometry.

This sub-model deals with the basic allometric relationships needed to convert the biomass values into variables of interest to forest managers. A first model used is the one relating the average tree stem biomass (w_s) to the mean diameter (over bark, B).

$$w_s = {}^{W_S}/_{N} = a_s B^{n_s} \quad (19)$$

Eq. 19

Where N is the tree density (stem ha^{-1}) and a_s and b_s are species-specific parameters, the constant and the power in the stem mass versus diameter relationship.

The estimation of tree height can be obtained from a similar allometric relationship that considers two explanatory variables (B and N) and three parameters: the constant, the power of stocking and the power of tree density (a_H, n_{HB}, n_{HN}).

Two alternatives have been proposed to derive the values of timber volume (inside bark). The first one is a similar allometric relationship with three parameters associated (a_V, n_{VB}, n_{VN}). The second one models the evolution of the bark and branch fraction (p_{BB}) over plantation age, obtaining finally the stand volume (m^3 ha^{-1}) through:

$$V = (1 - p_{BB})\ {}^{W_S}/_{\rho} \quad (20)$$

Eq. 20

Being ρ the timber basic density (t m^{-3}), which could be considered a species-specific parameter or further modelled depending on plantation age.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Stocking and mortality

This submodel deals with the evolution of N with time and thus with self-thinning and stem mortality. The self-thinning line gives maximum single-tree stem mass (kg tree^{-1}) at current stocking through:

$$w_{Sx}(N) = w_{S0}\left(\frac{1000}{N}\right)^{\frac{3}{2}} \quad (21)$$

Eq. 21

Where w_{Sx0} is maximum stem mass at 1000 trees ha^{-1} (species-specific parameter). When $w_S > w_{Sx}(N)$, stocking is reduced. The Thinpower parameter is considered as 1.5 by default, but can be modified if an alternative value for the species is known.

The density independent mortality is modelled through the probability of death $\Delta N = -\gamma_N N$. At the same time, the mortality rate γ_N can be modelled with plantation age considering four parameters: mortality rate for large t (γ_{Nx}), mortality rate at age 0 (γ_{N0}), the age at which the mortality rate has median value ($t_{\gamma N}$) and the shape of mortality response ($n_{\gamma N}$).

Finally, the tree mortality can derive in reductions of biomass components using three parameters: the fraction of mean single-tree foliage, stem or root biomass lost per dead tree (m_F, m_S, m_R).

3.2.2. Data source, field measurements and model inputs

Data source

Parametrization and calibration data for this study was collected from a poplar SRC plantation (SRC-trial1) established in early spring 2018 for a rotation length of three years and a planting density of 10,000 trees ha^{-1} (spacing 2 m × 0.5 m). The study site was located in central Spain (40° 27' 27'' N; 3° 45' 01'' W) at an elevation of 592 m a.s.l. The annual mean temperature is 14.66°C, the annual mean precipitation is 425.5 mm. The soil has a sandy loam texture with a pH of 8.6 and 0.86% organic matter.

The genotype used was 'AF2' (*Populus* × *canadensis* Mönch), which is widely used for the production of chip biomass in the Mediterranean area (Pannacci et al., 2009; Sabatti et al., 2014). It was specifically selected as a high biomass productivity clone by the private forest nursery company Alasia Franco Vivai (Savigliano, Italy) and has shown both high adaptability and the highest biomass productivity across Spain according to results obtained from a Poplar Plot Network (PPN) under SRC management with irrigation (Sixto et al., 2015).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The outdoors plantation (SRC-trial1) was established manually using hardwood cuttings of 25 cm in length. Two neighbouring plots were defined. The first (T1) was irrigated to field capacity. The second, adjacent plot (T2), was irrigated to 50% of field capacity. Precipitation was taken into consideration when calculating irrigation doses. A total of 590 trees were planted. Each plot (T1 and T2) consisted of five single rows with a total of 295 trees per plot, including inner and outer border rows to minimize border effects.

A drip irrigation system was used from May to October every year over the whole rotation period. Moisture in both plots was monitored using moisture sensors (SM200 Delta-T). Weed competion was avoided over all three years. Fertilization was not aplied.

Validation data for this study was collected from an adjacent poplar SRC plantation (SRC-trial2) established a year earlier than SRC-trial1 for a rotation length of three years (2017-2019) and a planting density of 10,000 trees ha^{-1} (spacing 2m x 0.5m) planted with 20-30 cm long hardwood cuttings in 30 L pots filled with the same soil layer and buried in the ground to simulate, as far as possible, the management conditions of a real plantation. Pots were used in this trial to study root biomass in subsequent studies. The SRC-trial2 was irrigated to FC using drip irrigation system from May to October every year over the whole rotation period.

Field measurements

Every month, on the 21st ± 3 days, during the 3 growing seasons of the rotation, 3 trees per water regime were monthly harvested and destructively-sampled, to measure foliage biomass, W_f (kg $tree^{-1}$) and stem biomass, W_s (kg $tree^{-1}$) per tree and water regime from the poplar SRC plantation SRC-trial1.

The frequency of root sampling biomass, W_r (kg $tree^{-1}$) was reduced to every second month, during the three years of the rotation, accounting for the increasing complexity of the root extraction procedure. Roots were extracted using a backhoe excavator. The soil extracts containing the sampled roots were cleaned and broken root tips were measured to estimate the remaining root biomass in the soil. Some losses in the root extraction cannot be completely avoided, hence the allometric relationship between the broken tip diameter and the remaining root biomass in the soil developed by Oliveira et al. (2018) was used. Total root biomass (W_r in kg $tree^{-1}$) was determined from the sum extracted roots and from the remaining root biomass estimated from the broken tip diameter.

Each fraction obtained each month were dried in a forced air oven at 60°C to constant dry mass. Dry biomass was determined using a balance (EU-C 7500PQ) to an accuracy of 0.1 g.

As part of this study, additional data from the PPN was used to support all parameters estimated, including gas exchange measurements, thus giving a broader perspective of the response in the Mediterranean area. The inclusion of the data from the PPN, which comprises 350 plots in 98 trials located at 30 different sites, means that the results will be more representative of the overall response under Mediterranean conditions in comparison to using data from only one specific trial. A detailed description of the PPN can be found in Sixto et al. (2015, 2013).

Model inputs

The 3-PG model had to be run to validate the parameterization proposed, comparing the predictions based on the parameterization identified in this study with the observed values of LAI, stem, root and leaf biomass recorded at the validation site (SRC-trial2). Data for initializing the simulation, such as observed initial stem and foliage biomass was 1 and 2.5 g tree^{-1} respectively and observed initial root biomass was 13 g tree^{-1}. The observed pattern of variation of allocation parameters in SRC-trial1 for T1 was applied. We have considered the fertility rate (FR) as 1, since no nutrient limitation was observed restricting poplar growth and considered a value of 2 years for the Full Canopy Age parameter, following the procedure of Forrester et al. (2014). For the third year in the validation data, the value of FR was set as 0.7 because the trees were growing in pots, which clearly reduced the volume explored by the roots in relation to the SRC-trial1.

In addition, site-specific input data and meteorological data were needed. Air temperature minimum (Tmin, °C), maximum (Tmax, °C) and mean temperature (Tm, °C), as well as air humidity (Hr, %) were taken from an experimental weather station 500 m from the study site. Vapour pressure deficit (VPD, mbar) was obtained as the difference among the saturated and actual vapour pression (e_s-e_a). es was estimated from T_{min} and T_{max} using the Tetens equation, whereas e_a was estimated from the monthly averages of Hr and e_s. Data on solar radiation, precipitation, and frost days were obtained from the Spanish Meteorological Service (AEMET) database for a station located 2.1 km away. All meteorological data corresponded to the actual period along which the experiment was performed.

As site-specific data, the ASWx=220 and ASWmin=75 were calculated for the site using the procedure developed by Domingo et al. (2006) using information of soil texture, organic matter and horizon disposal. Initial ASW was considered to be the field capacity, as the stand was initialized in the spring. As the texture was classified as sandy-loam, the parameters c_θ and n_θ were set to 0.6 and 7, respectively. The latitude of the trial site is 40.5N.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

3.2.3. Adapting the 3-PG to a deciduous SRC.

The structure and equations used by the 3-PG model (section 3.2.1.), which correspond to version 2.7 of the 3PGpjs Microsoft Excel spreadsheet code (Sands, 2010) had to be adapted to the fact that the species covered in this study is in fact deciduous and is grown in short rotations to produce biomass.

These modifications i) take into account the monthly variation of the leaf area index (LAI) throughout the growing season (rather than throughout the life of the plantation, (see section 3.2.4), ii) simulate leaf fall every year, considering litterfall rate as a function of the month (see section 3.2.5) and, iii) simulate leaf growth every spring from 10 % of the root biomass ($\eta_r = 0.10\ ^{0}/_{1}$), this fraction of root carbohydrates reserves will generate W_F every spring ensuring that the model will generate a LAI value to start a new growing season (Regier et al., 2010).

These modifications will ensure that the LAI along the dormant season will be null, thus no NPP is produced nor can be reductions of growth derived from frost days. The frost modifier is kept to account for late frost that could affect the new leaves. The null LAI also means no E_T is considered during the dormant season. Even if direct soil evaporation losses could be considered in the water balance, we estimated the presence of an anti-weed mesh in the trials would reduce losses to a minimum level.

In addition, the observed monthly variation pattern in the NPP allocation parameters to the different biomass components (W_F, W_S, and W_R) over the first rotation (3 growing seasons) with optimum irrigation (T1) and 50% irrigation reduction (T2) were implemented. To achieve this, iv) variables related to allometric relationships and partitioning, such as pFS2, pFS20, ηRx, and ηRn, were replaced with their corresponding observed monthly foliage, stem, and roots NPP distribution rates (η_F, η_S, and η_R) throughout the growing seasons (see section 3.2.8). This means Eq. (14) and (15) were not applied.

The age modifier f_{age} was set to 1 because, applying poplar-appropriate values of the related parameters (t_{max}=20 years, r_{age}=0.487, n_{age}=4) the values obtained for the very young ages observed in this study (0 to 3 years) were very close to 1.

Regarding the stand biometry sub-model, the adaptation consisted in the consideration of the number of stools per ha (instead of the total number of shoots) as representative of SRC density, the use of basal diameter of the dominant shoot as representative of B and the avoidance of timber volume calculation, as the stem biomass W_S is the variable of interest for poplar SRC.

USC DE SANTIAGO DE COMPOSTELA

Lastly, v) we included mortality following the procedure of Landsberg and Sands (2011), where the total mortality rate at the end of the first rotations was 5% based on expert knowledge and observations. No self-thinning was considered, as the SRC stands are managed to very short rotations. This approach reduces the number of parameters related to self-thinning and mortality to just the average rate of mortality and the parameters m_F, m_S, m_R.

Some variables in 3-PG are age dependent and are given by empirical relationships whose parameters are species-specific (Sands, 2004a). As regards the foliar fraction, variables such as the Specific Leaf Area ($\sigma_{(t)}$) and the Litterfall rate (γ_F) must be adapted to the fact that poplars are deciduous species in order to estimate the species-specific parameters associated with these variables on a monthly basis. The age predictor was replaced by a monthly predictor, the growth season month (Eq. 2 and 3).

On the left side of the flow diagram (Figure 3.2), we highlight the adaptations made in this study and the species-specific parameters studied. Users can enter species-specific values for up to 60 parameters describing tree physiology and allometric growth relationships. Our study primarily focused on proposing most of the parameters based on observed data (Figure 3.2). The remaining parameters were estimated values from previously published research on hybrid poplars, assumed values based on expert knowledge or best-fit of the model, and default 3-PG values were used for the remaining parameters.

All these changes have made version 2.7 of the Microsoft Excel 3PGpjs spreadsheet code, developed by Sands (2010), inapplicable. As a result, it was necessary to develop a new Excel spreadsheet that incorporates the changes in the equations. This new spreadsheet provides predicted values for biomass compartments over the three years of the experiment.

3.2.4. Temporal change in Specific Leaf Area ($\sigma_{(t)}$)

In order to obtain real values for Specific Leaf Area (SLA) throughout the rotation, 138 subsamples of 50 mature, randomly selected leaves (ss_{50}) from different parts of the crown of 3 representative trees per month and water scenario (T1 and T2) were fresh scanned during the first rotation to calculate the green leaf area of ss_{50}, in cm^2, using the ImageJ software (Abràmoff et al., 2004). The leaves were then dried at 60°C in a forced air oven to constant dry mass to obtain their individual dry weight using a balance (EU-C 7500PQ) with an accuracy of 0.1 g to calculate the dry leaf biomass of the sub-sample W_{fss50} (kg $tree^{-1}$).

The total leaf area measured for 50 random leaves per tree, associated with its dry mass, is the Specific Leaf Area, SLA (m^2 kg^{-1}), according to Eq. 22.

(22)

$$SLA = \frac{Leaf\ area_{ss50}}{W_{fss50}}$$

Eq. 22

Where SLA is the Specific Leaf Area ($m^2\ kg^{-1}$), Leaf $area_{ss50}$ is the leaf area of the sub-sample of 50 leaves per tree ($m^2\ tree^{-1}$) and W_{fss50} is the dry-leaf biomass of the sub-sample per tree ($kg\ tree^{-1}$).

Specific Leaf Area as a function of the growing season month (t, months), which describes the monthly change in SLA, and which is given by the empirical relationship (Sands and Landsberg, 2002a):

(23)

$$\sigma_{(t)} = \sigma_0 + (\sigma_1 - \sigma_0)\, e^{-(ln2)*\left(\frac{t}{t_\sigma}\right)^2}$$

Eq. 23

Where σ_0 is SLA at the beginning of the growing season ($m^2\ kg^{-2}$), σ_1 is SLA of mature leaves before complete abscission ($m^2\ kg^{-2}$), t is the growing season month (with t=1 for the first month showing leaves), and t_σ is the month of the growing season at which SLA reaches its median value.

3.2.5. Temporal change in Litterfall rate (γ_F)

The temporal change in Litterfall rate (γ_F) was calculated based on monthly changes in the total number of leaves (n_l) present on the tree. During the three years of the rotation, all leaves were counted from the bottom to the top of all stools, obtaining the total amount of leaves per month and sampled tree (three trees per month and water scenario T1 and T2).

We predicted the monthly theoretical n_l trend along the growing season (month) for both water scenarios (T1 and T2) using the best equation to fit our experimental data based on 170 observations. Quadratic models (Eq. 24) were fitted using the statistical programme R (R Core Team, 2019).

(24)

$$n_l = a * t^2 + \mathrm{b} * \mathrm{t}$$

Eq. 23

Where n_l is the number of leaves and t is the growing season month.

Litterfall rates were then derived from the variation in leaf number by calculating on a monthly time step the percentage of leaves that were abscised in that month with respect to the previous number of leaves present on the trees, as is the usual procedure in the 3-PG model (Landsberg and Waring, 1997). This means that the litterfall rate of the last month in which leaves are observed on the trees is necessarily equal to 100%.

3.2.6. Canopy conductance

In the field, stomatal conductance rarely operates at absolute maximum (Körner, 1995; Schulze et al., 1994). The absolute maximum stomatal conductance (g_s) achievable in the field occurs when species-specific plant growth conditions are optimum (Murray et al., 2019). To estimate the maximum canopy quantum efficiency (α_{Cx}), two additional data sets were used:

i) D1: data from the PPN under SRC management with irrigation and,
ii) D2: data from experimental trials in a greenhouse under controlled temperature (25±3 ºC max. and 10±3 ºC min.) and relative air humidity (≈70 %). Plants were regularly well watered.

Both data sets include different genotypes belonging to different hybrid groups of the *Populus* genus and autochthonous clones *P. alba* L. originally from Spain.

The data sets (D1 (n= 138) and D2 (n= 509)) were selected to capture as much variability as possible within the constraints of the study. However, we are aware that it may still not have fully captured the maximum canopy quantum efficiency α_{Cx}.

3.2.7. Gas exchange measurements

The Stomatal conductance (g_s, mol m^{-2} s^{-1}), photosynthetic assimilation rate (A, µmol CO_2 m^{-2} s^{-1}), leaf temperature (Tl, °C) and, Photosynthetically Active Radiation (PAR, µmol s^{-1} m^{-2}) were sampled throughout the growing seasons during the months from April to September in the field (D1) and in the greenhouse from May to July. Gas exchange measurements were taken between 9 and 11 am in both data sets (D1 and D2) on two fully expanded mature leaves per tree from the top of the canopy.

A portable photosynthesis system (LCPro+ with Broad Head, ADC BioScientific Ltd., Hoddesdon, UK) was used. The data was used in the parameterization procedure.

3.2.8. Allocation of Net Primary Production (NPP) to biomass components (foliage, W_F; stem, W_S; roots, W_R)

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 next month, always considering the constraint that the three rates should sum the unity.

This first pattern of variation along the growing season of the η_F, η_S and η_R was then smoothed considering the usual ranges of variation of these ratios (η_R is usually bound between 0.2 and 0.8), whereas the ratio η_F/η_S is close to 1 for young stands (in our case the early growing season) and declines towards 0.2 with age (later growing season in our study).

The variations of allocation parameters between the two irrigation regimes: 100% FC irrigation (T1) and 50% irrigation restriction (T2) and with plantation age (age 1, 2 and 3) for each regime were specifically explored. The final table of values provided in the one able to reduce to a minimum the residual among the predicted and observed total production of leaves, stem and roots.

3.2.9. Statistical analyses

3.2.9.1. Model evaluation

To evaluate the goodness-of-fit of the models, we used the proportion of variance explained by the models (pseudo coefficient of determination, *pse*-R^2) and the root of mean square error (RMSE).

(25)

$$pse\text{-}R^2 = R^2_{yi\hat{y}i}$$

Eq. 25

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

(26)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(yi - \widehat{yi})^2}{n}}$$

Eq. 26

Where $R^2{}_{yi\widehat{yi}}$ is the correlation coefficient for a linear regression between the observed and the predicted values of the dependent variable (Ryan, 2008), yi is the observed value, $\widehat{yi}$ is the estimated value, n is the number of data used in the fitting.

The effect of scenarios T1 and T2 on the different variables over the three growing seasons was analyzed using analysis of variance ANOVA (Generalized Linear Model procedure, GLM). Prior to the ANOVA, when normality was not fulfilled, data was transformed using the Box-Cox procedure.

All the analyses and graphing were performed using the R program (R Core Team, 2019) and the level of significance was set to p-value < 0.05 for all the analyses.

3.2.9.2. Model evaluation between irrigation scenarios

To compare the differences in the SLA models between scenarios (T1 and T2), the nonlinear extra sum of square method was used (Bates and Watts, 1988, pp. 103–104). This method was used to determine the simplest model to fit a data set adequately (Corral-Rivas et al., 2007; Huang et al., 2000). The method requires the fitting of full and reduced models. For the variables as a function of the length of the growing season, the full model corresponds to different sets of parameters for the two water scenarios (T1 and T2) and is obtained by expanding each parameter by including an associated parameter and a dummy variable to differentiate the water scenarios. The reduced model corresponds to the same set of parameters for both scenarios.

The appropriate test statistic uses the following expression. (Bates and Watts, 1988):

(27)

$$F = \frac{(SSE_R - SSE_F)/(df_R - df_F)}{SSE_F/df_F}$$

Eq. 27

Where SSE_R is the error sum of squares of the reduced model, SSE_F the error sum of squares of the full model, and df_R and df_F are the degrees of freedom of the full and reduced models, respectively. The non-linear extra sum of squares follows an F-distribution.

The reduced model is accepted at the specified α = 0.05, if:

$F > F_{critical}(1 - \alpha; df_R - df_F, df_F)$, reject H_0, separate models are required for separate scenarios; and If

$F \leq F_{critical}(1 - \alpha; df_R - df_F, df_F)$, accept H_0, the reduced model is appropriate for combined scenarios.

3.3. RESULTS AND DISCUSSION

3.3.1. Specific Leaf Area (SLA)

No significant differences in SLA were observed between the water scenarios T1 and T2 over the three years of the rotation (*p*-value=0.607, *p*-value=0.249 and *p*-value=0.647 respectively). Based on our observations, SLA follows a similar trend in each year of the rotation. Our results are in agreement with those of other authors who found no effect of water availability on SLA in hybrid clones *Populus × canadensis* Mönch (Marron et al., 2002; Monclus et al., 2009).

Temporal changes in SLA are described in Figure 3.3. The model (Eq. 22) was fitted based on observed SLA values (n= 128 trees) per month and water scenario T1 and T2 (Sands and Landsberg, 2002a) .

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

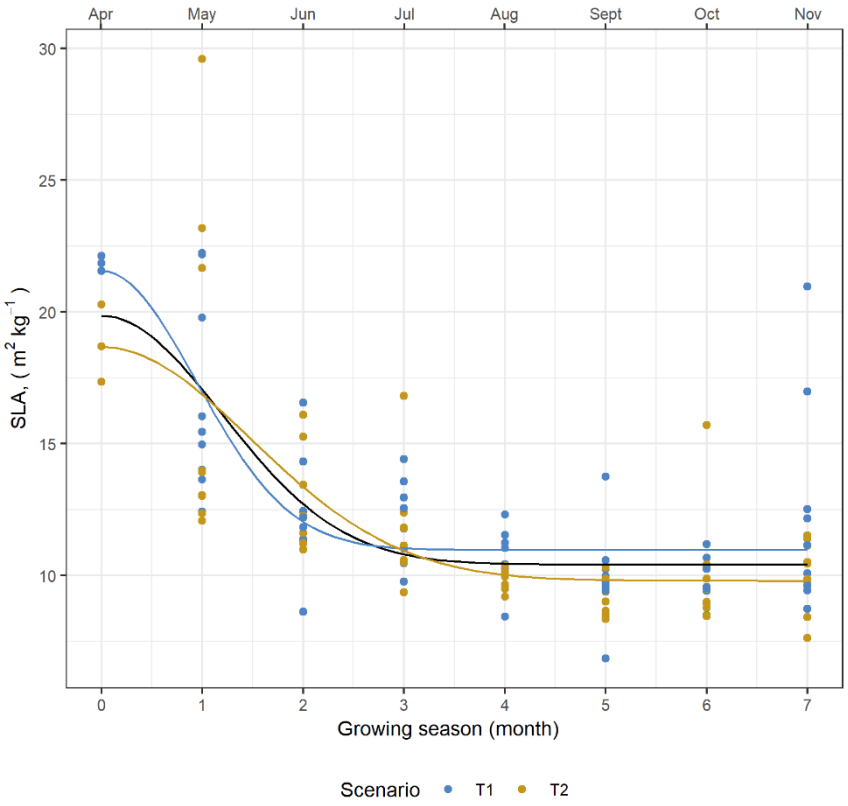


Figure 3.3 SLA (m^2 kg^{-2}) development over the growing season (month) for the three years of the first rotation and two water scenarios (T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC). Black solid line corresponds to all data including both scenarios of the first rotation (3 years).

Results of the nonlinear extra sum of squares method are shown in Table 3.1. The calculated F value for full and reduced SLA models is 1.756, which is lower than the $F_{critical}$ value at α= 0.05 (2.677). Therefore, H_0 is accepted, suggesting that the reduced model is appropriate for combined scenarios. Estimated coefficients and fit statistics of the model that describe the temporal change in SLA are given in Table 3.2.

Table 3.1

F-test of the water scenario differences for the SLA as a function of the length of the growing season models

	SSE	DF	n	*F*-value
Full model	879.93	122	128	1.756
Reduced Model	843.50	125	128	

SSE: error sum of squares; DF: degrees of freedom; n: number of observations. The F-value is calculated according to Eq. (10). Significant F-values if $F > F_{critical}$ at α = 0.05.

The results revealed that the SLA for mature leaves (σ_1) was 10.4 m^2 kg^{-2} and the SLA at the beginning of the growing season (σ_0) was 19.9 m^2 kg^{-2}. The month of the growing season at which SLA has a median value (t_σ) was 1.4, with all estimated parameters being significant (*p*-value < 0.001), Table 3.2.

Table 3.2

Parameter estimates and goodness-of-fit statistics for SLA as a function of the length of the growing season model with the equation:

Eq. 2 $$\sigma_{(t)} = \sigma_0 + (\sigma_1 - \sigma_0)\, e^{-(ln2)*\left(\frac{t}{t_\sigma}\right)^2}$$

Year	Scenario		Estimate	Std. Error	*t* value	Pr(>|t|)	RMSE	*pse*-R^2	DF
1,2,3	**T1&T2**	σ_0	19.863	0.865	22.972	<0.001			
		σ_1	10.413	0.304	34.238	<0.001	2.622	0.541	125
		t_0	1.402	0.152	9.212	<0.001			

T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC; σ_0 is SLA at the beginning of the growing season (m^2 kg^{-2}); σ_1 is SLA of mature leaves (m^2 kg^{-2}); t_σ is the month of the growing season in which SLA has median value; Std.Error: standard error; RMSE: root of mean square error; *pse*-R^2: pseudo coefficient of determination; DF: degrees of freedom.

Our results show that σ_0 and σ_1 were in the same range as those values given in the literature by Headlee et al. (2012) in their study of hybrid poplar as a short rotation woody crop in the North Central USA, σ_0 = 19 and σ_1 = 10 m^2 kg^{-2}. Others authors considered both parameters with the same values $\sigma_1 = \sigma_0$ = 10.8 m^2 kg^{-2} (Amichev et al., 2010), which in the case of poplar in SRC, σ_0 and σ_1 varies markedly from young to mature leaves. Here, we observed a declining trend over the life span of the leaf, starting with high SLA values of 20.31 ± 1.92 m^2 kg^{-2} for the first leaves to 11.24 ± 3.16 m^2 kg^{-2} at the end of the growing season, coinciding with the leaf fall (Table 3.3). Our results showed high variability in the first months of the growing season, probably because of the strong morphological changes that occur at that stage.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 3.3

Monthly SLA (m^2 kg^{-2}) values, mean ± sd values per growing season (month) of both water scenarios (T1 and T2).

Growing season (month)	SLA (m^2 kg^{-2})
April	20.31 ± 1.92
May	16.86 ± 5.00
June	12.46 ± 2.05
July	11.93 ± 1.88
August	10.28 ± 0.90
September	9.54 ± 1.37
October	9.88 ± 1.64
November	11.24 ± 3.16

For a model such as 3-PG, which calculates growth on the basis of intercepted radiation, the relationship between leaf area and foliage mass is of central importance (Feikema et al., 2010). The 3-PG output prediction is highly sensitive to SLA related parameters (Esprey et al., 2004; Nouvellon et al., 2010; Pérez-Cruzado et al., 2011) and detailed information on SLA, designed specifically to obtain σ_1, σ_0 and t_σ values, is still scarce for poplar plantations. To date, other authors have used SLA values from the literature to predict growth and yield of poplar plantations using the 3-PG model (Amichev et al., 2010; Hart et al., 2015; Headlee et al., 2012) as well as for deciduous trees in general (Jégo et al., 2017; Nölte et al., 2020; Potithep and Yasuoka, 2011). This study presents specific parameters for poplar SRC that were not previously available.

The latest approaches for adapting 3-PG to deciduous species have also addressed the optimization of the values of σ_1, σ_0, and t_σ, seeking to minimize the differences between the predicted and measured leaf area index (Jégo et al., 2017). The values obtained by these authors in the case of willows in short-rotation in Canada are in the same range as the values observed in this study.

3.3.2. Litterfall rate (γ_F)

The relationships between the number of leaves and time-course over the growing season for both water scenarios (T1 and T2) are shown in Figure 3.4 as obtained for quadratic models (Eq. 23). The equations considered achieved convergence and all estimated parameters *a* and *b* were significant (*p*-value < 0.001), Table 3.4.

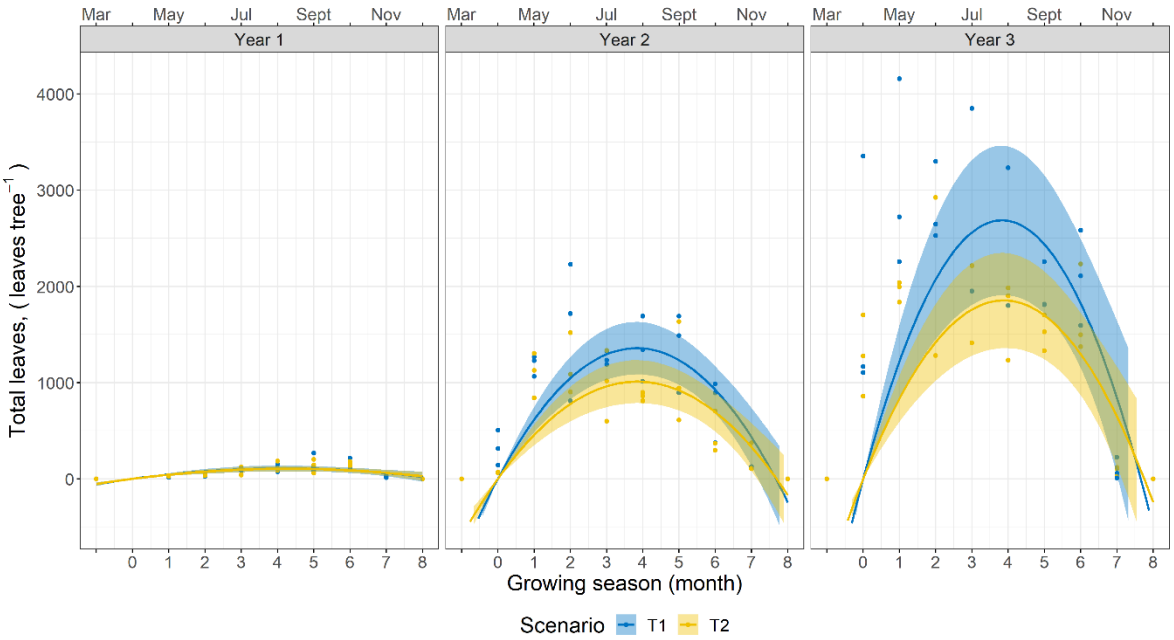


Figure 3.4. Development of the Total number of leaves (leaves tree^{-1}) over the growing season (month) for both water scenarios (T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC). Shaded areas correspond to 95% confidence interval.

While both scenarios had roughly the same number of leaves during this first year, the water restriction applied in this study, led to a clear reduction in the number of leaves in year 2 and 3 (Figure 3.4). Many agronomic practices, including irrigation, affect the number, size, and display of leaves (Nelson et al., 1981), water availability being one of the core factor affecting poplar foliage production and distribution (Cocozza et al., 2010; Fuertes et al., 2022; Gaudillere, 1989)

Table 3.4

Estimated parameters and goodness-of-fit statistics for the Total number of leaves (n_l) model as a function of the length of the growing season using Eq. 23:

Eq.3			$N_l = a * t^2 + \mathrm{b} * \mathrm{t}$						
Year	**Scenario**		**Estimate**	**Std. Error**	***t* value**	**Pr(>|t|)**	**RMSE**	***pse*-R^2**	**DF**
1	**T1**	a	-5.99	1.298	-4.615	<0.001	52.666	0.42	25
		b	50.567	8.493	5.954	<0.001			
	T2	a	-5.66	1.156	-4.893	<0.001	46.910	0.44	25
		b	48.5	7.565	6.411	<0.001			
2	**T1**	a	-92.43	11.54	-8.007	<0.001	470.127	0.66	28
		b	708.72	75.51	9.385	<0.001			
	T2	a	-68.39	9.446	-7.240	<0.001	384.696	0.59	28
		b	525.76	61.792	8.509	<0.001			
3	**T1**	a	-183.29	32.11	-5.709	<0.001	1231.638	0.46	26
		b	1403.63	213.07	6.588	<0.001			
	T2	a	-123.44	20.69	-5.965	<0.001	797.64	0.51	26
		b	956.85	136.58	7.006	<0.001			

T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC; Std.Error: standard error; RMSE: root of mean square error; pse-R^2: pseudo coefficient of determination; DF: degrees of freedom; t: growing season month.

Sands and Landsberg (2002a) recommended that further development (of 3-PG) should consider environmental effects on litterfall, such as water stress. Our results showed that litterfall varies seasonally, with no significant response to the irrigation regimes applied in this study (T2), *p*-value = 0.94, 0.98 and 0.94 respectively. However, γ_F varies markedly during leaf fall, starting in August with very small percentages of 0.704 ± 0.97 % to reach the maximum litterfall rate of 100 % in early December under the scenario without water restriction (T1), although it should be noted that leaf fall started a month later under the restricted water scenario (T2), Table 3.5.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 3.5

Monthy mean ± sd litterfall rate (%) during the first rotation: optimal (T1) and restrictive (T2) water scenarios.

		Growing season (month)					
	Scenario	**Jan - Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Litterfall rate (%)	T1	0	0.704 ± 0.97	7.15 ± 3.01	27.17 ± 7.22	60.05 ± 12.64	100
	T2	0	0	6.52 ± 3.13	25.66 ± 7.52	57.40 ± 13.16	100
	T1&T2	0	0.32 ± 0.74	6.84 ± 2.99	26.42 ± 7.19	58.73 ± 12.59	100

T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC. T1&T2 correspond to all data including both scenarios.

Based on these observations, litterfall rate for very young stands at the beginning of the growing season (γ_{F0}) was zero and the calendar month in which the litterfall rate presented a median value (t_{γ_F}) was mid-October, which in terms of the growing season month is t_{γ_F} = 6.5 (Figure 3.5).

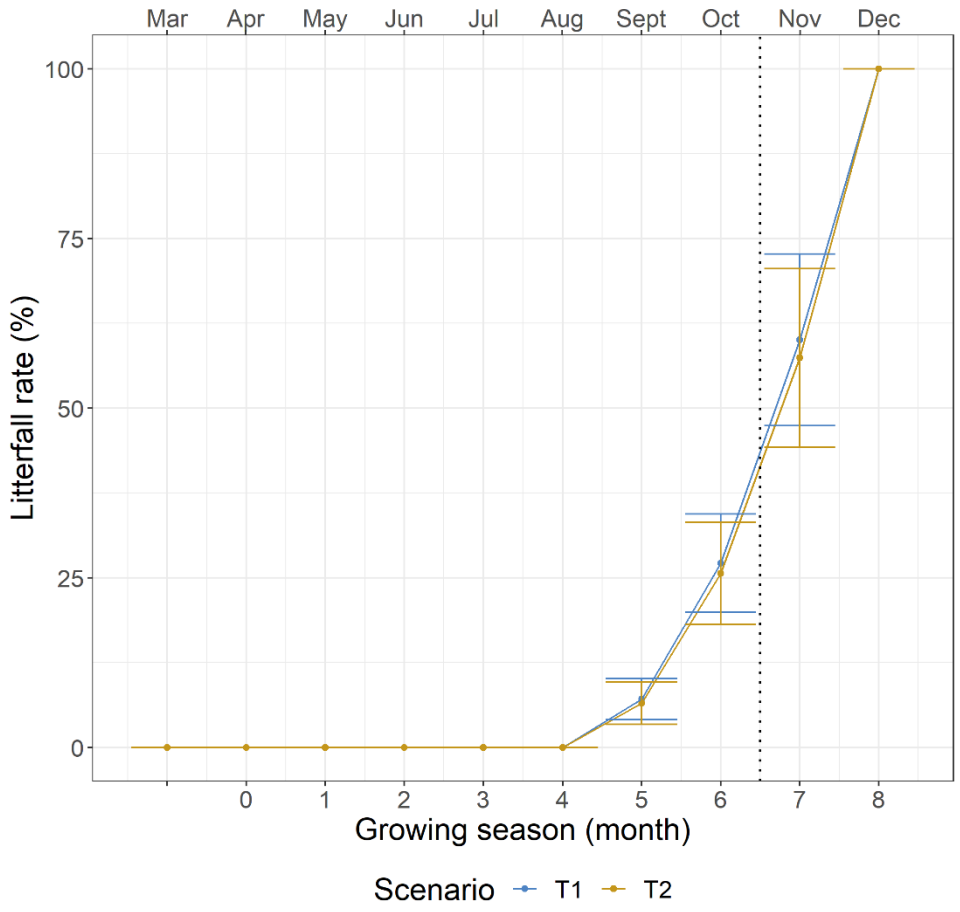


Figure 3.5. Monthly litterfall rate (γ_F) per growing season for both water scenarios (T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC). Vertical dotted line shows when litterfall rate reaches a median value.

According to other authors, leaf litter production for dense stands of hybrid poplars in Wisconsin started in mid-June and peaked in October, while in northern Wisconsin maximum leaf fall occurred in late October or early November (Zavitkovski, 1981). Another study of a SRC stand of hybrid poplars located in north-west France revealed litterfall began in July and continued until the end of November (Berthelot et al., 2000). In Spain, other authors have reported that leaf fall in short rotation plantations usually begins in mid-July and usually continues until the end of November (Pérez et al., 2021). The results obtained under Mediterranean conditions agree with those of this study, indicating that genotype and climate could affect litterfall patterns.

Previous studies applying 3-PG to deciduous trees have used values from the literature for γ_{F0} and t_{γ_F} in order to predict yield (Amichev et al., 2011; Forrester and Tang, 2016; Nölte et al., 2020; Potithep and Yasuoka, 2011) and the same approach was used in studies specifically focusing on poplar plantations (Amichev et al., 2010; Hart, 2014; Hart et al., 2015; Headlee et al., 2012; Zalesny et al., 2012). In these studies the common fitted value for the γ_{F0} parameter was close to zero, which is in line with our observations. In the case of the t_{γ_F} parameters it was difficult to compare values with those of other studies due to differences in rotation lengths, plantation densities, genotype or climate conditions.

In relation to leaf fall, some authors applying the 3-PG model for deciduous trees considered null litterfall during the growing season, arguing that litterfall of deciduous tree species is negligible during that period (Nölte et al., 2020). This may be the case under other climatic conditions where growing seasons are shorter. However, under Mediterranean conditions the growing season generally lasts from late March to late November, with the months of active tree growth being from June to September. Small rates of litterfall (although not negligible) were even observed in the mid growing season (June to September). Sands and Landsberg (2002b) recommended that monthly litterfall rates should ideally be site dependent, other authors also highlighting variations in litterfall depending on local conditions (Pérez-Cruzado et al., 2011). However, in studies where litterfall data was not available default values were applied (Hart et al., 2015; Headlee et al., 2012).

3.3.3. Maximum canopy quantum efficiency (α_{Cx})

Experimental poplar-specific values (n=647) for α_{Cx} are shown in Figure 3.6 for two different data sets (D1: field conditions in the Mediterranean and D2: controlled conditions). Both experiments show maximum photosynthetic rates ranging from 0.05 -

0.093 mol C mol PAR^{-1} in the case of D1 and from 0.05 – 0.08 mol C mol PAR^{-1} in D2, Figure 3.6.

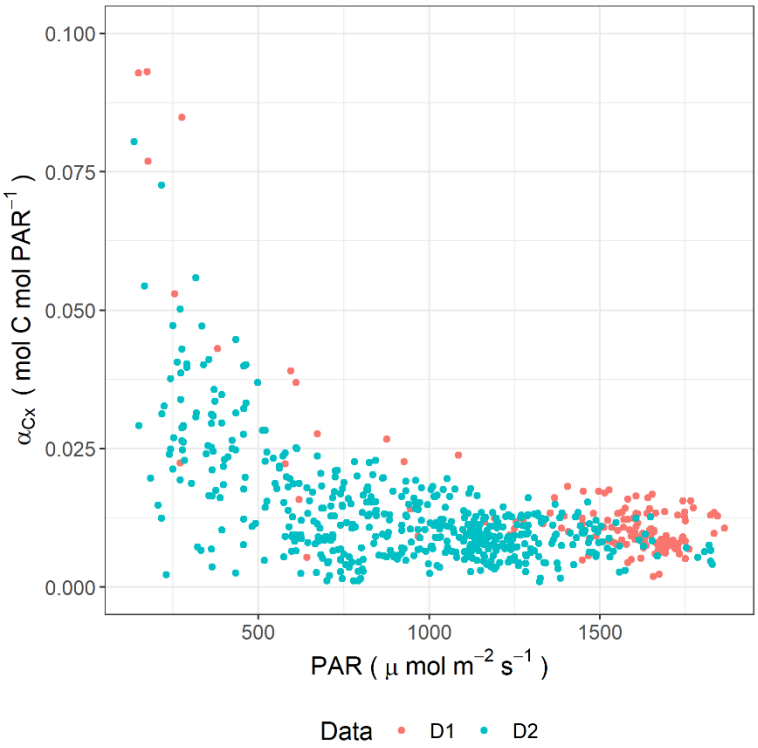


Figure 3.6. The maximum canopy quantum efficiency (α_{Cx}) for both data sets (D1: field conditions; D2: controlled conditions)

While the number of observations in D2 is such that it allows for a more comprehensive representation of the data, D1 is limited due to the fact that it is a field experiment, so the range of PAR measurements is more restricted. Despite this limitation, both data sets still obtain very high α_{Cx} values at low PAR (around 250 µmol s^{-1} m^{-2}). The value of α_{Cx} that best fits our observed and modeled data was 0.09 mol C mol PAR^{-1}.

The maximum canopy quantum efficiency (α_{Cx}) is considered to be among the six most important 3-PG parameters explaining growth differences. A sensitivity analysis performed on these parameters pointed to important changes in the predictions (Esprey et al., 2004; Forrester and Tang, 2016; Pérez-Cruzado et al., 2011). Almeida et al. (2004) observed that all biomass pools were highly sensitive to maximum canopy quantum efficiency. Furthermore, the 3-PG outputs also showed sensitivity to maximum canopy conductance, the above-mentioned studies highlighting the importance of these two parameters in the accuracy of the 3-PG predictions.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Waring et al. (1995), recommended the use of cuvette gas-exchange measurements in the upper, most active canopy strata in order to accurately estimate the maximum quantum efficiency. Our data shows a considerable range of solar radiation from 130 up to 1800 µmol s^{-1} m^{-2}. Nevertheless, we acknowledge that the study may not have captured the maximum parameter value due to certain experimental limitations such as measuring at specific times of day to ensure adequate temperature, solar radiation, irrigation, and humidity levels to simulate optimal plant growth conditions.

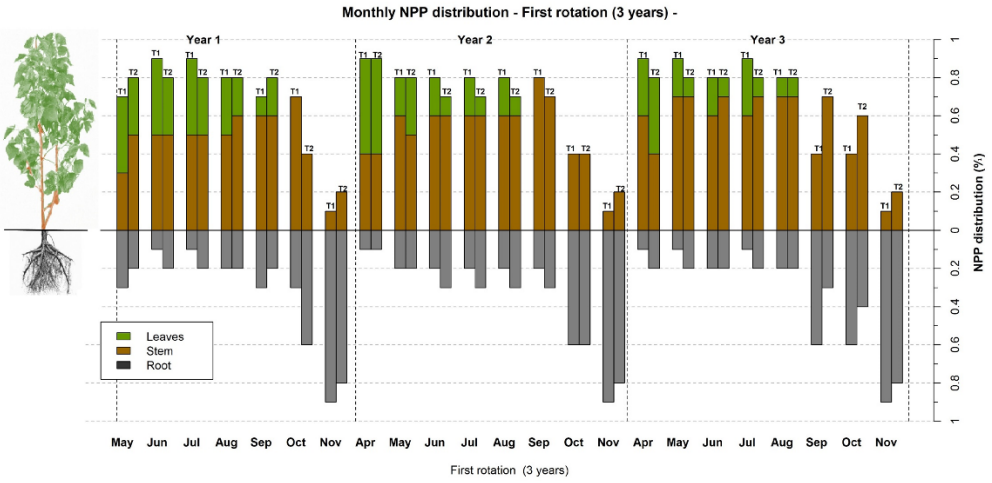
Previous studies concerning poplar biomass predictions using the 3-PG model used values taken from the literature of 0.08 mol C mol PAR^{-1} for α_{Cx} (Hart, 2014; Headlee et al., 2012; Zalesny et al., 2012). However, Hart et al. 2015, varied the α_{Cx} parameter used among the different poplar clones studied, proposing 0.11 molC mol PAR^{-1} (Raspalje), 0.09 molC mol PAR^{-1} (Beaupre), 0.08 molC mol PAR^{-1} (Fritzi) and 0.06 molC mol PAR^{-1} (Robusta). Our results show that the maximum α_{Cx} observed for the D1 dataset was 0.093 molC mol PAR^{-1} and for the D2 dataset it was 0.08 molC mol PAR^{-1}, which is in line with the values used in other studies for poplar plantations.

3.3.4. Monthly Net Primary Production (NPP) distribution

Poplar plantations are established by planting hardwood cuttings of 25 cm in length. During the first few months plant's rooting is essential, the total carbohydrates allocated to generate the root system are 20% higher than for the consecutive growing season in the optimum irrigation regime T1, being slightly different under water restricted conditions (T2) where the carbohydrates contribution to the root biomass was in general higher over the complete rotation (Figure 3.7). As the tree matures, it begins to allocate more carbohydrates to above-ground biomass, such as stem and leaf development. However, starting from August, the tree does not invest any additional carbohydrates towards foliage fraction, as the full foliage development has already been achieved. This strategy allows the tree to allocate a high amount of carbohydrates for stem growth in the consecutive months until the dormant 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 (Figure 3.7).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA



		Year 1							Year 2							Year 3							
		May	Jun	Jul	Aug	Sep	Oct	Nov	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
η_f	T1	0.4	0.4	0.4	0.3	0.1	0	0	0.5	0.2	0.2	0.2	0.2	0	0	0	0.3	0.2	0.2	0.3	0.1	0	0	0
	T2	0.3	0.3	0.3	0.2	0.2	0	0	0.5	0.3	0.1	0.1	0.1	0	0	0	0.4	0.1	0.1	0.1	0.1	0	0	0
η_s	T1	0.3	0.5	0.5	0.5	0.6	0.7	0.1	0.4	0.6	0.6	0.6	0.6	0.8	0.4	0.1	0.6	0.7	0.6	0.6	0.7	0.4	0.4	0.1
	T2	0.5	0.5	0.5	0.6	0.6	0.4	0.2	0.4	0.5	0.6	0.6	0.6	0.7	0.4	0.2	0.4	0.7	0.7	0.7	0.7	0.7	0.6	0.2
η_r	T1	0.3	0.1	0.1	0.2	0.3	0.3	0.9	0.1	0.2	0.2	0.2	0.2	0.2	0.6	0.9	0.1	0.1	0.2	0.1	0.2	0.6	0.6	0.9
	T2	0.2	0.2	0.2	0.2	0.2	0.6	0.8	0.1	0.2	0.3	0.3	0.3	0.3	0.6	0.8	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.8

Figure 3.7. Monthly distribution of Net Primary Production (NPP) over the first rotation (3 years) to the different fractions (leaves, stem and roots) of both irrigation regimes T1: optimum regime, irrigated to field capacity (FC); T2: Reduced irrigation, 50% of FC.

The 3-PG model can provide accurate descriptions of tree growth patterns (Landsberg et al., 2005), which is currently based only on average stem diameter (Sands, 2001). However, for fast-growing species, especially those established by cuttings, the monthly NPP distribution rates are sensible parameters for improving estimates of tree growth patterns. To date, to the best of our knowledge, there are no publications that define these parameters on a monthly basis for fast-growing species, specifically for poplar. This study aims to fill this gap and improve the estimation of different biomass components (foliar, stem, and root). The proposed monthly distribution of NPP during the first rotation appears 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 (Landsberg and Sands, 2011).

3.3.5. Model calibration and validation

The 3-PG model calibration was performed by adjusting leaf, stem and root biomass, and LAI based on monthly observed data from the SRC-trial1 for both irrigation scenarios

(T1 and T2), Table 3.6. Several statistical criteria (RMSE, MAE, Bias) were used to evaluate the model's performance during calibration steps.

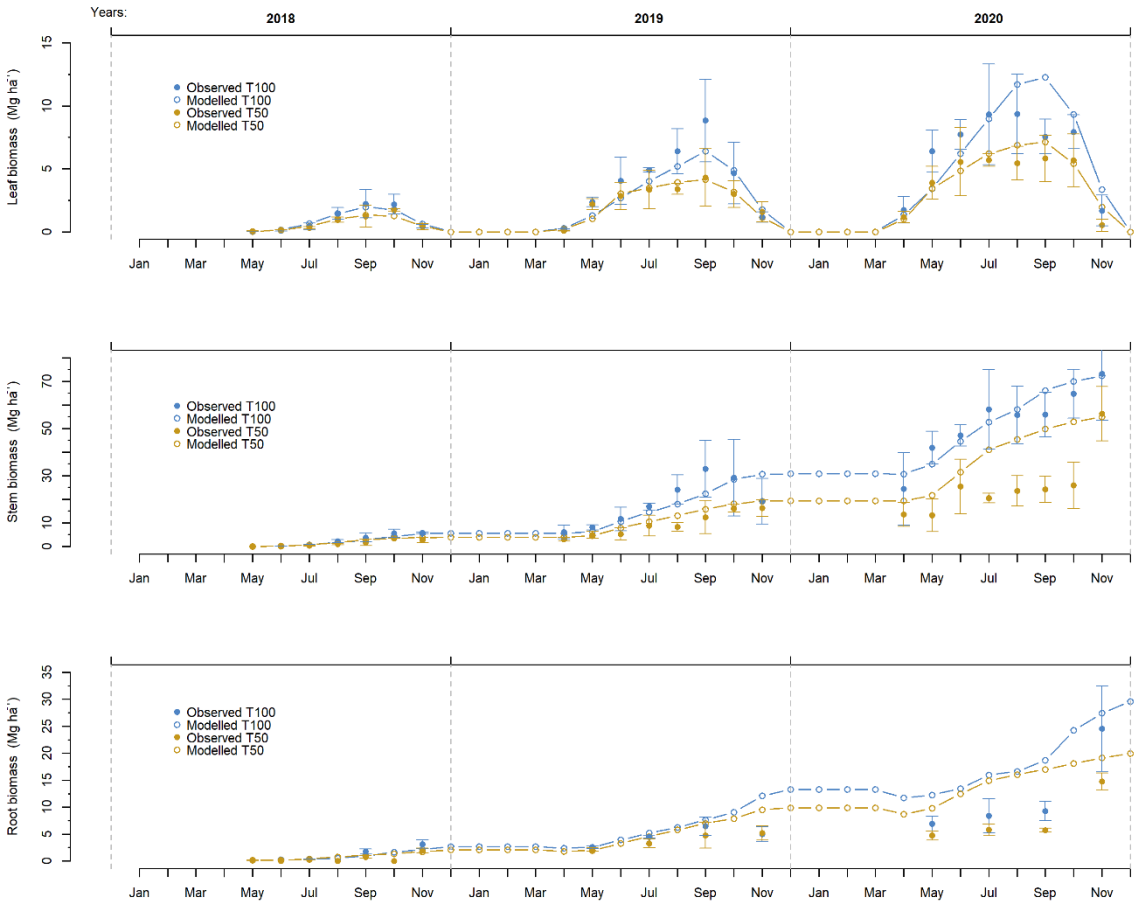


Figure 3.8. Observed vs. modelled data points of leaf, stem and root biomass (Mg ha^{-1}) for the calibration data with 3-PG model using the proposed parameterization of both water scenarios (T1: Optimal scenario, irrigated to field capacity (FC); T2: Restricted scenario, irrigated to 50% FC).

Table 3.6 Model performance indicators for evaluating the model´s ability to predict LAI, leaf, stem and root biomass for the first and consecutive rotations with the calibration and validation datasets.

		Calibration site (SRC-Trial1)				Validation site (SRC-Trial2)			
Rotation (years):		**2018** (T1/T2)	**2019** (T1/T2)	**2020** (T1/T2)	**Total** (T1/T2)	**2017**	**2018**	**2019**	**Total**
Leaf biomass (Mg ha^{-1})	RMSE	0.22/1.20	2.35/0.19	0.48/0.93	1.56/0.63	0.52	1.781	1.77	1.31
	MAE	0.16/0.99	1.92/1.13	0.36/0.78	1.06/0.43	0.45	0.77	1.22	0.43
	Bias	0.03/0.76	-0.61/0.03	0.07/-0.39	0.06/-0.10	0.37	1.07	-1.09	0.26
LAI (m^2 m^{-2})	RMSE	0.2/1.14	2.65/0.29	0.59/1.27	1.71/0.85	0.53	1.45	1.44	1.21
	MAE	0.14/1.07	2.19/0.19	0.55/1.01	1.18/0.6	0.46	1.03	1.56	0.52
	Bias	0.11/0.58	-0.95/0.07	-0.19/-0.97	-0.1/-0.39	0.32	0.95	-0.69	0.14
Stem biomass (Mg ha^{-1})	RMSE	0.70/0.68	6.01/2.65	5.73/17.41	4.91/10.39	2.53	6.74	5.10	4.69
	MAE	0.48/0.50	4.28/2.30	4.99/14.57	3.37/6.02	2.0	5.39	4.39	3.54
	Bias	0.42/-0.49	1.40/-2.2	-1.1/-14.23	0.23/-5.87	1.99	5.39	-1.43	1.98
Root biomass (Mg ha^{-1})	RMSE	0.63/0.62	3.6/2.5	6.76/7.99	4.43/4.35	1.49	1.36	7.13	3.88
	MAE	0.45/0.44	2.25/1.99	6.3/7.46	3.0/2.72	1.12	1.77	7.09	2.73
	Bias	0.43/-0.38	-2.23/-1.91	-6.3/-7.46	-2.7/-2.68	1.08	-0.78	-7.09	-1.59

RSME: 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. Rot: rotation (3 years).

We determine as many parameters specific to 'AF2' (*Populus* × *canadensis* Mönch) as possible based on our own measurements. Overall, 16 out of 37 were observed and 6 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 3.7).

Table 3.7. List of 3-PG parameters and values applied to hybrid *P. x canadensis* ('AF2'). Default values are those used by Sands and Landsberg (2002).

MEANING	SYMBOL (UNITS)	SITE/SPECIES SPECIFIC	PARAMETERIZATION	VALUE
Allometric relationships and partitioning				
Ratio foliage:stem partitioning at B = 2cm	p_2	Species	Observed	According to Figure 3.7
Ratio foliage:stem partitioning at B = 20cm	p_{20}	Species	Observed	According to Figure 3.7
Constant in stem mass and basal diameter relationship over bark	a_S	Species	(Oliveira et al., 2017b)	0.0758
Power in stem mass and basal diameter relationship over bark	n_S	Species	(Oliveira et al., 2017b)	2.5787
Maximum fraction of NPP to roots	η_{Rx}	Species	Observed	According to Figure 3.7
Minimum fraction of NPP to roots	η_{Rn}	Species	Observed	According to Figure 3.7
Temperature and frost modifier				
Minimum temperature for growth	T_{min} (ºC)	Species	Proposed	5
Optimum temperature for growth	T_{opt} (ºC)	Species	Proposed	22
Maximum temperature for growth	T_{max} (ºC)	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	γ_{F0} (month)	Both	Observed	0
Age at which litter fall rate = ½($\gamma_{Fx} + \gamma_{F0}$)	$t_{\gamma F}$ (month)	Both	Observed	6.5
Average monthly root turnover	γ_R (month)	Both	Default	0.015
Conductance				
Maximum canopy conductance	g_{Cx} (m s^{-1})	Species	Default	0.02
Canopy LAI for maximum canopy conductance	Lc_x (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_θ = 0.5	c_ϑ	Site	Sandy loam texture	0.6
Power of moisture ratio deficit in f_θ	n_ϑ	Site	Sandy loam texture	7
Specific leaf area				
Specific leaf area at age 0	SLA_0 (m^2 kg^{-1})	Species	Observed	19.9
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	0.093
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

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

After calibrating the model, the stem, foliar, and root biomass, as well as the LAI of the calibration dataset, were accurately predicted (Figure 3.8). Notably, the model performed better for leaf biomass and LAI, exhibiting a high fit ($R^2 > 0.8$) and the smallest bias, as detailed in Table 3.6.

For stem biomass, the RMSE values were 4.91 and 10.39 Mg ha^{-1} for T1 and T2, respectively, during the first rotation. Observing lower values of RSME and Bias in the first and second year for both treatments, T1 and T2, which was consistent with the findings of researchers who also calibrated the 3-PG model (Headlee et al., 2012; Nölte et al., 2020). Due to the lack of observed root biomass data, comparing our results with other similar studies was challenging. Nevertheless, we obtained reasonable RSME (4.43 and 4.35 Mg ha^{-1} for T1 and T2 respectively) and bias values (-2.7 and -2.68 Mg ha^{-1} for T1 and T2, respectively) for this variable.

The performance of the 3-PG model is shown in Figure 3.9 and Table 3.6, considering four model out-puts (leaf, stem and root biomass, and LAI).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

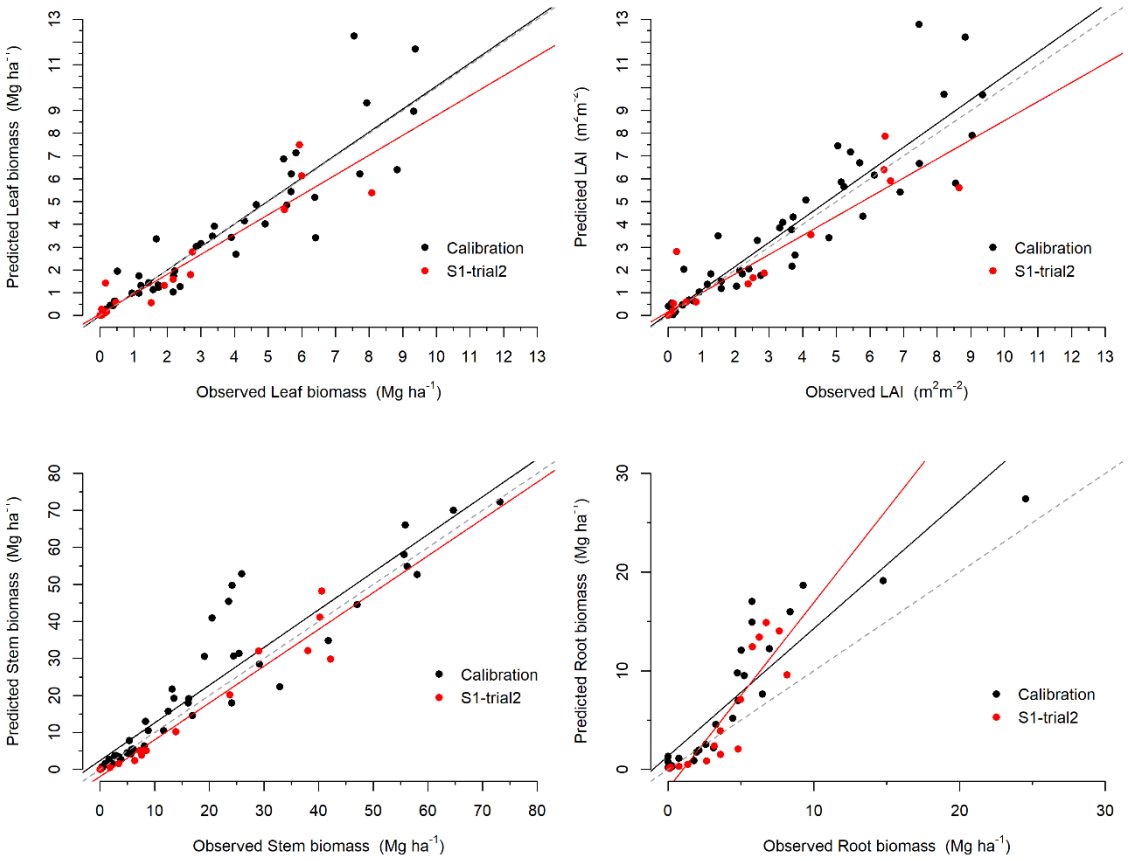


Figure 3.9. Observed vs. modelled averages of leaf, stem and root biomass (Mg ha^{-1}) for the calibration data (black) and validation (red) site, with 3-PG model using the proposed parameterization applied to hybrid *P. x canadensis* ('AF2').

Based on the parameterization changes proposed for the 3-PG, we compared the predicted LAI, stem, root and leaf biomass (W_s, W_r and W_f) with those observed in the SRC-trial2. The predicted values are realistic and fit well with the observed values. In most cases, the slopes of the relationships between the predicted and observed values were nearly 1, indicating a good fit. However, an exception was observed in root biomass, primarily due to the difficulty in accurately simulating the pot effect in the validation datase. (Figure 3.8). Related to above ground biomass, RSME for the validation and calibration data are in line to those reported by other authors using 3-PG model to simulate Hybrid poplar biomass (Headlee et al., 2012).

The proposed parameterization related to partitioning, SLA and litterfall rate variables allows realistic estimates of the changes during the growing season of the different biomass fractions, especially leaf biomass and LAI. This allows null values for both variables during the dormancy months. Moreover, since LAI varies on a monthly basis,

the predictions of GPP (Gross Primary Productivity) and, eventually, NPP, would be much more realistic on a monthly basis, since the 3-PG model is based on the leaf surface interception of photosynthetically active radiation. The pattern of peaking and decreasing foliar biomass and LAI, which is an effect of the decrease in foliar biomass allocation and increase in litterfall along the growing season, is also well resolved with the parameterization proposed. This allows realistic predictions of foliar litterfall and thus of patterns of nutrient contributions to soil via senescent leaves. The modifications made to the partitioning also address the changes in the distribution of allocated carbohydrates, primarily because the model needs to account for annual leaf production, characteristic of deciduous species.

3.4. CONCLUSIONS

Adapting the 3-PG model architecture to SRC deciduous poplar plantations, as well as employing species-specific parameters based on observed data, are key to provide the most accurate estimates and realizing the full potential of the 3-PG model. Furthermore, it is of particular interest to take into account the poplar plantation response to irrigation restriction in the context of climate change. No significant differences in SLA and litterfall rates were found between water scenarios T1 and T2, the trend being similar over the 3 years of the first rotation and the resulting parameters could be applied to both irrigation scenarios T1 and T2. The SLA variation for deciduous species can be modelled on a monthly scale over the course of the growing season. Values for fully developed leaves from 19.9 $m^2 kg^{-2}$ at the beginning of the growing season to 10.4 $m^2 kg^{-2}$ after only 3 months of growth were found for both irrigation scenarios T1 and T2.

Monthly litterfall rates for poplar leaves should be taken into account, as non-zero litterfall rates were found as soon as late August and lasted until early December. Additionally, the highly-sensitive parameter α_{Cx} reaches an observed maximum α_{Cx} of 0.093 molC mol PAR^{-1}, which allows us to gain an insight into this highly sensitive parameter, bearing in mind the lack of observed values for these plantation systems.

The proposed parameterization matched well with LAI, stem, root and leaf biomass prediction in the validation dataset. The patterns of monthly change of LAI and leaf biomass along the growing season show a late maximum for both variables in September-October and a sustained reduction till December. Null values are predicted by 3-PG with the parameterization proposed for four months. The results are useful to provide realistic predictions of leaf litterfall and nutrient contributions to soil via senescent leaves. The adjustments to the partitioning effectively handle the changes in carbohydrate distribution by accounting for the annual leaf production characteristic of deciduous species.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



Chapter 4

AN ECONOMIC OVERVIEW OF *POPULUS* SPP. IN SHORT ROTATION COPPICE SYSTEMS UNDER MEDITERRANEAN CONDITIONS: AN ASSESSMENT TOOL FOR DECISION-MAKING

This chapter under the consent of the publisher was redrafted after: **Fuertes, A.,** Oliveira, N., Cañellas, I., Sixto, H., Rodríguez-Soalleiro, R., 2021. An economic overview of *Populus* spp. in Short Rotation Coppice systems under Mediterranean conditions: An assessment tool for decision-making. Renew. Sustain. Energy Rev. 151. https://doi.org/10.1016/j.rser.2021.111577. More information about this publication can be found in Preface.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 4: AN ECONOMIC OVERVIEW OF *POPULUS* SPP. IN SHORT ROTATION COPPICE SYSTEMS UNDER MEDITERRANEAN CONDITIONS: AN ASSESSMENT TOOL FOR DECISION-MAKING

4.1. INTRODUCTION

In the context of the development of the bioeconomy, woody biomass as raw material for obtaining energy and/or bioproducts is considered a key resource (McEwan et al., 2020; Scarlat et al., 2015). The objectives as regards renewable energy sources, as an integral part of energy transition (EC, 2018), are increasingly ambitious in Europe (32% in 2030). In this context, planted forests can contribute to achieving this goal (Freer-Smith et al., 2019).

In general, the *Salicaceae* family and specifically the *Populus* genus is represented by species and hybrids of importance for wood production in many parts of the world (Bradshaw et al., 2000) including under Mediterranean conditions (Pérez-Cruzado et al., 2014). Poplar plantations growing in short rotation could represent a source of biomass and bioproducts in certain territories and scenarios, assuming sustainable management as part of the whole context at rural landscape level. In many cases, that complementarity will be key not only in terms of raw material supply but also from the perspective of achieving a just transition in the process of decarbonisation. In continental Mediterranean areas, this opportunity for increasingly depopulated regions should be explored.

The use of biomass for a range of applications such as heat for domestic thermal facilities, biomass-based electricity, biochar or second-generation biofuels, as well as the different bioproducts derived from lignocellulosic biomass (biopolymers, additives for construction, biochemicals for biomedicine, etc.) is steadily increasing (Popa and Volf, 2018). This makes it necessary to consider all aspects related to sustainability and profitability as it is vital that the two are compatible. Although the establishment of Short Rotation Coppice (SRC) is strongly influenced by economic factors (Hauk et al., 2014), other issues related to sustainable management are also considered (Scarlat et al., 2015).

In addition, there is increasing interest in the contribution of planted forests to carbon dioxide fixation as a fast capture tool (Bastin et al., 2019), this contribution varying depending on the final use of the wood. In terms of absorption, this may refer to the entire tree, when the purpose is not for energy, or limited to fractions with no energy use such as roots and leaves, considering the remaining wood as a neutral balance. In

relation to roots and leaves, it has been estimated that under Mediterranean conditions the accumulation of below-ground carbon is around 1.0 Mg C ha^{-1} yr^{-1} for the first and second rotation (Oliveira et al., 2018) and 2.5 Mg C ha^{-1} yr^{-1} in the case of the litter (Oliveira et al., 2020a).

Many analyses of these plantations have been undertaken from an economic perspective, although with different considerations (Mitchell et al., 1999; Wolbert-Haverkamp and Musshoff, 2014), and some of them have also considered carbon sequestration (Shooshtarian, 2015). A review carried out by Hauk et al. (Hauk et al., 2014) found that 43% of the studies revealed economic viability whereas 19% pointed to lack of viability. The remaining 38% showed mixed results. Recently, in certain areas of Canada, Liu et al (Liu et al., 2007) identified a positive net return on marginal land with biomass prices of around 23.8 € Mg^{-1} , the average production cost being around 92.02 € ha^{-1}. In the western USA, the current market pricing for biomass resulted in negative financial returns from woody biomass plantations (Chudy et al., 2019). Poplar SRC has been identified as an opportunity to diversify the income of farmers in some areas of Germany with a positive annuity difference of up to 63 € ha^{-1} (Busch, 2017), although this is lower than that obtained from annual crops in this country (Schweier and Becker, 2013).

In some studies, the cost of plant material was identified as the highest of those produced in the establishment phase, the cost-benefit ratio being favourable under the specific site conditions (Dhillon et al., 2001). Although there are many examples of commercial cultivation in Central Europe , Schweier and Becker (Schweier and Becker, 2013) have considered the possibility of extending the rotation or modifying the system used for the harvest to achieve the desired profitability. In southeastern USA, higher raw material prices and increased productivity have been identified as necessary for the viability of these crops (Ghezehei et al., 2019).

Under Mediterranean conditions, a reliability assessment has been undertaken considering different scenarios for power generation (Gasol et al., 2009). The costs and benefits are closely linked to the yields obtained, which are dependent on the base materials used and the crop design (density) among many other factors. Economic evaluations are therefore very dependent on the specific scenarios on which they are based. In this regard, a comparison of irrigated poplar plantations in southern Italy, one with a short rotation period (5 years) and another with a very short rotation period (2 years) revealed a much higher gross margin under the first scenario, even better than traditional cereal farming (Testa et al., 2014). In the south of Spain, the economic analysis carried out on a commercial plantation identified the price of land rent, harvesting and transportation as the most relevant production costs (San Miguel et al., 2015).

USC DE SANTIAGO DE COMPOSTELA

The costs derived from crop production contribute significantly to the final cost of the biomass (De Wit and Faaij, 2010; Gasol et al., 2010) and there are many aspects of the agronomic process that could be optimized through applying science and innovation. Therefore, it is necessary to identify these aspects correctly as a first step to finding alternative solutions. In this type of study, the conclusions obtained often refer to very specific situations (Schweier and Becker, 2013; Vanbeveren et al., 2015). In fact, assumptions are frequently made in the analyses regarding important aspects such as the performance of different rotations, productivities and cultural operation costs, for which experimental data is not available although they are backed up by extensive experience (El Kasmioui and Ceulemans, 2013; Faasch and Patenaude, 2012).

Based on the information obtained from an extensive network of plots located throughout Spain, which cover the entire area where poplar cultivation is viable and which are characterised by the need for irrigation due to the Mediterranean summer drought, the aims of the present work are to: i) identify the crop production costs (economic analysis) associated with poplar cultivation in SRC over the whole life cycle under Mediterranean conditions, ii) carry out a financial analysis and a sensitivity analysis that identifies the most economically relevant cost factors in two different yield scenarios, iii) analyse the influence of discount rates and biomass prices on the profitability of the investment in those same scenarios and, iv) develop a decision tool based on an extensive experimental database for poplar cultivation under Mediterranean conditions (with irrigation).

4.2. MATERIAL AND METHODS

4.2.1. Data sources

The information used in this work comes from a Poplar Plot Network (*PPN*) under SRC management. The establishment of this *PPN* began in 2005 and some of these plots were harvested in 2018. It comprises 350 plots (sampling units within the trials), 98 trials located in 30 different locations under Mediterranean conditions and includes 48 genotypes belonging to different hybrid groups of the *Populus* genus (*P.* x *canadensis* Mönch*; P.* x *generosa* Henry*; P. deltoides* March. and *P. alba* L.), (see Figure 4.1). The set of sites that make up the *PPN* are framed in Mediterranean climate conditions characterized by a marked summer drought. The average temperature (T) in the vegetative period (April-September) ranged between 15.9 and 22.5° C, the average annual T being 14.4° C for the set of plots. Precipitation during the vegetative period ranged between 120 and 308 mm, with a mean value for the whole years of 543 mm. Therefore, additional irrigation was required in all sites during the summers. Around one third (32%) were trials with an area greater than 4 ha (between 4 and 19 ha, specifically) established for both experimental and commercial purposes. A detailed description of

most of this *PPN* can be found in Sixto et al. (Sixto et al., 2015, 2013) and González et al. (González-González et al., 2017).

Since 2005 this network has been monitored, so dasometric and production data is available as well as, in most cases, a list of the cultural operations that have been carried out (fertilization schedule and doses, frequency of the cultural operations such as weeding, pest control and irrigation regimes in each rotation of the cycle). For the purpose of this work, different data from the *PPN* have been used to address all the parameters used in this study, including cultural operations, management, productivity and economic data.

Detailed data from 9 trials located at 6 different sites within the network for which economic information was available, were collected and analysed to determine the costs associated with cultural operations. All trials, with an area ranging from 1.25 to 12 ha, provide real cultural operation data for at least two consecutive harvests. The trials were established with an initial density of 6666 cuttings ha^{-1} and a rotation length of 3 years. Therefore, these densities and rotation lengths (considering 4-rotation cycles), will provide the starting premises for the economic analysis carried out in this study, since most of the data on cultural operation costs within the *PPN* correspond to this design.

In order to limit the assumptions made in the study, all the information available from the *PPN* was recorded, including data for economic cultural operation costs, yield information, fertilization doses, frequency of the cultural operations such as weeding and pest control along with irrigation regimes in each rotation of the cycle.

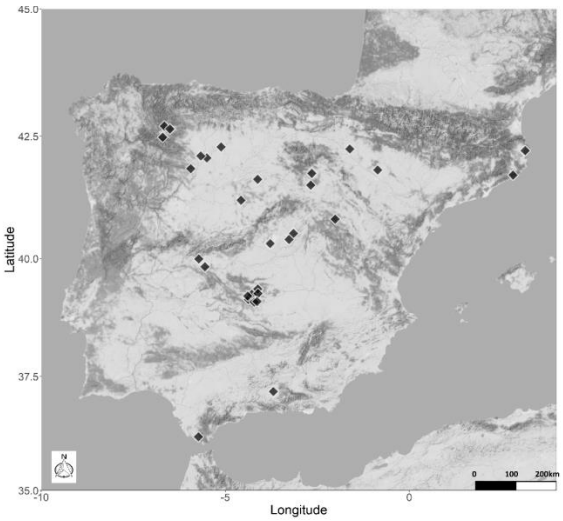


Figure 4.1. Site locations of the Poplar Plot Network (*PPN*).

4.2.2. Yield data

We have considered a SRC cycle of 12 years, which includes 4 rotations of 3 years. This number of rotations in a cycle of 12 years is the most predictable for a 'plantation type' under Mediterranean conditions according to the results obtained for the whole *PPN* and the rotation of maximum volume production for the majority of clones (Oliveira, 2012).

The yield value used for the 1st rotation corresponds to the average value for the plots of the *PPN* with an initial density of 6666 cuttings ha^{-1}. Taking into account that the *PPN* includes a large number of clones that are undergoing evaluation, in this "Baseline scenario" we have assumed the site productivity based on the average yield of the two most productive clones in each plot (n= 44 plots within 8 trials at 8 different sites), these two clones being those best adapted for the particular site conditions. Despite only using 8 out of the 30 *PPN* sites, these plots encompass a broad set of environments and genotypes growing under Mediterranean conditions.

In order to compare different scenarios and perform a sensitivity analysis, we have defined another scenario characterised by higher productivity, which we have named "Optimum scenario". This scenario was calculated using the highest yield of the most productive clone in the best 20 plots, covering densities from 4762 to 13,333 cuttings ha^{-1} (n= 20 plots within 12 trials at 8 different sites).

The yield value of the 2nd and 3rd rotation for both scenarios was taken from the experimental production increment found in those plots where data for 2 successive rotations were available within the *PPN*. The production of the 2nd rotation is obtained by applying a percentage of 137% (standard error (SE) equals to 15.2% based on n= 34 plots within 10 trials and 7 sites) to the 1st rotation and in the case of the 3rd rotation, a percentage of 136% is applied to the 1st rotation (SE equals to 23.8% based on n= 13 plots within 4 trials and 4 sites). Since no experimental data were available for the last rotation, the production of the 4th rotation was calculated using the trend of the average growth rate, the productivity in this case being 97% applied to the 1st rotation. In this regard, these results are in line with those cited in the literature by other authors of similar productivity trends among rotations (Štochlová et al., 2019), although different values might be due to different climatic conditions, clones used and management practices. The different yields used in this work for both scenarios are shown in Table 4.1.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 4.1

Yield for 4 rotations of 3 years in two different scenarios. Cycle of the SRC: 12 years.

Rotation	Baseline scenario		Optimum scenario	
	Dry Biomass Yield (DBY) odt (Mg ha^{-1} yr^{-1})	Fresh Biomass Yield (FBY) M≈ 55% (Mg ha^{-1} yr^{-1})	Dry Biomass Yield (DBY) odt (Mg ha^{-1} yr^{-1})	Fresh Biomass Yield (FBY) M≈ 55% (Mg ha^{-1} yr^{-1})
1st	13.80	30.56	25.64	56.52
2nd	18.91	41.87	35.13	77.43
3rd	18.77	41.56	34.87	76.87
4th	13.39	29.64	24.87	54.82

Yield for the 2nd, 3rd and 4th rotations obtained by applying a percentage of 137%, 136% and 97% respectively to the 1st rotation yield.

M: average moisture content found in the *PPN*; odt: oven-dry tonnes.

4.2.3. Cultural operation inventory

We have listed the relevant operations for optimal development of the plantation, taking as a reference the operations carried out in the *PPN*. Most of the operations performed in the *PPN* followed a common protocol described in Sixto et al. (Sixto et al., 2010).

Irrigation was applied in each trial according to the evapotranspiration (ETP) of the plantation area. The irrigation doses used in this work are based on the experience gained from the *PPN* (Figure 4.2).

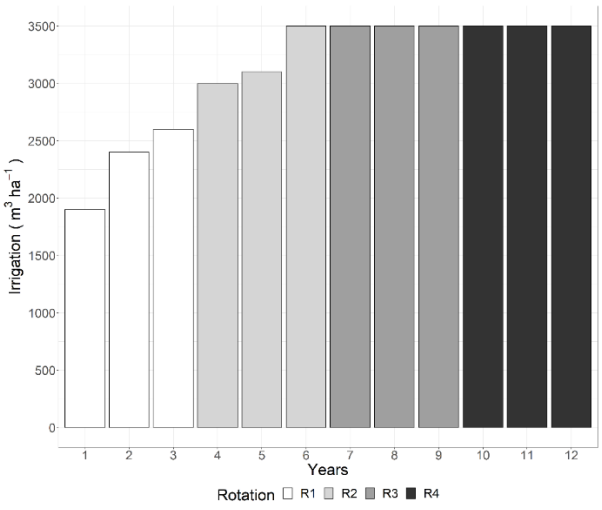


Figure 4.2. Irrigation doses for SRC cycle of 12 years with 4 rotations of 3 years.

Weed control treatments were limited to those considered essential to maintain low infestation. A pre-planting treatment for perennial weeds where necessary was included as a variable (v) cultural operation (Table 4.2). Although this was the common protocol applied to the *PPN*, in certain situations, the absence of control or extemporaneous invasions caused a level of infestation that led to a greater need for further treatments.

Fertilization was not applied in 40% of the *PPN* trials at the beginning of the cycle. In the remaining trials (60%), this application was mainly carried out with a 20N: $8P_2O_5$: $10K_2O$ (NPK) inorganic fertilizer, between 200 and 600 kg ha^{-1} yr^{-1}. In some limited trials, calcium ammonium nitrate at 27% was used. For the purpose of this work, NPK fertilization has been included in the list of cultural operations. We considered this cultural operation as a variable (v) operation depending on the management and consisting of one application of 300 kg ha^{-1} in the first year of each rotation.

Finally, in relation to pests and diseases, the applications were sporadic in the *PPN* and limited to pest control. There were occasional fungal diseases but these did not require treatment, partially thanks to the use of plant materials with a high degree of tolerance to the climatic conditions. In any case, it is advisable to use tolerant plant material. For these reasons, this cultural operation has been considered as a variable (v) operation, depending on the needs of each plantation or even each rotation.

The details of the cultural operations based on well-managed poplar SRC under Mediterranean conditions and the timing of applications throughout the entire cycle are shown in Table 4.2. In order to facilitate cost analysis, these costs have been separated into three cost categories: land costs (L), cultural treatments (C) and irrigation cost (I). Irrigation has been considered as an independent category from the rest of the cultural treatments, since it is a practice that is not generalized outside the Mediterranean area.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 4.2

Selected cultural operations structured in different categories considering land costs (L), cultural treatments (C) and irrigation cost (I).

Cost type		Cultural operation	Cycle year											
			0	1	2	3	4	5	6	7	8	9	10	11	12
SRC management	L	Insurance		x	x	x	x	x	x	x	x	x	x	x	x
	L	Soil survey	v												
	L	Land rental		x	x	x	x	x	x	x	x	x	x	x	x
Soil preparation	C	Subsoiling[a]		x											
	C	Fertilization[b]		v			v			v			v		
	C	Ploughing[c]		x											
Planting	C	Cutting stems		x											
	C	Planting[d]		x											
Weed control	C	Pre-emergence*[e]		v			x			x			x		
	C	Post-emergence*[e]		x			x			x			x		
	C	Mechanical [f]		x	x		x	x		x	x		x	x	
Pest control	C	Chemical[e]		v			v			v			v		
Irrigation	I	Irrigation system		x											
	I	Maintenance			x	x	x	x	x	x	x	x	x	x	x
	I	Water&Electricity		x	x	x	x	x	x	x	x	x	x	x	x
Harvest	C	Cut-and-chip[g] harvesting[h]				x			x			x			x
Stool removal	C	Chemical[e]													x

x: needed cultural operation; v: variable cultural operation, depending on the management; *: Chemical treatment. [a] Tractor (71- 151 kW)+ subsoiler: 1.3 Machine hours ha^{-1} ; [b] Tractor (90 kW)+ spreader: 1.2 Machine hours ha^{-1}; [c] Tractor (151kW)+ cultivator 3 rows and 25 tines: 3.5 Machine hours ha^{-1}; [d] Tractor (167 kW)+ Biopoplar 2 rows planting: 3.3 Machine hours ha^{-1}; [e] Tractor (90 kW)+ sprayers: 1.2 Machine hours ha^{-1}; [f] Tractor (90 kW)+ cultivator 9 tines chisel: 5.5 Machine hours ha^{-1}; [g] Cut and chip harvester (377 kW)+ coppice header Biopoplar: 3.5 Machine hours ha^{-1}; [h] Tractor (151kW)+ trailer: 2.4 Machine hours ha^{-1}.

4.2.3.1. Chip biomass sale price

The chip biomass price assumed in this study is 40 € Mg^{-1} at the plot entrance (M≈ 55%) in accordance with the actual market and pricing obtained from the sector.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.2.4. Economic Feasibility

The decision to implement a poplar SRC almost always depends on its economic profitability. To carry out the economic feasibility study, i) all cultural operation costs registered in the database of the *PPN* were quantified, ii) two typical budgeting indicators to estimate financial viability of the project were calculated: Net Present Value (NPV) and Land Expectation Value (LEV), iii) a sensitivity analysis based on two different scenarios was carried out (Table 4.1) taking into account the main costs of the poplar SRC, iv) the influence of varying discount rates has been analysed, considering the effect of different biomass prices on the profitability of the investment through a graphical output in which the IRR in two different scenarios can be compared (Table 4.1) and, v) an assessment tool for decision-making has been proposed that allows variations in productivity and chip biomass price to be contemplated in order to evaluate the profitability of poplar SRC investments under Mediterranean conditions.

4.2.4.1. Cultural operation cost analysis

We have calculated the average costs of each cultural operation carried out in 9 large-scale commercial plantations belonging to the *PPN*. The respective cultural operation considered is shown in Table 4.2.

All values are expressed for the same base year in euros per hectare. 2011 was taken as reference year since almost all the plantations from which we obtained the economic data were established that year. All average costs including the cost of the agricultural supplies (e.g. herbicide, fuel, fertilizer, etc.) were measured before taxes.

4.2.5. Financial analysis

4.2.5.1. Net present value

Net present values were calculated based on 2011 prices and assuming a real discount rate of 5% over the lifetime of SRC (12 years), which includes 4 rotations of 3 years. The discount rate value of 5% has been assumed taking into account the economic evaluation review by Hauk (Hauk et al., 2014) of 37 SRC studies (the majority in Europe). This review revealed that interest rates used for economic calculation varied from 3 to 7%, with a median rate of 5.5%. Recently, Soliño et al. (2018) in a study of landowners' attitudes towards woody energy crops, demonstrated that the discount rate implicitly used exceeds the 4% rate commonly used in forest economics literature.

To calculate all the outflows, we use average costs for each cultural operation carried out in 9 large-scale commercial plantations belonging to the *PPN*, and the cultural operations needed in a well-managed poplar SRC under Mediterranean conditions

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

(Table 4.2). The revenues were calculated based on a chip biomass price of 40 € Mg^{-1} (M≈ 55%) and the biomass production shown in Table 4.1, according to Eq.1.

$$NPV = \sum_{t=1}^{n} (R_t - C_t) e^{-i(t-1)}$$

Eq.1

where *NPV* is the Net Present Value (€ ha^{-1}), *t* is time (years), *n* is lifetime of the plantation (years), *i* is the discount rate and cash flow is the revenues (*R*) minus costs (*C*) for each year (€ ha^{-1}).

Net Present Value is an indicator of absolute profitability associated with an investment. Another important indicator for relative profitability is the ratio between Profit and Investment (Díaz-Balteiro et al., 2014), according to Eq. 2.

$$Q = \frac{NPV}{K}$$

Eq.2

where Q is the ratio between Profit and Investment, *NPV* is the Net Present Value (€ ha^{-1}) and *K* is the investment payment.

4.2.5.2. Land Expectation Value

The estimation of the theoretical land value is known as the Land Expectation Value (LEV). The LEV represents the value of all future costs and revenues assuming that the rotation will be replicated an infinite number of times in the future (Díaz-Balteiro et al., 2014), according to Eq. 3.

$$LEV = \frac{NPV}{e^{it} - 1}$$

Eq.3

where *LEV* is the Land Expectation Value (€ ha^{-1}), *NPV* is the Net Present Value (€ ha^{-1}), *t* is time (years) and *i* is the discount rate.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The most important cultural operation costs have been identified and three independent sensitivity analyses were carried out using the following variables:

(i) Land rental costs, considering a range from 0 to 600 € ha^{-1}

(ii) Water and electricity costs within Irrigation cost. This factor has been considered in order to quantify the impact of this practice, considering a range of irrigation dose reduction of up to 25% and a range of irrigation dose increment of up to 15%

(iii) Cut-and-chip harvesting costs, considering higher and lower costs for this practice compared with our database prices with a range from 2 to 6.5 € Mg^{-1}

These three variables were analysed in two different yield scenarios described in Table 4.1. Valuations were carried out using the "ggplot2" package implemented in R 3.6.3. (Wickham, 2011).

4.2.6. Analysis of different discount rates and biomass prices linked to an evaluation of the Internal Rate of Return

Different discount rates ranging from 0% to 15% and biomass prices with a range from 30 to 100 € Mg^{-1} (M≈ 55%) were tested in order to analyse the influence of this parameter on NPV under the two scenarios proposed (Table 4.1).

The diagrams have been built with NPV on the y-axis, the discount rate on the x-axis and the different biomass prices plotted on the isolines solving Eq. 1.

Graphical representations of the interaction of these three parameters: discount rates, biomass prices and the NPV values were created using the "lattice" package implement in *programme R* (Sarkar and Sarkar, 2007). The xyplot function was used to produce a two-dimensional graphic in which the NPV obtained after 12 years is related to the value of the discount rate and the sale price of the chip biomass. The rate that is produced when reference lines cut the x-axis for a NPV value equal to zero will be the Internal Rate of Return (IRR) of the investment.

An investment is viable if the internal rate of return λ (Eq. 4) is higher than the discount rate (i), according to Eq. 4.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$NPV = 0 = \sum_{t=1}^{n} (R_t - C_t) e^{-\lambda(t-1)}$$

Eq. 4

where *NPV* is the Net Present Value (€ ha^{-1}), *t* is time (years), *n* is lifetime of the plantation (years), cash flow is the revenues (*R*) minus costs (*C*) of each year (€ ha^{-1}) and λ is the Internal Rate of Return (IRR).

IRR is easily identified in the graphical output provided in this study and is represented for all possible biomass prices and discount rates evaluated under the two different scenarios (Table 4.1).

4.2.7. Simple assessment tool for decision-making

An assessment tool based on real-cost data was developed, focusing on the interaction between productivity and chip biomass price using a simple diagram. It allows these factors to be varied from the perspective of decision-makers in order to obtain information on the profitability of investments based on Eq. 1.

This tool was built by putting the average productivity (M≈ 55%) of the first rotation (3 years) on the y-axis, the chip biomass price on the x-axis and plotting the resulting NPV values obtained after 12 years on the isolines solving Eq. 1.

Graphical representations of the interaction of these parameters were created using the "lattice" package of the *statistical programme R* (Sarkar and Sarkar, 2007).

4.3. RESULTS AND DISCUSSION

4.3.1. Cultural operation cost analysis

The respective cultural activity average costs per hectare and per tonne are shown in Table 4.3. The frequency represents the number of annuities in which this cost has occurred throughout the entire growth cycle of 12 years.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 4.3

Average cost per hectare and per tonne of the selected cultural operations separated into different categories according to land costs (L), cultural treatment costs (C), and irrigation cost (I).

Cost type		Cultural operation	Mean Costs (€ ha^{-1})	Baseline Scenario	Optimum Scenario	Frequency of activities per cycle
				Mean Costs (€ Mg^{-1})	Mean Costs (€ Mg^{-1})	
SRC management	L	Insurance	5.77	0.16	0.09	12
	L	Soil survey	92.59	0.21	0.12	1
	L	Land rental	473.18	13.18	7.12	12
Soil preparation	C	Subsoiling	97.32	0.23	0.12	1
	C	Fertilization[a]	156.47	1.45	0.79	4
	C	Ploughing	63.62	0.15	0.08	1
Planting	C	Cuttings[b]	1030.77	2.39	1.29	1
	C	Planting	339.26	0.79	0.43	1
Weed control	C	Post-emergence[c]	71.68	0.67	0.36	4
	C	Mechanical	75.08	1.39	0.75	8
	C	Pre-emergence[c]	67.43	0.16	0.08	1
Pest control	C	Chemical	165.73	1.54	0.83	4[d]
Irrigation	I	Irrigation system	1683.34	3.91	2.11	1
	I	Maintenance	27.39	0.70	0.38	11
	I	Water&Electricity	253.11	7.05	3.81	12
Harvest	C	Cut-and-chip harvesting	556.37	5.16	2.79	4
Stool removal	C	Chemical	67.43	0.16	0.08	1

[a] 300 kg ha^{-1} NPK 20-8-10; [b] 6666 cuttings ha^{-1}; [c] Chemical; [d] Considering a repeated treatment after 2 weeks.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The two highest costs in the 1st year, as regards the establishment of the SRC, were attributable to the implementation of the irrigation system 1683.34 € ha^{-1} and the cost

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

of the cuttings 1030.77 € ha^{-1} (Table 4.3). The combination of these two factors account for 2714.11 € ha^{-1} representing 16.03% of the total. The establishment costs, including cuttings and planting together with the soil survey, subsoiling and irrigation system, are of considerable importance for the farmers given that the revenues are deferred over time. Unlike agricultural crops, SRC are characterised by high initial costs and long-term irregular revenues (Faasch and Patenaude, 2012).

Among the costs of the SRC corresponding to each year, the highest was land rental cost. We have assumed a land rental cost of 473.18 € ha^{-1}, which is the average rental price in the *PPN.* This cost is lower than the average price of irrigated agricultural land lease in Spain (565 € ha^{-1}), which varies depending on location, starting at 350 € ha^{-1} up to 780 € ha^{-1} (Ministerio de Agricultura, 2013). Studies conducted under Mediterranean conditions have identified land rental as the most critical factor (Gasol et al., 2009), while others have reported that it can have an important effect on financial profitability (Pra et al., 2019). Elsewhere in Europe, other authors have also identified this factor as having a major impact on the profitability of the plantation when considering a land rental of 250 € ha^{-1} (El Kasmioui and Ceulemans, 2013).

According to our study, irrigation costs, which comprise the irrigation system, maintenance and the annual costs of water and electricity over the whole cycle (12 years) total 5021.96 € ha^{-1}. Irrigation is an indispensable operation not only for the survival of the plants under Mediterranean conditions but also to achieve the productivities considered in this study (Garavilla, 2004), which are clearly higher than those attained in other non-irrigated areas of Europe (El Kasmioui and Ceulemans, 2013). In this study, a drip irrigation system was used for more efficient water use, despite the initial investment costs being high (Schweier and Becker, 2013).

Details of the main costs grouped into the three different categories are analysed in Figure 4.3 in order to identify the cost factor which most affects the profitability of the SRC. In this regard, the main cost factor is land rental which accounts for 31.88% of the total. The second most relevant cost factor is the water and electricity associated with irrigation, which account for 16.61%. Finally, cut-and-chip harvesting represents 11.87%. These three-unit cost factors represent 60.36% of the total cost of the project.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

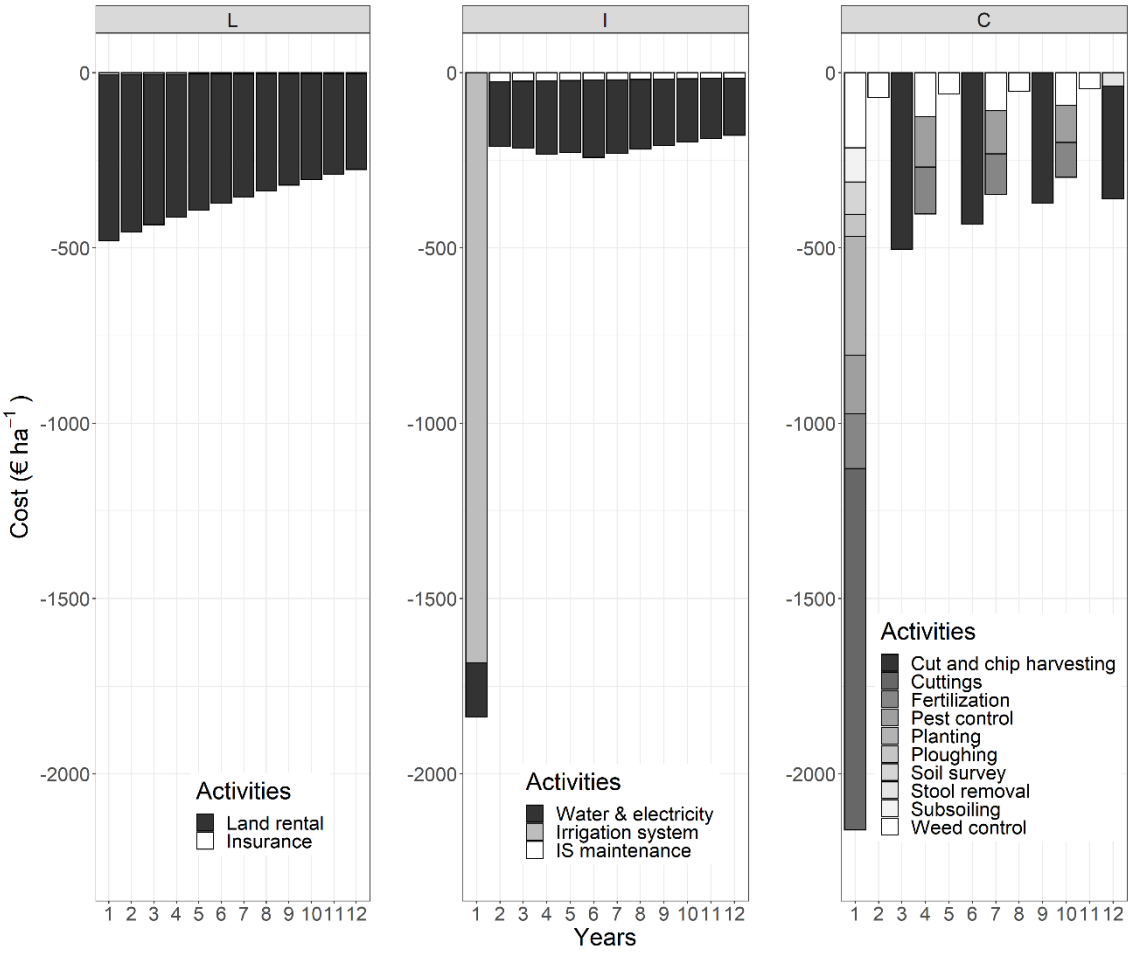


Figure 4.3. Yearly Cash out-flows per operation.

I: Irrigation costs, C: Cultural costs, L: Land costs, IS: Irrigation system

Evaluated at present values, the three different cost categories (cultural, land and irrigation cost) account for 37.22%, 32.27% and 30.51%, respectively, of the total costs. Total irrigation costs identified in this study have a greater impact than those reported by other authors under similar conditions (Manzone et al., 2014), which made up 11.7% of the total SRC economic cost. This is mainly due to the difference in irrigation system used and the lack of implementation at the beginning of the plantation. Land costs are strongly dependent on the location of the SRC, which makes comparisons difficult. The percentage corresponding to cultural operation costs of 37.22% is lower than that observed in other studies (Manzone et al., 2014).

In line with the results found in this study for the remaining cultural operation costs, which have a minimal impact on the profitability, other authors have found that maintenance costs, fertilization, pest control, and weed control, account for only a small share of the overall costs (Hauk et al., 2014).

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.3.2. Financial Analysis

Figure 4.4 shows the present values of the yearly cash flows of the poplar SRC, including the three cost categories and the revenues for the Baseline scenario (Table 4.1). Under this average productive scenario and considering all cultural operations included in a well-managed SRC under Mediterranean conditions (Table 4.2), the NPV was -1105.54 € ha^{-1} over the lifetime of 12 years, and the LEV was -2450.28 € ha^{-1}.

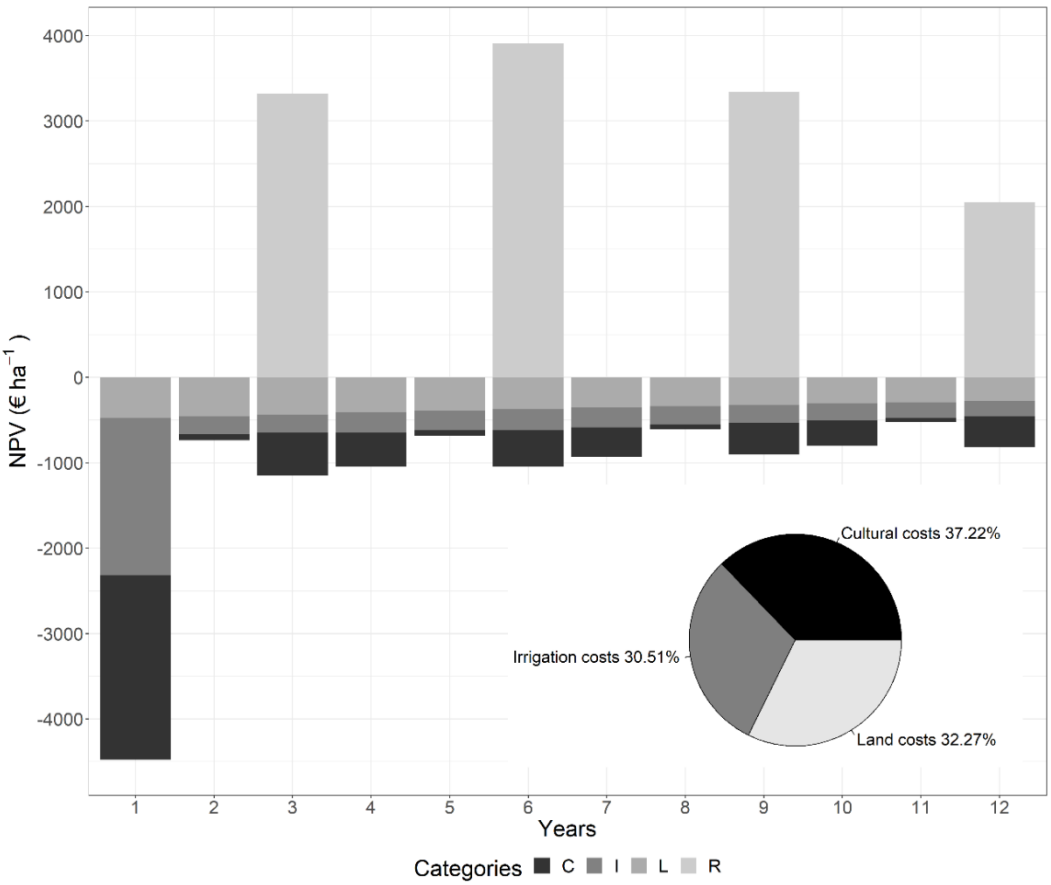


Figure 4.4. Cash in-out-flows per year according to Baseline scenario.

I: Irrigation costs, C: Cultural costs, L: Land costs, R: Revenues (Chip biomass)

In the Optimum scenario (higher productivity) the NPV is positive, reaching a value of 9620.30 € ha^{-1}, with a LEV of 21,233.13 € ha^{-1}. This shows the importance of achieving an optimum level of productivity to compensate the investments made in the plantation. The profit:investment ratio under the Baseline scenario is 0.92, meaning that for each euro invested, the plantation has generated a discounted profit of 0.92 €. This indicator of relative profitability reveals that the investment would not be attractive for investors. However, under conditions of higher productivity (Optimum scenario) this ratio is 1.70, which could change the perspective of the investor.

NPV values reported in other studies within Europe were positive in some cases and negative in others, ranging from 250 to -485 € ha^{-1} (El Kasmioui and Ceulemans, 2013; Gasol et al., 2009; Mitchell et al., 1999). Results reported by Faasch and Patenaude (Faasch and Patenaude, 2012) in Germany revealed higher SRC profitability, reaching a total of 3830 € ha^{-1}. However, the differences in biomass price and in the lifetime of the plantation along with the fact that irrigation is necessary in our case makes it difficult to compare NPV values.

Along with ensuring an optimum level of productivity, another key factor for plantation profitability is the biomass price. In this study, the only input considered was the chip biomass produced to obtain energy. Quantifying extra inputs such as ecosystem services should lead to improved returns. One of the main ecosystem services of these plantations is the reduction of greenhouse gases and carbon sequestration (Hillier et al., 2009; Smith, 2004; Walter et al., 2015). However, it is also important to consider that SRC reduce soil erosion, groundwater nitrate content and surface runoff (Langeveld et al., 2012). They also provide diversity in the agricultural landscape and are a reservoir of different fauna (birds, arthropods, etc.) (Schulz et al., 2009). Additionally, SRC can be used in phytoremediation (Dimitriou et al., 2009). It is therefore necessary to develop valuation systems for ecosystem services and quantify them with a market price. These new inputs would make poplar SRC investments viable under conditions of average productivity. Moreover, given the current dynamic development of the bioproduct markets (Budzianowski, 2017), the combination of biomass as a raw material for obtaining bioenergy along with the supply of bioproducts could improve the economic and resource-use efficiency of biomass and provide additional revenues.

The profitability of poplar SRC depends heavily on plant density and coppice rotation. Some authors have found that poplar plantations with higher densities than that used in this study are more productive (Cañellas et al., 2012), although when it comes to minimising costs, other authors have chosen lower densities, thus assuming lower productivities (Testa et al., 2014) and longer rotations (5-7 years), but better chip qualities and therefore higher market prices (Verlinden et al., 2015). However, longer rotations produce trees with larger diameters, which makes harvesting more difficult. Furthermore, Timber Investment Management Organizations normally reduce the rotation age to achieve a quicker return on the high establishment costs (Lacy, 2006). In line with the rotation length chosen in this study, other authors concluded that with 3-year harvest rotations, poplar SRC can contribute to agronomic and environmental sustainability thanks to its high yield and energy efficiency (output/input) (Nassi O Di Nasso et al., 2010).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.3.3. Sensitivity analyses

Figure 4.5 shows how the variation of the three most influential cost factors: land rental costs, the inputs linked to irrigation and the harvesting system under two scenarios based on their productivity (Table 4.1) affect the economic results.

4.3.3.1. Land rental costs

The economic results are very sensitive to land rental costs. In the Baseline scenario (Figure 4.5, left side) for the real average rental price, NPV is -1105.54 € ha^{-1}. In the Optimum scenario, associated with a more productive situation (Figure 4.5, right side), the NPV reaches 9620.30 € ha^{-1}. To obtain a positive NPV in the Baseline scenario, land rental costs have to be lower than 353.67 € ha^{-1}. A totally different situation is that of the Optimum scenario, which achieves positive NPV values over the entire price range.

There is a reasonable possibility that farmers own the land and in such cases this becomes a negligible cost. Where that is the case, even in the least productive scenario (Baseline scenario), a positive NPV of 3271.94 € ha^{-1} would be achieved. In the Optimum scenario the NPV would reach a value of 13,997.80 € ha^{-1}.

Other possibilities such as farmers' associations or consortia with companies could also be considered as a means to minimise this cost. Additionally, some authors have highlighted non-agricultural values such as the environmental values (landscape, biodiversity, leisure, cultural inheritance, a guarantee of food supply, food safety, and rural culture), which enable the creation of new utilities associated with the land factor (Czyzewski and Matuszczak, 2016; Delbecq et al., 2014). These environmental values are part of the ecosystem services of these poplar SRC linked to the land factor, the specific cost of which will be reduced where these services have a market price.

4.3.3.2. Drip irrigation costs (water and electricity)

In Figure 4.5, we analyse the impact on the NPV of a -25% to +10% change in water consumption with no effect on biomass productivity through improving water use efficiency. The NPV displays scarce sensitivity to these changes, the Baseline scenario values remaining negative over the whole range of irrigation considered while values remain positive under the Optimum scenario.

Irrigation requirements are highly dependent on site characteristics, such as soil and climatic conditions, as well as on the age and density of the plantation (González-González et al., 2017), ranging from 800 to 4000 m^3 ha^{-1} yr^{-1} (Sixto et al., 2013). Under Mediterranean conditions, it has been shown that irrigation can be reduced by around 20% without significant loss in biomass production for the most productive genotypes (González-González et al., 2017). Considering this premise, under the Optimum

scenario, the resulting NPV is equal to 10,076.48 € ha^{-1} when the irrigation dose is reduced by 20%.

In parts of Europe where irrigation is not applied , precipitation always has a positive effect on the growth of poplar SRC (Bergante et al., 2010), regardless of the genotype, the most important period in terms of precipitation being from May to July (Gallardo, 2014). Other authors have also highlighted the dependency on irrigation in Mediterranean areas in order to reach these high productivities per hectare and have pointed to the environmental disadvantage associated with this high water consumption (Gasol et al., 2009; Hennig et al., 2015). Water is a limited resource in Spain and other Mediterranean areas, hence the use of irrigation is an aspect of major concern given the overuse of this scarce natural resource (Scarlat et al., 2015).

The transition towards a bioeconomy-based model involves challenges such as the sustainability of biomass raw material. In this context, other methods of irrigation should be considered, for example using recycled waste water, combined with the selection of suitable genetic material. Another avenue of interest is to identify genotypes with greater hydric stress tolerance allowing irrigation doses to be reduced without affecting productivity.

In this context, progress has been made in different areas such as the search for drought tolerant genetic material (Viger et al., 2016), the study of water use efficiency (González-González et al., 2017; Navarro et al., 2018) or the reuse of water from different sources (Bustamante et al., 1998), although there is still a lot of work to be done if irrigation doses are to be reduced without affecting productivity.

The possibility of irrigating SRC using recycled wastewater could constitute a new approach for sustainable biomass production and potential economic savings. In fact, this possibility has been explored in the USA, where recycled wastewater is used for the production of poplar biomass for a biorefinery (Haider et al., 2018). Similarly, research conducted in Sweden points to the environmental advantages as well as economic benefits to farmers of using sewage sludge and wastewater in SRC (Dimitriou and Rosenqvist, 2011). More specifically, under Mediterranean conditions, a vegetation filter for pollutant removal using poplar SRC was evaluated over a 3-year period. This vegetation filter was irrigated using recycled wastewater and displayed efficient removal of wastewater-originated pollutants (Miguel et al., 2014).

This challenging new irrigation scenario provides the possibility of combining biomass production with water reuse, thus modifying the economy of the plantation. In this regard, progress is being made in the selection of materials for Mediterranean conditions that can be irrigated with reused water (Pradana et al., n.d.). Furthermore, the use of solar energy for the electrical requirements of the irrigation system combined with the use of waste water would further improve the profitability and sustainability of the poplar SRC.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.3.3.3. Cut-and-chip harvesting costs

Sensitivity of the NPV to the variation in cut and chip harvesting costs per unit biomass was low. For the Baseline scenario, it was not possible to achieve a positive NPV only by reducing this cost. However, in Optimum scenario we achieved improved returns for the 12- year cycle, with values of up to 9000 € ha^{-1} over the entire range of costs for cut-and-chip harvesting.

Many studies have shown that the cut-and-chip harvesting cost has an important impact on the economic feasibility of poplar plantations (Berhongaray et al., 2013; Vanbeveren et al., 2015), highlighting the fact that modern technology allows a notable reduction in harvesting cost (Spinelli and Magagnotti, 2011). Over the *PPN* as a whole, the most efficient harvesting system was the cut-and-chip system, which converts the standing biomass into chip biomass in a one-step operation. The average cut-and-chip harvesting costs found in the *PPN* were 5.16 € Mg^{-1} (M≈ 55%). This harvesting system is recommended for SRC given the high performance, productivity and profitability associated with this system (Vanbeveren et al., 2015). The cutting head is a specialised 'coppice header' attached to a harvester. Other options should be explored to further reduce the cost of harvesting.

A review of harvesting costs carried out by Vanbeveren et al. (Vanbeveren et al., 2017) concluded that this cost can vary considerably, from 6 to 99 € Mg^{-1} (M≈ 55%). If these costs are compared with the average cut-and-chip harvesting costs (9 € Mg^{-1}) calculated using models developed by other authors (Spinelli et al., 2009; Vanbeveren et al., 2018), we find that our cost is lower, mainly due to higher productivities achieved in the *PPN*.

In order to minimise these costs, the shared use of agricultural equipment among several farmers, such as large machines operated by contractors, would contribute to optimise economic results since these machines are generally too expensive for individual farmers (Gasol et al., 2009).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

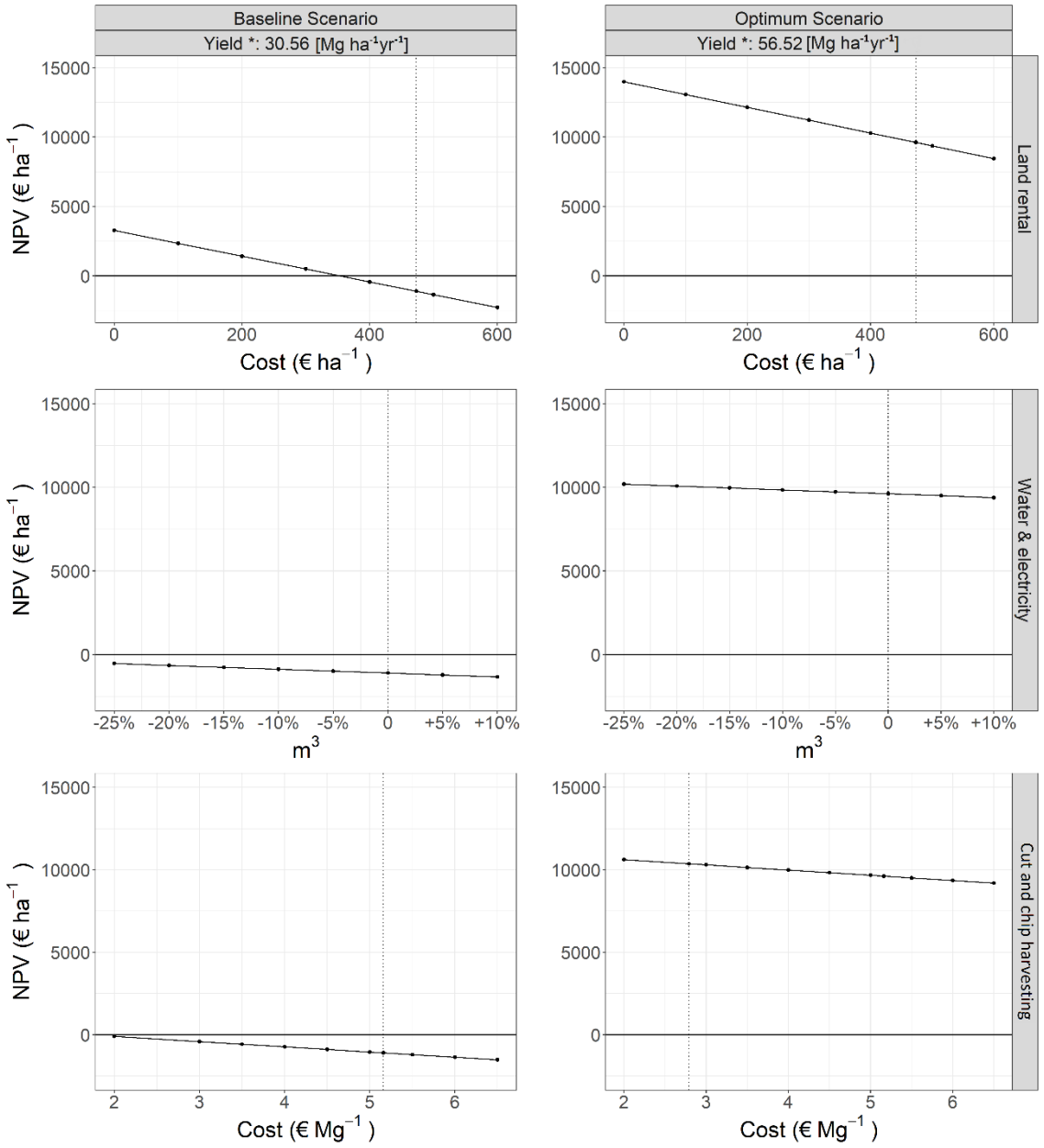


Figure 4.5. Results of the sensitivity analyses showing the impact of the three highest costs identified under two different yield scenarios.

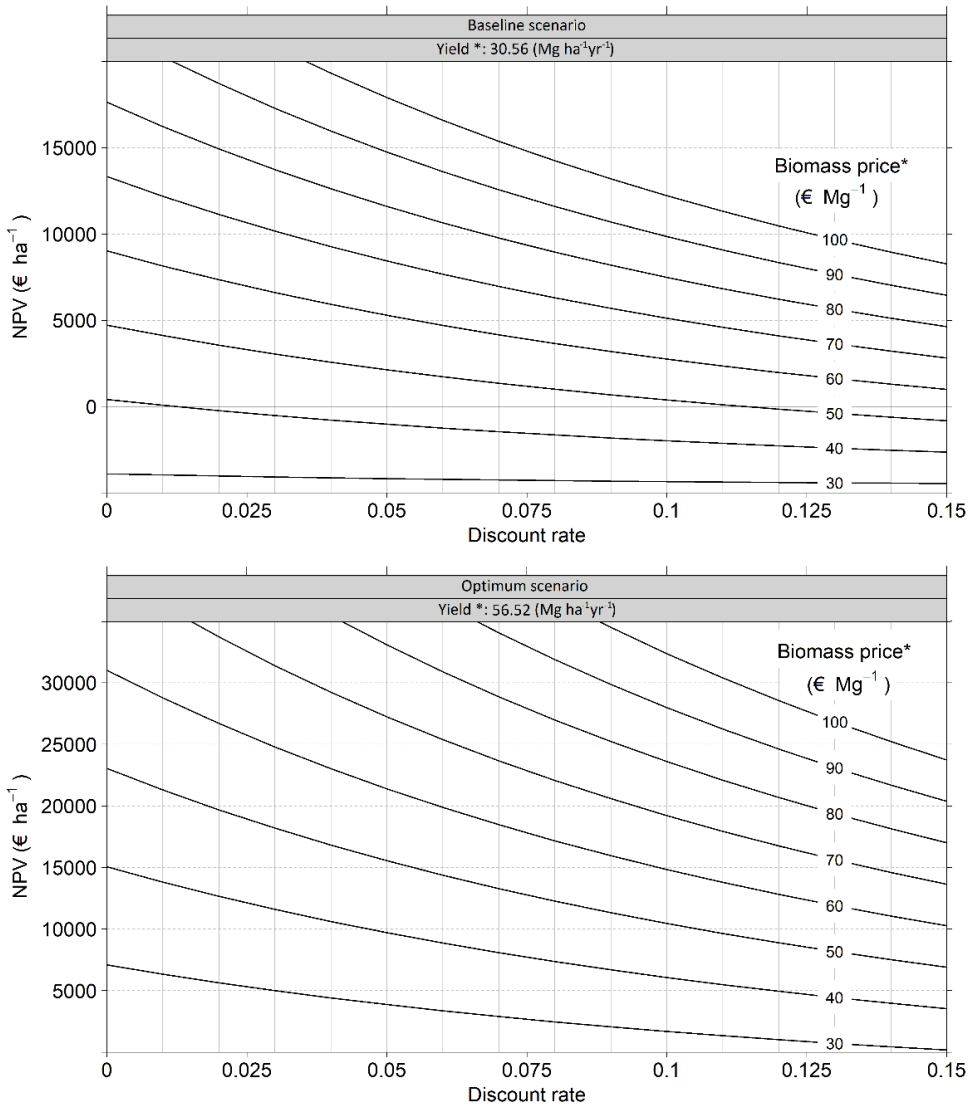
*: Yield with a M≈ 55%; cycle: 12-year SRC (4 rotations of 3 years); dotted line in the graphs shows average cost values used in this study (Table 4.3).

4.3.4. Analysis of different discount rates and biomass prices linked to an evaluation of the Internal Rate of Return (IRR).

Discount rates play a major role when valuing forests and plantations, as highlighted by many authors (Díaz-Balteiro, 1998; Leech, 2014). Choosing the appropriate discount rate is an important factor when choosing the best scenario from among different alternatives (Díaz-Balteiro, 1998).

The choice of discount rate depends on the decision-makers (Díaz-Balteiro et al., 2014) and, as stated by Wagner (Wagner, 2012), there is no single rate which can be applied for all plantations. This study uses a 5% real discount rate, although different discount rates were also tested to provide further information on which to base the decisions of investors.

Figure 4.6 shows the estimated NPV value for a SRC cycle of 12 years (4 rotations of 3 years) according to possible biomass price and different discount rates under both studied scenarios (Table 4.1). The resulting rate where the reference lines cut the x-axis for a NPV value equal to zero shows the internal rate of return (IRR) on the investment.



*: M≈ 55%; Cycle: 12-year SRC (4 rotations of 3 years).

Figure 4.6. Relationship between discount rates, biomass prices and NPV in Baseline scenario and Optimum scenario linked to the IRR of the investment. Diagram of IRR (Diagram-IRR).

For higher chip biomass prices, the reference lines will take longer to cut the x-axis, obtaining higher IRR values. These results enable managers to compare the investment with alternative investments.

According to the Baseline scenario with an annual biomass productivity of 30.56 Mg ha^{-1} yr^{-1} (M≈ 55%) and the chip biomass price used in this study (40 € Mg^{-1}), the Diagram-IRR (Figure 4.6, top) shows an IRR of around 1%, which is lower than the discount rate used (5%). To achieve an IRR above the discount rate used in this study and reach positive NPV values, biomass price should be higher than 43.34 € Mg^{-1}.

In the Optimum scenario (Figure 4.6, bottom) with an annual biomass productivity of 56.52 Mg ha^{-1} yr^{-1} (M≈ 55%) and the chip biomass price used in this study (40 € Mg^{-1}), we reached an IRR of around 27%, which is substantially higher than in the other scenario. Investors, therefore will see a more attractive investment under this optimum yield scenario.

The IRR provides the decision-maker with useful information, especially as regards quantifying the maximum cost of the capital so that the profitability of investments can be determined (Götze et al., 2008). In North America, a financial analysis of poplar plantations showed average IRR values for all the studied scenarios of around 3.58% (Anderson and Luckert, 2007). Results of the survey by Manley (Manley, 2017) suggested that in New Zealand IRR is in the range of 4%-9.2% with an average of 7%, while in southern United States it is between 6.4% and 9.1% according to Tankersley (2006). In central Europe (Serbia), IRR values for commercial poplar plantations were estimated between 4.3 to 6.9 % (Keča et al., 2012). In Europe, under Mediterranean conditions, some authors have estimated IRR in the range of 2%-8% for investments in poplar plantations with lower densities and longer rotations (Borelli and Facciotto, 1996). Under the same Mediterranean conditions, other authors point to opportunities for reasonably attractive investment returns (IRR > 5%) from forest plantations, particularly for landowners and those in the forest products industry (Pra et al., 2019), with reported IRR ranging from negative values up to 11.9% in the best cases (Pra and Pettenella, 2019).

Hauk et al (Hauk et al., 2014) stated that IRR is not suitable for comparing investments with different upfront costs, which makes it difficult to compare our results with those of others authors, mainly due to the differences in rotation and cycle lengths, densities and cultural operations applied. Figure 4.6 shows different IRR values under the Baseline and Optimum scenarios. The IRR is obtained when the reference lines cut the x-axis for a NPV value equal to zero, thus providing a straightforward way to check this factor depending on biomass prices and the real discount rate chosen.

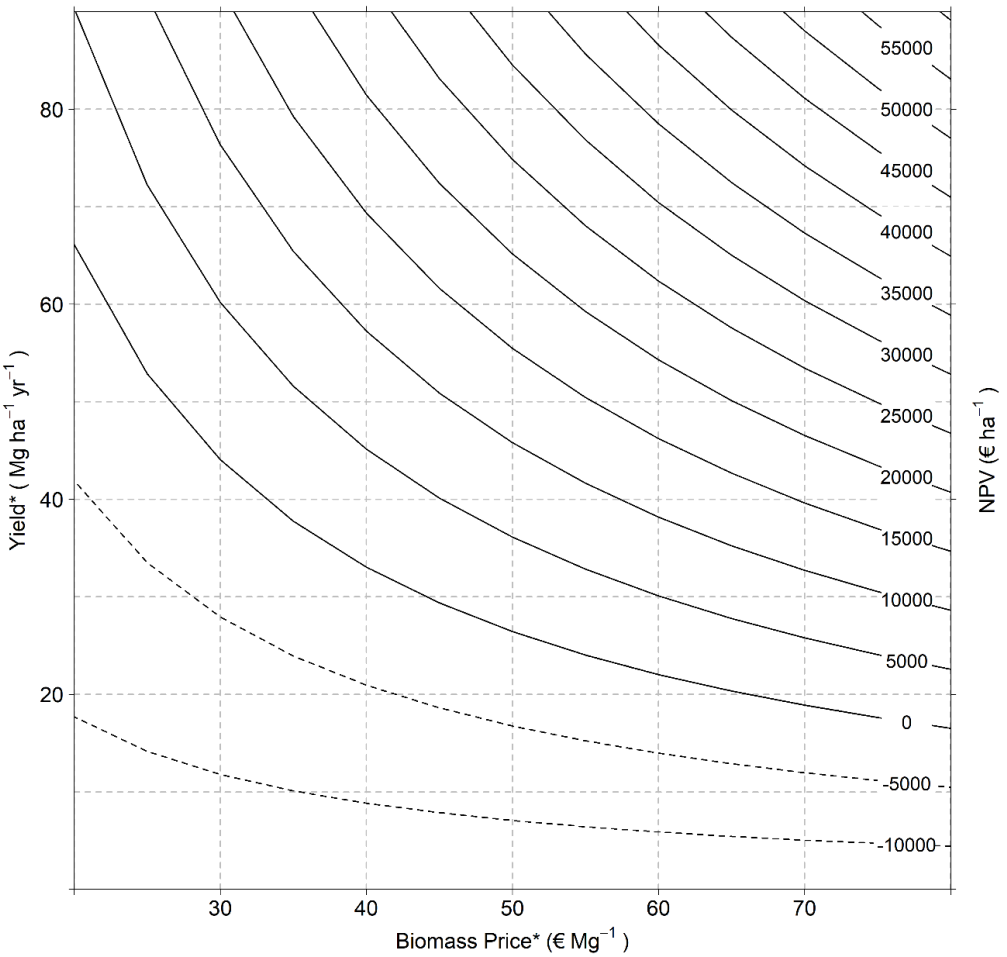
USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

4.3.5. Simple assessment tool for decision-making

Realistic yield data are essential for evaluating the economic viability of SRC (Hauk et al., 2015). The need for accurate tools to estimate biomass in poplar SRC has been widely addressed (Brahim et al., 2000; Laureysens et al., 2003; Paris et al., 2011; Verlinden et al., 2013) and the importance of a real economic analysis has also been studied (Hauk et al., 2015, 2014; Manzone et al., 2014; Testa et al., 2014). This highlights the need to develop an economic analysis based on real data under Mediterranean conditions which necessitate the use of irrigation systems. Moreover, it is necessary to develop profitability assessment tools for decision-makers which are both easily applied and suited to SRC grown under these climatic conditions. Landowners currently seem to be reluctant to establish SRC, even on marginal land, because of the uncertainty regarding the possible economic returns on their investment (McEwan et al., 2020). In this regard, we have developed an assessment tool that allows a graphical evaluation of the final NPV achieved from the investment over the 12 year cycle of the poplar SRC according to the chip biomass price scenarios and biomass production expected by the farmers from their land at the end of the 1st rotation with M≈ 55%. This is shown in the Diagram of Productivity and biomass Price (Diagram-PP) in Figure 4.7. It should be noted that the discount rate fixed for this diagram was 5% and that the biomass production has been calculated by applying the percentages shown in Table 4.1.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA



*: M≈ 55%; Cycle: 12-year SRC (4 rotations of 3 years); Dotted lines in the graphs show negative NPV values.

Figure 4.7. Diagram of Productivity and biomass Price (Diagram-PP).

Analysing our assumed productivity scenarios; in the Baseline scenario (biomass productivity: 30.56 Mg ha^{-1} yr^{-1} with M≈ 55%), the break-even point is reached when the chip biomass price is higher than 43.34 € Mg^{-1} or annual production is greater than 33.23 Mg ha^{-1} yr^{-1} with M≈ 55%. According to the more productive scenario, the Optimum scenario (biomass productivity: 56.52 Mg ha^{-1} yr^{-1} with M≈ 55%), the break-even point is reached when the chip biomass price is higher than 23.52 € Mg^{-1}.

Biomass prices are often a source of uncertainty for investors, as a range of factors can directly affect them: local demand and supply, distance to facilities or size of the supplier crops, characteristics of the chip depending on its end use, to name just a few. Chip biomass is generally the only source of income while the previously mentioned ecosystem services are not taken into account. If the latter were to be considered then total income would be increased and SRC would be inviting more attractive investment.

The availability of management tools is a key factor in managing this type of plantation. The diagram developed here enables the NPV value for a 12-year SRC cycle under

Mediterranean conditions to be calculated, and thus facilitate decision-making based on the benefits that can be obtained at different times depending on the market demands.

The tool developed can be used following a simple procedure to plan and manage irrigated poplar SRC under Mediterranean conditions in accordance with the final objectives desired.

4.4. CONCLUSIONS

Given the appropriate conditions, poplar plantations could be a profitable option for farmers, contributing to a robust, diversified energy mix that takes advantage of complementary renewable energy sources. Poplar plantations also provide offsite-benefits in terms of the bioeconomy and reducing harvesting pressure on natural forests.

The findings of this work point to the potential profitability of poplar SRC under Mediterranean conditions (with irrigation) as long as the investment required is accompanied by high productivities and reasonable biomass price thresholds. The critical cost factors are land rental, water and electricity associated with irrigation and cut-and-chip harvesting, the land rental cost being an important factor affecting the profitability of the plantation.

Exploring the possibility of producer associations to mitigate the costs of land rent, developing other methods of irrigation (both in terms of technology and source of the water used) and the introduction of local and associated harvesting options are key to promoting poplar SRC in rural areas of southern Europe. Additionally, it is important to take into account that selecting appropriate genotypes for the site conditions is crucial for optimizing production.

This study reveals that economic viability of poplar SRC will be achieved either by ensuring optimum productivity or through an increase in the market prices, associated with more diversified energy use and/or bioproducts, along with the quantification of ecosystem services, which currently do not have a market price.

The combination of biomass as a raw material for obtaining bioenergy along with the supply of bioproducts could improve economic and resource-use efficiency of biomass and provide additional revenue.

Additionally, a tool for decision-makers is provided that allows the profitability of a poplar SRC with drip irrigation to be evaluated, comparing NPV values derived from different levels of productivity and biomass prices. This tool provides a simple approach for managing SRC in accordance with the final objectives desired.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



Chapter 5

ASSESSING THE POTENTIAL OF POPLAR SHORT ROTATION PLANTATIONS TO CONTRIBUTE TO A LOW-CARBON BIOECONOMY UNDER WATER-LIMITED CONDITIONS

This chapter under the consent of the publisher was redrafted after: **Fuertes, A.**, Oliveira, N., Cañellas, I., Sixto, H., Rodríguez-Soalleiro, R., Hanewinkel, M., Sperlich, D., 2023. Assessing the potential of Poplar Short Rotation plantations to contribute to a low-carbon bioeconomy under water-limited conditions. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2023.119062.
More information about this publication can be found in Preface.

This investigation was conducted during a research stay at the Chair of Forestry Economics and Forest Planning, University of Freiburg, Germany.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CHAPTER 5: ASSESSING THE POTENTIAL OF POPLAR SHORT ROTATION PLANTATIONS TO CONTRIBUTE TO A LOW-CARBON BIOECONOMY UNDER WATER-LIMITED CONDITIONS

5.1. INTRODUCTION

Forest-based sequestration projects such as plantations for biomass production have been proposed as key elements in the mitigation of global warming by sequestering CO_2 in woody biomass and in the soil (Grafton et al., 2021) while also generating co-benefits such as landscape diversity, reduction of soil erosion and nutrient leaching, increased biodiversity, phytoremediation or floodplain management (Haughton et al., 2016; Henri and Johnson, 2005; Oliveira, 2019). In rural areas, they can promote employment and thus contribute to smart green growth (Scarlat et al., 2015).

At global scale there are two broad types of forest-based carbon sequestration projects: i) afforestation (often with fast-growing species) and/or reforestation, and ii) forest conservation (Grafton et al., 2021). Short rotation plantations have much higher growth rates than regular forests and are seen as the most effective short to medium term carbon sequestration tool (Bastin et al., 2019; Grafton et al., 2021). They provide a source of raw material for bioenergy and/or bioproducts (Herold et al., 2021), thus helping to meet renewable energy targets while increasing soil carbon content on agricultural land in the short term (within the first 10 years) (Grafton et al., 2021), therefore contributing to a low-carbon bioeconomy (Grafton et al., 2021; Oliveira et al., 2020b; Pawson et al., 2013).

Poplar short rotation coppice (SRC) systems achieve high productivity in a short period of time (Oliveira et al., 2020b), storing a large amount of carbon (C) in the different biomass fractions (Berhongaray et al., 2017). The *Populus* genus posesses various traits that make it suitable for the production of biomass under a wide range of environmental conditions (Dickmann et al., 2001). Poplar SRC systems under Mediterranean conditions are particularly productive, although irrigation is often required.

Despite the high productivity and the great potential of poplar SRC under Mediterranean conditions to contribute to a low-carbon bioeconomy, the pressure of climate change means that it is of increasing importance to take water scarcity into consideration. Productivity may be seriously limited by water deficit during the growing seasons (González-González et al., 2017), irrigation generally being a necessary requirement to ensure the survival of poplar plantations, particularly under Mediterranean conditions (Padrón and Orensanz García, 1987). However, as climate change progresses, water

limitation and the need for irrigation is also becoming a concern in climatic zones which are currently not water limited (Coyle and Coleman, 2005; L. Dimitriou et al., 2009; Schweier and Becker, 2013; Yan et al., 2016). In this context, it is crucial to evaluate the impact of water restriction on the productivity of this land-use system, especially under the predominantly water-limited Mediterranean conditions. Plantation owners need to evaluate the impact on the profitability of their investment and the associated C stock potential in order to make reasoned business decisions. If the total C sequestration potential of a plantation is to be adequately determined, it is necessary to take into account not only the commercial fraction, but also the roots and leaves. Belowground biomass plays an important role in carbon sequestration, although scarce studies have focused on quantifying its contribution (Oliveira et al., 2018).

An economic assessment of poplar SRC systems is therefore crucial to complement ecological impact analyses. Most publications, however, have only considered income from chip biomass, (Fuertes et al., 2021; Laina et al., 2022; San Miguel et al., 2015; Schweier and Becker, 2013; Testa et al., 2014), with fewer studies including carbon payments (Díaz-Balteiro and Romero, 2003; Shooshtarian, 2015). The results of these studies vary considerably and present a high degree of uncertainty due to differences in site conditions, the genotypes selected according to productivity, cultural operations applied, land rental costs, different discount rates used, market prices for chip biomass and availability of public subsidies (Fuertes et al., 2021; Hauk et al., 2014; Laina et al., 2022). In particular, it is important to include extra payments for carbon sequestration in the calculation of poplar SRC plantation investment. In Spain for instance, the first mandates became available in 2014, which award a market price for the sequestered carbon dioxide in tree plantations, excluding plantations with a rotation of less than 8 years (BOLETÍN OFICIAL DEL ESTADO, 2014; MITERD, 2019). Payments for carbon sequestration therefore represent potential additional income, which will influence the economic viability of poplar SRC plantations and may increase their attractiveness from the perspective of landowners and investors. Addressing economic uncertainties associated with discount rates, biomass and carbon market prices, as well as ecological uncertainties related to possible future climate change, such as water restrictions, is thus crucial to increase awareness of the potential of poplar SRC systems to contribute to a low-carbon bioeconomy.

However, the climate change mitigation potential is not limited to the actual carbon sequestered in the plantation and use as a renewable bioenergy source. The conversion of lignocellulosic biomass into high-value bioproducts provides a promising alternative to petroleum as a renewable source of carbon, providing extra revenue from the biomass and extending the carbon sequestration potential of these systems. The EU's Green Deal policies are likely to enhance demand for biomass, either in the form of renewable bioenergy or bio-based products to replace fossil products (Herold et al.,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

2021). The use of carbon farming practices in agriculture and forestry can enhance carbon storage sustainably and create a new business model for farmers and foresters (Commission, 2022). Poplar has high cellulose content (42–49%), low amounts of ash and extractives (0.6–2.7 and 1.4–3.6%, respectively), and moderate lignin and hemicellulose contents (21–29 and 16–23%, respectively), which make it a desirable feedstock for bio-based products (Ibarra et al., 2017; own unpublished data, n.d.; Sannigrahi et al., 2010).

Through this study, we aim to quantify the biomass production and C sequestration potential of a poplar SRC plantation under regular- and water-limited conditions and to further assess the economic impact. Therefore, we used an irrigation-restriction experiment as well as an extensive dataset from a network of irrigated poplar SRC plots covering the entire range of cultivation in Spain. The objectives of this work are:

i) To quantify the productivity and accumulated carbon in above and below-ground biomass in poplar SCR plantations with business-as-usual (BAU) management, under conventional irrigation regime (T1 - irrigated to field capacity (FC)) and under irrigation reduction (T2 – to 50% FC).
ii) To evaluate the impact of irrigation regimes T1 and T2 on the profitability of business-as-usual (BAU) and the potential economic benefit of extra payments for carbon sequestration (BAU+C).
iii) To address the uncertainty of price variability in chip biomass and in sequestered carbon, as well as variability in discount rates for both studied scenarios (BAU and BAU+C) and under irrigation regimes T1 and T2.
iv) To investigate alternative biomass uses in long-lived bioproducts in order to compare their climate mitigation potential with conventional short-lived bioenergy end-use.

Overall, we aim to provide policy decision makers and owners with an ecological-economic assessment of the potential of poplar short rotation plantations to contribute to a low-carbon bioeconomy under water-limited conditions.

5.2. MATERIAL AND METHODS

5.2.1. Study design

Our study considers standard SRC poplar plantations under Mediterranean conditions with a 12-year plantation cycle, comprising 4 rotations of 3 years each (Sixto et al., 2010). For the first rotation (single-shoot) we used detailed experimental data from a SRC plantation (SRC-trial) and for successive rotations (multi-shoots), the data used in this

work came from the Poplar Plot Network (PPN) dataset. The PPN comprises 350 plots in 98 trials located at 30 different sites under Mediterranean conditions Sixto et al. (2015, 2013).

5.2.2. SRC-Trial

The SRC-trial was established in 2018 central Spain at a density of 10,000 trees ha^{-1} (2m x 0.5m) using the 'AF2' genotype (*Populus* × *canadensis* Mönch). This genotype is widely planted for the production of chip biomass in the Mediterranean area (Pannacci et al., 2009; Sabatti et al., 2014) due to its high productivity and adaptability to various environmental conditions (Sixto et al., 2015). Under restrictive water conditions, this genotype had previously showed significantly higher IWUE values along the rotation (Fuertes et al., 2022). These values were indicative of the capacity of the leaf to regulate photosynthesis and stomatal conductance and therefore the suitability of the genotype for adaptation to restrictive water conditions endured over time. The study site (40° 27' 27'' N; 3° 45' 01'' W) is at an elevation of 592 m a.s.l, with an annual mean temperature of 14.66°C. The soil has a sandy loam texture with a pH of 8.6 and 0.86% organic matter.

The SRC-trial was established manually using hardwood cuttings of 25 cm in length and two irrigation regimes (T1 and T2) were defined. T1 was irrigated to field capacity and served as the optimum regime as applied under business-as-usual management. T2 was irrigated to 50% of the field capacity. Each regime (T1 and T2) consisted of five single rows with 295 trees, including inner and outer border rows to minimize border effects, ensuring that each subsample has its own edge. A drip irrigation system was used from May to October every year during the entire rotation. Moisture in both plots was monitored using moisture sensors (SM200 Delta-T). Weed competition was prevented over all three years. Fertilization was not applied.

5.2.3. PPN trial

The PPN comprises 350 plots in 98 trials located at 30 different sites under Mediterranean conditions (Sixto et al. (2015, 2013). The PPN exhibits edaphic variability typical of irrigated areas in Spain, with pH levels ranging from 5.09 to 9.82 and organic material percentages ranging from 0.03 to 4.59 %. Regarding climate, there is considerable macro and micro climatic variability within the network, although overall, it can be classified under Mediterranean climatic conditions. Both the establishment and management of the plantation are similar to those described for the SRC-trial, encompassing in this case a total of 3 consecutive rotations at some of the test sites.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.2.4. Biomass estimation

5.2.4.1. Above-ground biomass

Every month, on the 21st ± 3 days, during the 3 growing seasons of the rotation, 3 trees per water regime were harvested, measured and destructively-sampled from April to November of 2018 until 2020, to obtain the above-ground W_s (kg tree^{-1}) biomass per tree and water regime. In total, 138 out of 590 sampled trees were harvested at the end of the first rotation.

While the above-ground woody biomass data for the 1st rotation was collected from the intensive field experiment (SRC-trial), for the 2nd and 3rd rotations the above-ground woody biomass values were modelled based on the experimental production average increment found in those plots where data for at least 2 successive rotations (with the similar planting density) were available in the PPN (Fuertes et al., 2021). The resulting increments were applied for both irrigation regimes (T1 and T2).

Since no experimental data from the PPN dataset were available for the last rotation, the production of the 4th rotation was calculated using the average growth rate trend (Fuertes et al., 2021).

The modelled productivity in this study is in line with that cited in the literature by other authors, with similar productivity trends among rotations (Štochlová et al., 2019), although different values might be due to different climatic conditions, clones used and/or management practices.

5.2.4.2. Below-ground biomass

In the SRC-trial, the frequency of below-ground biomass sampling W_r (kg tree^{-1}) was limited to every other month during the three years of the rotation, accounting for the increasing complexity of the root-extraction procedure. As a result, 72 trees were sampled for above- and below-ground biomass in the first rotation under both water regimes (T1 and T2).

For the below-ground biomass, roots were extracted using a backhoe excavator. The soil extracts containing the sampled roots were cleaned and dried in a forced air oven at 60°C to constant dry mass. Dry root biomass was determined, using a balance (EU-C 7500PQ), to an accuracy of 0.1 g. Broken root tips were measured to estimate the remaining root biomass in the soil and the stumps were separated from the roots. A degree of root loss during the extraction cannot be completely avoided, hence we used the allometric relationship between the broken tip diameter and the remaining root biomass in the soil developed by Oliveira et al. (2018). Total below-ground biomass (W_r in kg tree^{-1}) was determined from the sum of the stump, the extracted roots and the remaining root biomass estimated from the diameter of the broken tip.

USC DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

So, the 1st rotation data was collected from the SRC-trial. For the 3rd rotation, the below-ground biomass values for both regimes were estimated using the observed root:shoot ratio values found in those PPN plots within the same planting density. In cases where there were multiple shoots due to coppicing, all shoots from the same stool were considered together in the calculation of the root:shoot ratio. Since no experimental root biomass data for the same planting density was available for the 2nd and 4th rotation, these data were estimated based on rotation-time changes in the below-ground biomass. We predicted the theoretical value for below-ground yield per rotation (every 3 years) and water regime (T1 and T2) trends using the best equation to fit our experimental data.

A non-linear allometric relationship Eq.1 was fitted using nonlinear least squares to approximate the observed response per water regime and rotation, using the statistical programme R (R Core Team, 2019).

$$W_r = a * t^b$$

Eq.1

Where W_r (Mg ha^{-1}) is the below-ground biomass, t is time (years) and *a* and *b* are fitting parameters.

The equations considered achieved convergence and all estimate parameters *a* and *b* per irrigation regimes (T1 and T2) as well as goodness-of-fit statistics are shown in Table 5.1.

Table 5.1

Parameter estimates and goodness-of-fit statistics for the below-ground yield (W_r, Mg ha^{-1}) as a function of the time (t, years) model with Eq.1:

Eq.1		$y_b = a * t^b$						
Regime	**Fitting parameters**	**Estimate**	**Std. Error**	***t* value**	**Pr(>|t|)**	**RMSE**	***pse*-R²**	**DF**
T1	a	5.934	2.591	2.290	<0.051	8.999	0.806	8
	b	0.955	0.216	0.216	<0.01			
T2	a	4.244	1.212	3.499	<0.001	4.636	0.895	10
	b	0.981	0.139	7.060	<0.001			

T1: irrigated to field capacity (FC); T2: irrigated to 50% FC; Std. Error: standard error; RMSE: root of mean square error; pse-R²: pseudo coefficient of determination; DF: degrees of freedom.

5.2.5. Quantification of carbon sequestration

To determine above and below-ground concentrations of C (%) the SRC trial was used. The different fractions from each harvested tree per month and water regime (T1 and T2) were dried in a forced air oven at 60°C to constant dry mass then weighed using a balance (EU-C 7500PQ) with an accuracy of 0.1 g.

Carbon was determined through dry combustion analysis using an automated analyser (LECO; mod CN-2000, St joseph MI, USA). The concentrations of the different elements were calculated on a dry mass basis and expressed as mg g^{-1} of dry mass.

5.2.6. Economic impact analyses

5.2.6.1. Irrigation regime evaluation

To evaluate the economic impact of irrigation regimes T1 and T2 of the two considered scenarios (BAU and BAU+C), all cultural operation costs for well-managed poplar SRC plantations under Mediterranean conditions were taken from Fuertes, et al. (2021). All average costs, including the cost of the agricultural supplies (e.g., herbicide, fuel, fertilizer, etc.) were measured before taxes.

To assess the profitability from harvested biomass we calculated the Net Present Value (NPV) according to Eq.2 and Land Expectation Value (LEV) according to Eq.3. The chip biomass price assumed in this study was 88 € t^{-1} (odt) at the farm gate in accordance with the actual market and pricing obtained from the sector (Fuertes et al., 2021). A sensitivity analysis was carried out to investigate the impact of variation in chip biomass prices.

$$NPV = \sum_{t=1}^{n} (R_t - C_t) e^{-i(t-1)}$$

Eq.2

Where *NPV* is the Net Present Value (€ ha^{-1}), *t* is time (years), *n* is lifetime of the plantation (years), *i* is the discount rate and cash flow is the revenue (*R*) minus costs (*C*) for each year (€ ha^{-1}).

Hauk et al (2014) showed that the discount rates in 37 SRC studies in Europe varied from 3 to 7%. We assumed a real discount rate of 5% based on previous studies (Diaz-Balteiro and Rodriguez, 2006; Hauk et al., 2014). To account for this variability, we additionally conducted a sensitivity analysis for the discount rate.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

$$LEV = \frac{NPV}{e^{it} - 1}$$

Eq.3

Where *LEV* is the Land Expectation Value (€ ha^{-1}), *NPV* is the Net Present Value (€ ha^{-1}), *t* is time (years) and *i* is the discount rate.

We used the LEV to find the economically optimum rotation length and to analyse the impact of the different irrigation regimes. The LEV represents the value of all future costs and revenues assuming that the rotation will be replicated an infinite number of times in the future (Díaz-Balteiro et al., 2014), according to Eq. 3.

5.2.6.2. Carbon benefits

For the economic analysis of BAU+C we also calculated revenues from C payments. A reference price of 10 € for each tonne of carbon per hectare captured was used (Diaz-Balteiro and Rodriguez, 2006; Nölte et al., 2018). A sensitivity analysis was carried out to investigate the impact of variation in carbon sale prices.

To analyse the economic and environmental implication of the root-extraction practice in the context of carbon benefits, we used the average cost of root extraction practice of 81 € t^{-1} (odt) from Spinelli et al. (2005). The costs include root extraction, cleaning, loading and transportation (over a 20 km distance). For the revenue from root biomass, we considered the stump mass found in this study, which at the time of the first rotation harvest was 33 % and 26 % of the total root biomass for irrigation regimes T1 and T2 respectively. For *in-situ* stump grinding cost, we assumed 450 € ha^{-1}, referring to an operation which smashes the stumps and incorporates the woody debris into the soil, restoring the area for the next crops (Laina et al., 2022).

5.2.6.3. Analyses of uncertainty in the socio-economic framework

Different discount rates ranging from 0% to 13%, biomass prices with a range from 80 to 140 € t^{-1} (odt) and carbon prices with a range from 10 to 30 € t^{-1} were tested in order to analyse the influence of this parameter on NPV under the two irrigation regimes (T1 and T2). This analysis allows these factors to be varied from the perspective of decision-makers in order to obtain information on the profitability of investments based on Eq. 2.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.2.7. Life cycle analyses of carbon emission

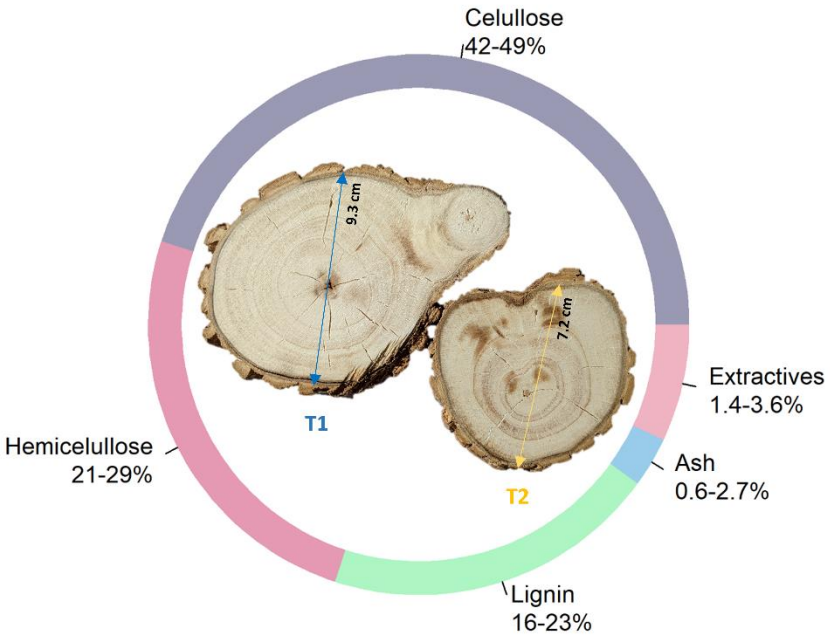
5.2.7.1. Carbon stored in biomass-derived products

In our BAU scenario, 100 % of chip biomass is used for bioenergy. We then analysed other promising potential future uses of chip biomass as bioproducts (BP) that would increase the efficiency of carbon sequestration in poplar SRC plantations. We thus assumed, in a second scenario, the end-use of lignocellulosic biomass as 50% bioenergy use and 50% bioproducts (50 % BP).

Figure 5.1 gives an overview of the most promising bioproducts which are derived from the three primary lignocellulosic biomass components and which could replace petroleum-derived products in the future. Research and development on most of the bioproducts obtained from lignocellulosic biomass are, however, at their initial stage for commercial level production due to the challenges of high-energy consumption, investment cost, and process efficiency. Other bioproducts, such as dissolving pulp that is spun into textile fibres from high purity cellulose, furfural which is a valuable platform chemical from hemicellulose, carbon foams, battery anodes from lignin, and bio-based plastic from cellulose and lignin, can be introduced directly into current markets (Adler et al., 2022; Alonso et al., 2017; European Bioplastics, 2018; Motagamwala et al., 2018).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA



Cellulose based-bioproducts	Hemicellulose based-bioproducts	Lignin based-bioproducts
- Bioplastic	- Thin biofilms	- Bioplastics
- Ionic liquids	- Drug capsules	- Adhesive
- Composites	- Xylan	- Carbon materials
- Adsorbents	- Furfural	- Aerogels
- Carbon nanoparticles		- Dye dispersants
- Aerogels		- Antioxidant (cosmetics)
- Glucan		
- Textile fibers		

Figure 5.1. Overview of possible bioproducts to replace petroleum-derived products, made from the main components of lignocellulosic biomass. The composition of the different fractions (%) of the hybrid poplar "AF2" (odt) have been taken from our own unpublished data and from the literature (Ibarra et al., 2017). Basal tree samples from the studied poplar plantation at harvest time (first rotation) under both irrigation regimes T1: optimum regime, irrigated to field capacity (FC); T2: Reduced irrigation, 50% of FC.

After screening the literature on the most promising potential bioproducts currently available (Figure 5.1), we chose the bio-based plastic polyethylene furanoate (PEF) for our scenario of alternative end-uses of poplar-SRC-derived biomass. PEF is a 100% bio-based polymer, fully recyclable and can easily be disposed of in the established recycling streams (Bioplastics, 2017). It posesses improved material properties of high commercial interest (Motagamwala et al., 2018; Rosenboom et al., 2018) and holds great potential to replace fossil-based polyethylene terephthalate (PET) - the latter being one of the world's most dominant polymers on the market with a production of more than 50 Mt yr^{-1} (European Bioplastics, 2018; Rosenboom et al., 2018). Furthermore, it can be used for the production of packaging (rigid and flexible), textiles,

films and other everyday items, hence is considered a promising renewable resource-based bioplastic (European Bioplastics, 2018; Jong et al., 2022).

Plastic products are highly variable in terms of material properties as well as in their lifespan, which can range from one up to 50 years of potential service life (Plastics Europe, 2019). Therefore, we conducted a life-cycle carbon emission analysis of one plantation cycle (12 years) in order to gain a conservative general overview of the potential to sequester C in bioproducts. Through the example of PEF we illustrate just one promising example of how lignocelullosic biomass can be used to produce bioproducts which can sequester C in the mid- to long-term, thereby contributing to a low-carbon economy.

5.2.7.2. Conditions and assumptions for life cycle analyses of carbon emission

A number of factors and limitations were taken into consideration for this study:

i) Land conversion emissions were zero because no primary forest or land use change was involved.
ii) Above-ground biomass decomposition was zero because there was no woody debris left after each harvest.
iii) We assumed that 100% of the above biomass was used to produce electricity.
iv) Emissions associated with operational activity (transportation of cuttings, soil preparation, weeding, planting, irrigation, harvesting, transport to a power plant and conversion to electricity) were considered and values were taken from Djomo et al. (2019).
v) We considered two scenarios: BAU (where 100 % of above biomass is used for bioenergy) and 50%-BP (where 50% of above biomass is used to bioenergy and 50% is used to produce the bio-plastic product PEF). The 50%-BP scenario takes into account two end-of-life options: recycling and incineration without energy recovery. As a result, we conducted three different tests per water regime T1 and T2:

- Test-1: BAU (Business-as-usual, 100% lignocellulosic biomass as bioenergy).
- Test-2: 50% BP-Recycling, (50% lignocellulosic biomass as bioenergy 50% bioproduct. End-of-life: recycling).
- Test-3: 50% BP-Incineration, (50% lignocellulosic biomass as bioenergy 50% bioproduct. End-of-life: Incineration without energy recovery).

USC UNIVERSIDADE

There are several sources of uncertainty to consider in this section of the study. Firstly, the lifespan of different PEF bio-plastic product categories varies considerably. Secondly,

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

the rates of plastic incineration and recycling (Geyer et al., 2017). In this study we assumed lifespans of 15 years for the bioproducts, considering full recyclability or incineration without energy recovery as end-of-life options.

We have used a conservative estimate of 20 kg of biomass feedstock required for the production of 1 kg of PEF, consistent with the findings of Bishop et al. (2022). Additionally, we considered a value of with 5.26 kg CO_2 per kg of PEF produced, based on the research by Gerritse (Gerritse, 2019). However, it is important to note that the biomass sources and methodologies employed in these previous studies differ from those used in our study due to the limited existing research on the impact of PEF, despite the growing interest in the topic.

For this analysis we used the Bern model, which is the state-of-the-art global carbon cycle model (Levasseur et al., 2010). This model has been adopted by the IPCC for climate projections and calculation of the GWP for several GHGs (Forster et al., 2007).

Calculations for carbon accounting are prone to double counting because of the complexity introduced by multiple variables (CICES, 2018). We verified all variables for an accurate carbon accounting and to prevent double counting in the calculations (Benítez-Ponce et al., 2018; Mbow et al., 2013).

5.2.8. Statistical analyses

To evaluate the goodness-of-fit of the models, we used the proportion of variance explained by the models (pseudo coefficient of determination, *pse*-R^2) and the root of mean square error (RMSE).

$$pse\text{-}R^2 = {R^2}_{yi\widehat{yi}}$$

Eq.4

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(yi - \widehat{yi})^2}{n}}$$

Eq.5

Where ${R^2}_{yi\widehat{yi}}$ is the correlation coefficient for a linear regression between the observed and the predicted values of the dependent variable (Ryan, 2008), yi is the observed value, $\widehat{yi}$ is the estimated value, n is the number of data used in the fitting.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

The effect of water regimes T1 and T2 on the different variables over the three growing seasons was analyzed using analysis of variance ANOVA (Generalized Linear Model procedure, GLM). Prior to the ANOVA, when normality was not fulfilled, data were transformed using the Box-Cox procedure.

All the analyses and graphing were performed using the R program (R Core Team, 2019) and the level of significance was set to p-value < 0.05 for all the analyses.

5.3. RESULTS AND DISCUSSION

5.3.1. Experimental results for above and below-ground biomass during the first rotation

In the establishment year, above-ground biomass increased monthly in both irrigation regimes. T2 reduced productivity by half (54 %, p-value=0.052) although this was not significant due to the large variability of the young plantation as a whole during the year of establishment.

In contrast, in the following two years of the rotation, the reduced water regime T2 caused a significant decrease in the above-ground biomass (p-value=0.0012 and p-value < 0.0001 for years 2 and 3, respectively). This 50% water restriction resulted in a 23 % reduction in productivity at the end of the first rotation (Table 5.2).

Several authors have found that water scarcity leads to a reduction in productivity during the growing seasons (Cañete-Salinas et al., 2019; L. Dimitriou et al., 2009; González-González et al., 2017). The increasing limitation of water for irrigation as climate change advances is likely to not only be an issue under Mediterranean conditions, but also in other climate zones which are not yet suffering water limitations. Short rotation poplar plantations are highly productive within a short timeframe – even on marginal agricultural sites (Schweier et al., 2017) - but irrigation is essential to achieve high productivity and to ensure the survival of trees under Mediterranean conditions, as well as in other regions (Padrón and Orensanz García, 1987; Schweier and Becker, 2013; Yan et al., 2016).

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 5.2

Above-ground biomass (Mg ha^{-1}) and below-ground biomass (Mg ha^{-1}) at the end of the different growing seasons during the first rotation: optimum (T1) and reduced (T2) irrigation regimes.

	Regime	Growing season (years)		
		1st	2nd	3rd
W_s	T1	5.77 ± 0.34	19.09 ± 9.66 *	73.17 ± 19.81 *
(Mg ha^{-1})	T2	2.64 ± 1.08	16.19 ± 3.43 **	56.17 ± 11.48 **
W_r	T1	3.12 ± 0.82	5.44 ± 1.39	23.14 ± 11.08
(Mg ha^{-1})	T2	1.94 ± 0.44	5.51 ± 1.43	16.68 ± 1.84

W_s:above-ground biomass in oven-dry matter; W_r: below-ground biomass in oven-dry matter; T1: optimum regime, irrigated to field capacity (FC); T2: Reduced irrigation, 50% of FC.

Different number of * show significant differences between water regimes for the same year.

The 23 % reduction in productivity of above-ground biomass at the end of the first rotation (3 years) was lower in comparison with the results reported by González-González et al. (2017) for plants growing under similar climatic conditions but poorer soil (less organic matter) and double the planting density, which probably increased competition.

The overall loss in productivity of the below-ground biomass was found to be 41.2 % at the end of the first rotation (9.45 Mg ha^{-1} year^{-1} (odt) (T1) and 5.56 Mg ha^{-1} year^{-1} (odt) (T2), Table 5.2), with non-significant differences in below-ground productivity per year between the different water regimes T1 and T2 (*p*-value = 0.094, *p*-value = 0.957 and *p*-value = 0.376 for years 1, 2 and 3, respectively), probably due to the low number of values and high variability found.

5.3.2. Above and below-ground biomass for one complete plantation cycle

At the end of the lifecycle of the poplar plantation (12 years), the total harvested above-ground biomass was 343.89 and 264.79 Mg ha^{-1} (odt) for T1 and T2 respectively, while the accumulated below-ground biomass was 63.75 Mg ha^{-1} and 48.64 Mg ha^{-1} for T1 and T2 respectively (Figure 5.2, a and b). The root:shoot ratios increased; ranging from 0.23 – 0.89 over the course of the 4 rotations. After the first rotation, the root system is well established, which is reflected in the increment in above-ground biomass of 37 % and 36 % in the second and third rotations, respectively. In the 4th rotation, the exhaustion of the stumps eventually reduced the above-ground productivity. In this regard, these results are in line with those cited in the literature by other authors of similar

productivity trends in the consecutive rotations (Schiberna et al., 2021; Štochlová et al., 2019).

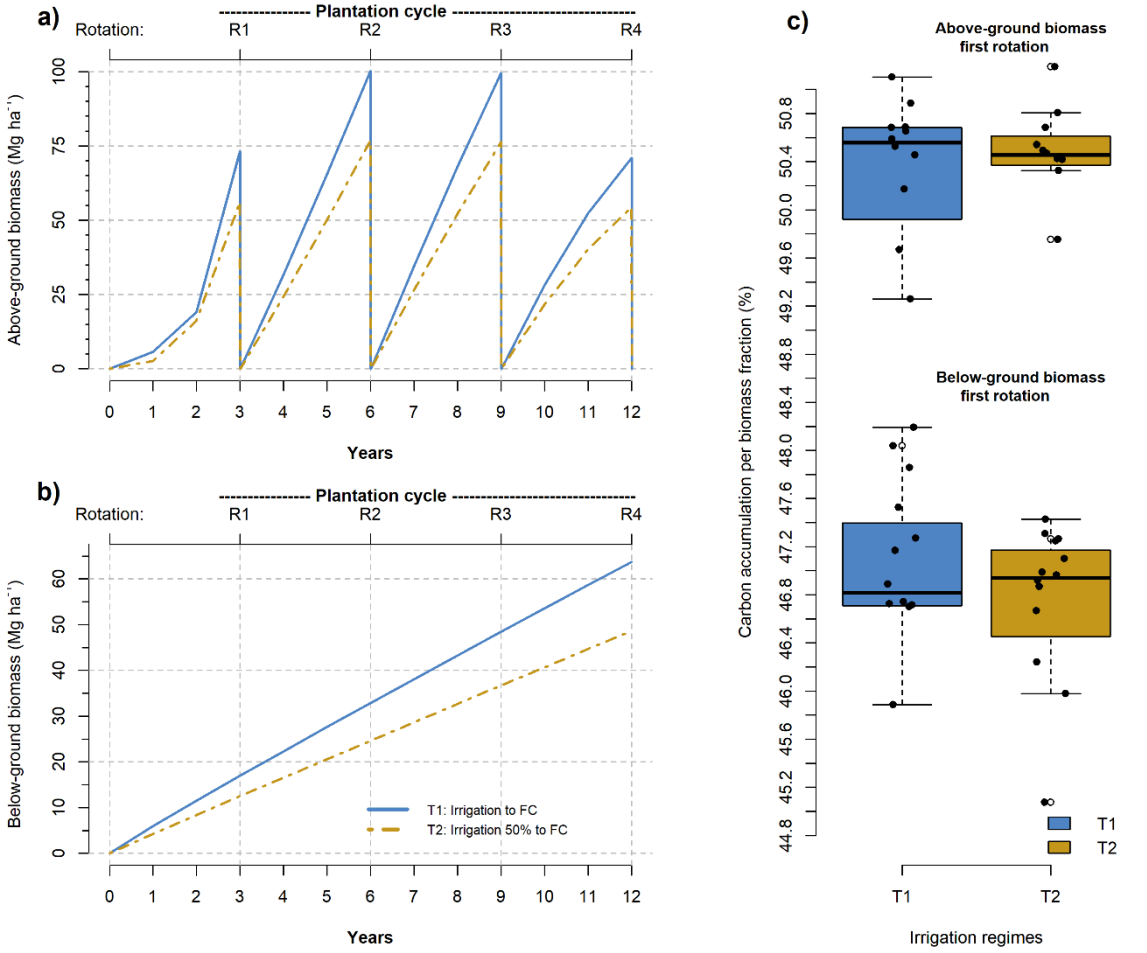


Figure 5.2. Development of above-ground biomass yield (a) and accumulated below-ground biomass (b) over one plantation cycle (12 years) of hybrid poplar ´AF2´ with 4 rotations (R1-R4) for two irrigation regimes T1 and T2. Biomass is measured for R1 and modelled for R2, R3 and R4 based on allometric growth functions. Boxplots show the total carbon accumulation per biomass fraction (c) at the end of R1 for T1 and T2 with monthly observed values (black dots). T1 is irrigated to field capacity (FC) and T2 is irrigated to 50 % FC. Biomass values are dry biomass yield in oven-dry tonnes (odt) per ha.

5.3.3. Above and below-ground carbon stocks

5.3.3.1. Fractions of C concentrations (%) in above and below-ground biomass

The concentrations of C (%) in the above-ground biomass fraction scarcely varied over the whole first rotation cycle, ranging from 48 to 51 % for regime T1 and from 47 to 51 % for regime T2 (Figure 5.2, c). In the below-ground biomass fraction, C concentration was slightly lower than in the above-ground biomass, ranging from 43 to 48 % for regime T1 and from 45 to 47 % for regime T2 (Figure 5.2, c). The below-ground concentration

of C is consistent with other studies (Fang et al., 2007; Oliveira et al., 2018). In Oliveira et al, the root concentration of C varied from 45.95 to 46.30 % for three different poplar genotypes ('AF2', 'I-214' and 'Monviso') growing under similar Mediterranean conditions. The average C (%) at harvest time was 51 % in the above-ground biomass and 47 % for the below-ground biomass for both T1 and T2. These percentages were then used for further economic analyses of potential C payments.

5.3.3.2. C sequestration potential in above and below-ground biomass

The optimum irrigation regime (T1), shows an above-ground C content from 35.9 to 50.7 Mg C ha^{-1} depending on the productivity of the different rotations, making a total above-ground C content potential at the end of the plantation cycle of 174.0 Mg C ha^{-1}. The reduced irrigation regime (T2) resulted in a 23 % reduction in above-ground C content.

With the development of the root system over the lifespan of the poplar plantation, the below-ground C content increased from 7.9 to 29.8 Mg C ha^{-1} for T1. This increase was 26 % lower for T2.

Table 5.3

Below and above-ground C content for 4 rotations of 3 years in two different Irrigation regimes T1 (optimum) and T2 (50% reduced irrigation). Plantation cycle of the SRC: 12 years.

Rotation	T1			T2		
	Below-ground carbon (Mg C ha^{-1})	Above-ground carbon (Mg C ha^{-1})	Whole tree (Mg C ha^{-1} yr^{-1})	Below-ground carbon (Mg C ha^{-1})	Above-ground carbon (Mg C ha^{-1})	Whole tree (Mg C ha^{-1} yr^{-1})
1st	7.94	37.02	14.98	5.84	28.42	11.42
2nd	15.39	50.72	19.46	11.53	38.93	14.89
3rd	22.67	50.35	19.29	17.17	38.65	15.74
4th	29.84	35.91	14.45	22.77	27.56	11.08

The average yearly below-ground C content was 2.5 and 1.9 Mg C ha^{-1} yr^{-1} for T1 and T2. These values were higher than those reported in the literature: 0.85-1.5 Mg C ha^{-1} yr^{-1} (Fang et al., 2007) for 4-year rotation length and lower density plantations (500-1,111 trees ha^{-1}). Under Mediterranean conditions, with same plant density and the same rotation length as in this study, although with lower above and below-ground

productivity, average yearly below-ground C content ranged from 0.89–0.91 Mg C ha^{-1} yr^{-1} (Oliveira et al., 2018). These differences may be due to the high yields found in our site conditions, even under water restrictions.

Accounting for the entire above- and below-ground woody biomass, the average C content potential for the whole plantation cycle found in this study was 17.0 and 13.3 Mg C ha^{-1} yr^{-1} for the different irrigation regimes T1 and T2, respectively. In addition, if leaf biomass is taken into account, C content increases by 2.2 and 1.4 Mg C ha^{-1} yr^{-1} for T1 and T2, respectively (Fuertes et al., 2022). In any case, where only the woody biomass is considered, the average absorption of $CO_{2equivalent(eq)}$ per tree was 0.0063 Mg CO_{2eq} per year in T1 and 0.0049 in T2.

Poplar plantations with a rotation length of less than 8 years are not included in the C payment projects in Spain (MITERD, 2019). Currently, the Spanish Environmental Ministry calculates the CO_{2eq} absorption rate for a plantation based on the species and rotation length, with 30 years being the minimum time period of the project. This time period includes all cuttings per rotation. The landowners must therefore replant the poplar plantation after each cycle to ensure the minimum total time period is met. The estimation of the total plantation absorption (CO_{2eq} ha^{-1}) at the end of the entire time period will be calculated from the estimated average absorption in each rotation (MITERD, 2019).

In the case of poplar SRC plantations, due to their capacity for rapid growth over a short period of time, the absorption of CO_{2eq} per tree, even in year 3, already plays an active role in C sequestration, the amount sequestered being on average 190 and 146 CO_{2eq} ha^{-1} per rotation (3 years) for the different irrigation regimes T1 and T2, respectively. According to figures from the Spanish Ministry for the Environment (2019), CO_{2eq} absorption values per tree are similar to those of poplar plantations aimed at veneer production, which are normally managed with a rotation length of 13 years and a density of 400 trees ha^{-1} (Garnica et al., 2018), reaching 44 CO_{2eq} ha^{-1} per rotation. Today, these latter, traditional plantation systems produce both traditional roundwood up to a diameter of 8 cm (82.9 %) as well as chip biomass from the tops and branches (17.1 %) in the same supply system (Laina et al., 2022).

In the context of climate change, poplar SRC systems can play an important role in absorbing CO_2 and reducing pressure on natural forests. As a result of the increased demands for lignocellulosic-based bioproducts, the C absorbed by these plantations is stored for even longer in the bioproducts derived from them, increasing still further the potential of poplar SRC plantations to mitigate climate change. Therefore, these plantations should play a more prominent role in strategies and projects aimed at C sequestration.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.3.4. Economic evaluation of revenues from biomass (BAU) and additional revenues from potential carbon payments (BAU+C)

We calculated the NPV from the accumulated discounted cash flow for the full plantation cycle (i = 5 %). In the business-as-usual scenario with optimal irrigation (T1), the NPV was 6,461 € ha^{-1}. The productivity loss of 23 % due to irrigation reduction decreased the NPV by half (Figure 5.3 and Table 5.4).

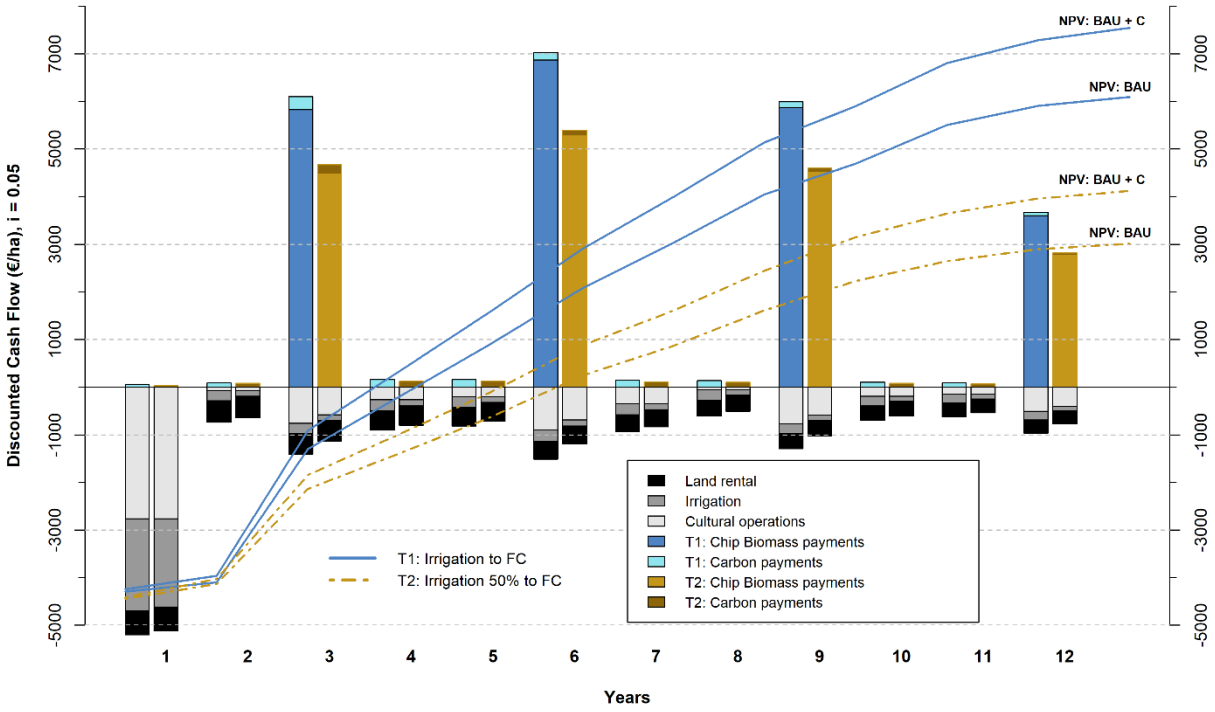


Figure 5.3. Accumulated discounted cash flow for the full poplar plantation cycle of 12 years with revenues from biomass payments (Business-as-usual -BAU) and from additional payments for carbon sequestration (BAU + Carbon) for two irrigation regimes T1 (Irrigated to field capacity) and T2 (Irrigated to 50% field capacity). The applied interest rate (i) was 5 %. The considered establishment costs were for land rental, irrigation, and cultural operations.

When an additional payment of 10 € Mg^{-1} C for carbon sequestration (BAU+C) was assumed, the NPV value increased to 8,024€ ha^{-1} and to 4,330€ ha^{-1} for regime T1 and T2, respectively. The effect of including the payment for carbon sequestration diversifies the plantation incomes, introducing an annual payment which contributes to recovering the investment one year earlier in both irrigation regimes (T1 and T2), thus making poplar plantations economically more attractive.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

We used the LEV to analyse the effect of irrigation and C payments on the optimum economical rotation length. The optimum LEV value between the studied scenarios, BAU and BAU+C, was not affected as a consequence of introducing a carbon payment of 10 € Mg^{-1} C. However, regime T1 achieved an optimum LEV one year earlier (year 10) than the reduced irrigation regime T2, the optimum LEV being 14,803 and 18,376 € ha^{-1} for the BAU and BAU+C scenarios, respectively, Figure 5.4.

In the reduced irrigation regime T2, the optimum LEV was reached in year 11 with 7,112 and 9,819 € ha^{-1} for the BAU and BAU+C scenarios, respectively. This was 48 % lower in the former scenario and 53 % lower in the latter compared to our optimum regime T1. The experimental irrigation restriction therefore not only had a negative impact on productivity, but also a notable impact on the profitability of our poplar plantation. Moreover, the decrease in carbon fixation had an additional negative impact on the climate change mitigation potential of the plantation.

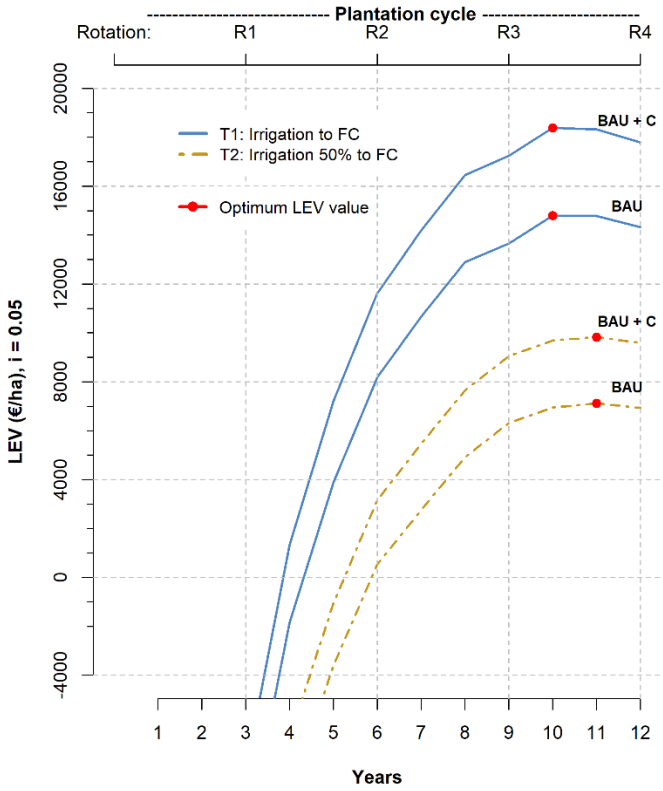


Figure 5.4. Effect of irrigation and C payments on the land expectation value (LEV) and the economically optimum rotation length for two irrigation regimes: T1 (Irrigated to field capacity) and T2 (Irrigated to 50% field capacity) in two scenarios: a) Business-as-usual (BAU) and BAU plus additional payments for carbon sequestration (BAU + C). The interest rate (i) applied was 5 %. The establishment costs considered included land rental, irrigation, and cultural operations. Negative values below -4000 € are not displayed for greater clarity.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 5.4

NPV and LEV from the accumulated discounted cash flow for the full plantation cycle of 12 years in two different scenarios (BAU and BAU+C) considering irrigation regimes T1 (Irrigated to field capacity) and T2 (Irrigated to 50% field capacity).

	Irrigation regimes			
	T1		**T2**	
Scenario	NPV (€ ha^{-1})	LEV (€ ha^{-1})	NPV (€ ha^{-1})	LEV (€ ha^{-1})
BAU	6,460.89	14,319.73	3,132.54	6,942.87
BAU + C	8,023.57	17,783.21	4,330.09	9,597.07

BAU (Business as usual); BAU + C (BAU considering additional carbon payment)

5.3.5. Economic and environmental implications of the root-extraction practice

The below-ground biomass is an important fraction of the total biomass pool of the plantation, accounting for 19 % and 21 % of the total tree biomass at the end cycle for T1 and T2, respectively. Root extraction, despite the high costs, remains an attractive option for landowners to increase their revenue from the plantations and/or to clear their fields (Spinelli et al., 2005). However, roots are also an important source of carbon storage in the soil, which at the end of the plantation cycle in our study amounted to 29.9 Mg C ha^{-1} and 22.8 Mg C ha^{-1} for T1 and T2 respectively.

We compared the economic impact of two root management procedures at the end of the plantation cycle under the BAU scenario, both of which end with cleared fields. One technique is that of root extraction, where the roots are removed with an excavator and the biomass is sold. Under another technique, that of grinding, the roots are ground, but are incorporated into the soil and thus remain in the field. There is an important difference between the two techniques in terms of climate change mitigation, since the C content of the roots in the latter case, (grinding) is incorporated into the soil. The costs of the root extraction were 1,704 € ha^{-1} for T1 and 1,025 € ha^{-1} for T2. The additional revenue from extraction and sale of the root biomass increased the NPV by 4.96 % for T1 and 6.92 % for T2 compared with the grinding method. We used the market price of 88 € t^{-1} (odt), as for the above-ground biomass, although the lower biomass quality would probably mean the price would be slightly lower.

By assuming a payment for C within the framework of climate change mitigation, sustainable management of the plantation is a prerequisite, which precludes the root

extraction practice given the present fragility of soil ecosystems (Bellassen et al., 2022). We consider that the SRC plantation system should not receive any additional payments for C sequestration when the root extraction practice is applied, but that the practice of incorporating the ground roots into the soil should be economically incentivized. However, recent legislation in Spain, within the Common Agricultural Policy, entitles the onwers of woody crops to receive a subsidy when pruning residues are crushed and left on the ground as mulch to promote more sustainable soil management practices. To our knowledge, this legislation does not explicitly prohibit extraction and sale of the root biomass in SRC plantations (Ministerio de Agricultura, 2022). We suggest that this policy should be extended to SRC plantations to promote the practice of stump grinding at the end of the rotation cycle. Based on this assumption, if we compare the BAU+C scenario with the BAU, introducing payment for the root biomass, the root extraction practice is no longer competitive. This finding is supported by the results of our study when additional C payments were included (BAU+C): The LEV or NPV of the BAU scenario fall below the BAU+C scenario. The break-even point at which the practice of root extraction would cease was a minimum C price of 2 and 1.7 € Mg C ha^{-1} for T1 and T2, respectively.

A recent Forest Research report by the European Climate Foundation on the Carbon Impacts of Biomass highlighted the positive impact of forest bioenergy initiatives where these are explicitly associated with afforestation activities, while supplies of forest bioenergy from stumps, including roots, are strongly disfavoured (Matthews et al., 2018). This is supported by the recent European Green Deal proposal, aimed at promoting sustainable carbon farming solutions which contribute to carbon storage in soils (Commission, 2022). A payment scheme within a national policy framework to sequester C should thus preclude the root extraction practice given the fragility of the soil ecosystems and their important role in climate change mitigation (Bellassen et al., 2022).

In short, we have shown that poplar SRC plantations have a high C sequestration rate and the potential to further improve their C stocks in the soils through the slow decomposition of remaining stumps and roots while at the same time providing long-term sources of nutrients for the plantation (Alam et al., 2013). A recent study of a poplar SRC plantations in Slovakia revealed that the potential soil organic carbon (SOC) increased on average by 29% during the 20 years of the plantation cycle, considering 5 rotations (Fürtner et al., 2022), highlighting the importance of taking the environmental benefits of the plantation into account. A carbon certification scheme can thus contribute to improving the climate change mitigation potential and help us move towards a low carbon bioeconomy by including economic incentives for the incorporation of woody biomass from roots and stumps into soils.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5.3.6. Addressing uncertainty in our socio-economic framework through sensitivity analyses

Most landowners willing to invest in poplar SRC plantations are accustomed to making decisions under conditions of considerable uncertainty. We therefore aimed to provide a practical approach to address this uncertainty, helping decision-makers to determine possible economic returns on their investment.

We combined different discount rates (from 1 to 13 %), chip biomass (from 80 to 140 € Mg^{-1}) - and carbon prices based on the productivity of the irrigation regimes T1 and T2 and their carbon sequestration potential (Figure 5.2 and Table 5.3). The estimated NPV value is presented in Figure 5.5. Two major sources of uncertainty under the BAU scenario are the income from chip-biomass and the discount rate applied. Additional payment for C sequestration can increase the NPV. We therefore analysed the increment levels to be added to BAU based on three carbon prices (10, 20 and 30 € Mg^{-1}) for the same range of discount rates.

The red dots in Figure 5.5 show the studied regimes (T1 and T2), providing a sense of the wide variation in NPV as regards market prices and the final discount rate applied in the project.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

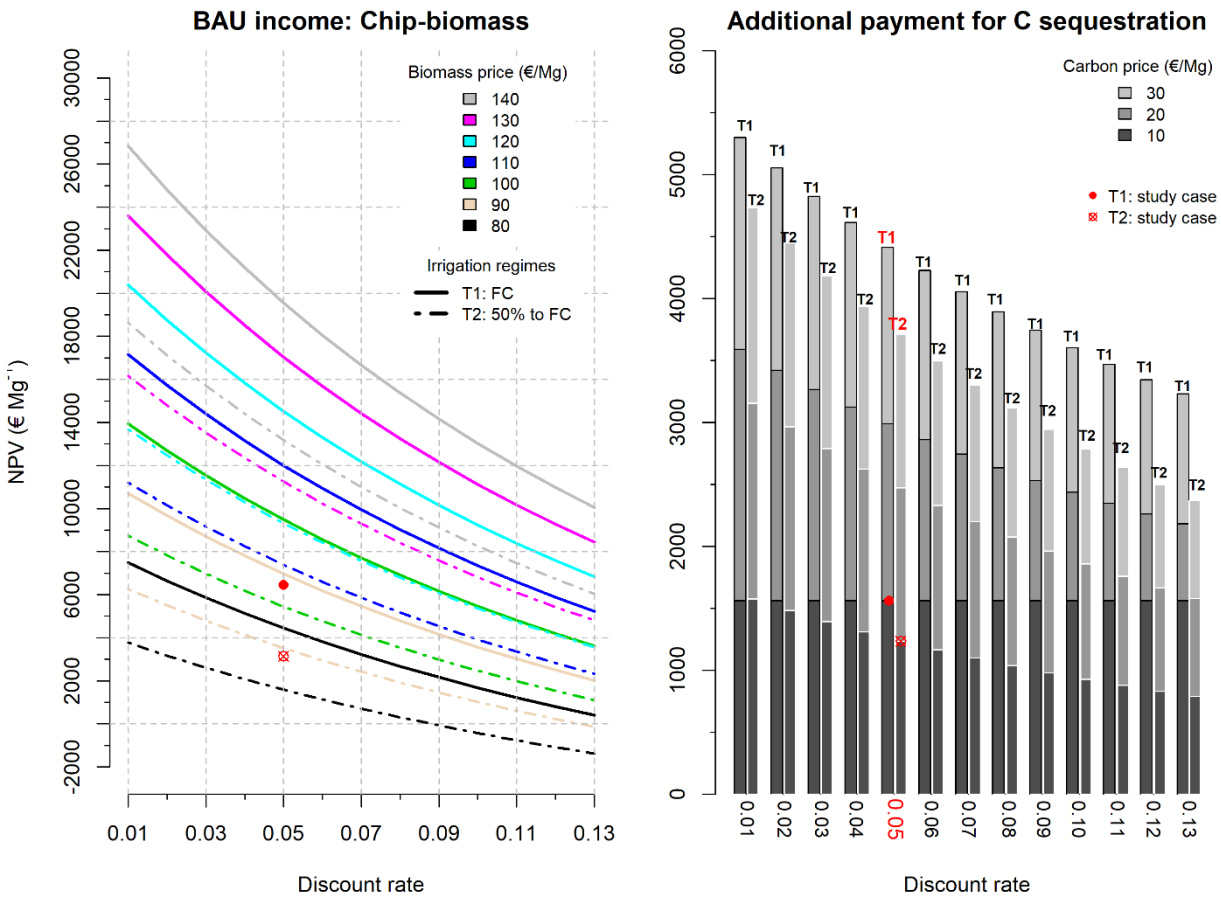


Figure 5.5. Addressing uncertainty linked to discount rates, biomass and carbon market prices in two different irrigation regimes T1 (Irrigated to FC) and T2 (Irrigated to 50% FC). FC: field capacity and considering two scenarios: BAU (Business-as-usual) and BAU + Carbon (Business-as-usual considering the Carbon payment for ecosystem services). The red dots show our case study: T1 (solid circle) and T2 (crossed circle). The establishment costs considered included land rental, irrigation, and cultural operations.

According to the assumptions our study and the observed productivity under the two water regimes applied (T1 and T2), the break-even point was reached in the BAU scenario when the chip biomass price exceeded 62.36 € Mg^{-1} (odt) for T1 and 71.08 € Mg^{-1} (odt) for T2, respectively. When accounting the additional payment for C sequestration of 10 € Mg^{-1} C (BAU+C), the break-even point was lower: 56.57 € Mg^{-1} (odt) for T1 and 65.61 € Mg^{-1} (odt) for T2, respectively. There is only one scenario in which profitability falls into negative figures, which is when irrigation is restricted (T2), with a very low biomass price (80 €), when no additional C payments are included and when the discount rate reaches 0.09 % (Figure 5.5), highlighting the profitability of poplar SRC plantations even under the worst-case scenario proposed.

Chip biomass is generally the only source of income while additional payments for C sequestration are usually not taken into account for poplar SRC systems. If the latter were to be implemented, total income would increase and poplar plantations would become more attractive to investors.

Figure 5.5 enables the NPV value to be calculated for a 12-year plantation cycle under Mediterranean conditions with different irrigation regimes, and thus facilitate decision-making based on the benefits that can be obtained depending on the demands of the market.

5.3.7. Analysis of the climate mitigation potential of alternative biomass uses

Wood-based products can contribute to climate change mitigation by prolonging the storage of carbon in the anthroposphere (Aryapratama and Pauliuk, 2022).

The impact of carbon flow on net emissions according to the different studied tests (BAU, 50% BP-Recycling and 50% BP-Incineration) and for both irrigation regimes (T1 and T2) is shown in Figure 5.6.

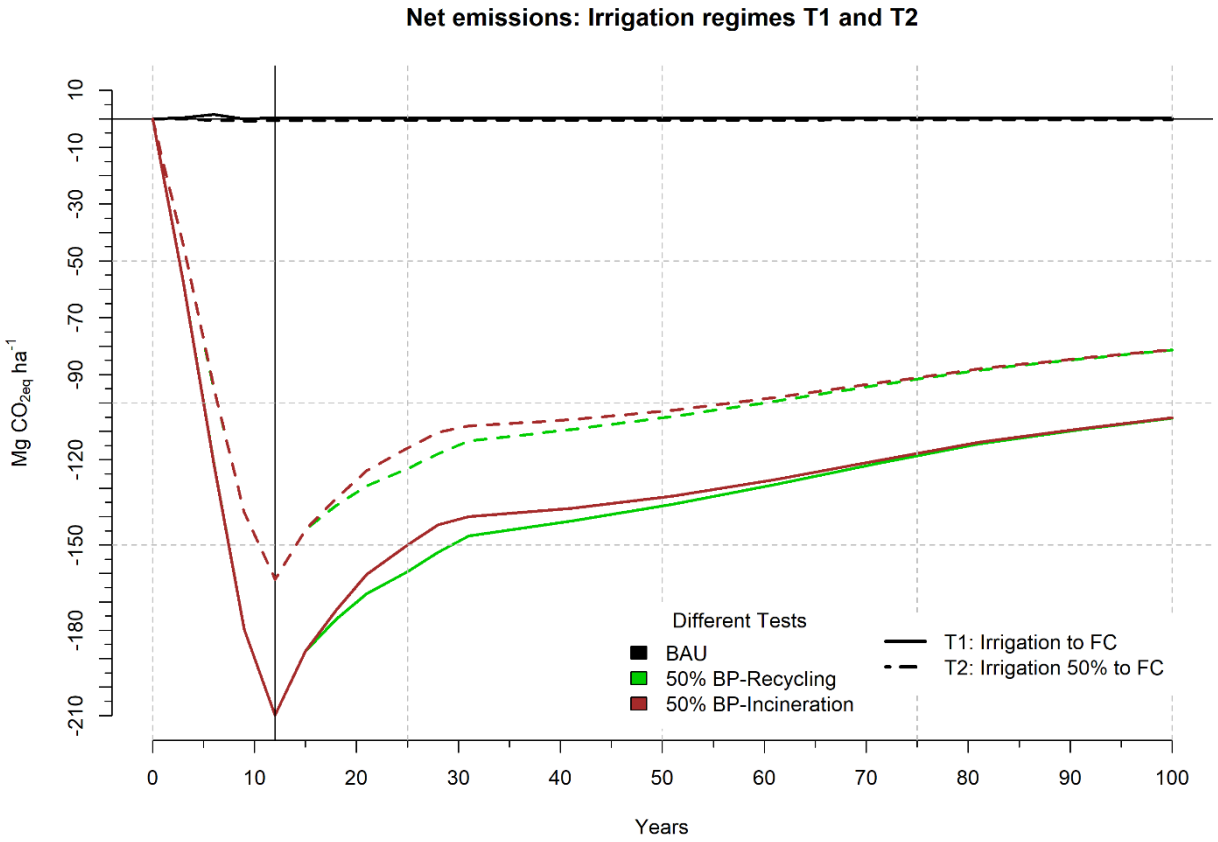


Figure 5.6. Net carbon balance over a 100-year timeframe considering above-ground biomass of a poplar plantation cycle of 12 years per irrigation regime, T1 (Irrigated to FC) and T2 (Irrigated to 50% FC) including three tests: BAU (business-as-usual, 100% lignocellulosic biomass as bioenergy); 50% BP-Recycling, (50% lignocellulosic biomass as bioenergy 50% bioproduct with EoL recycling) and 50% BP-incineration (50% lignocellulosic biomass as bioenergy 50% bioproduct with EoL incineration. FC: field capacity. EoL: end-of-life. Vertical black line shows the end of the plantation cycle.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Both BAU tests in the different irrigation regimes display a close-to-zero net emission balance. With 50% of the biomass being used for bioproducts, the initial emissions dropped dramatically, reaching the minimum peak in year 12 with -209.91 and –162.15 Mg CO_{2eq} ha^{-1} for T1 and T2, respectively. Plantation growth during these years contributed to this decline due to the high poplar plantation sequestration rates.

The bioproducts, therefore, play a crucial role in storing the C contained in biomass, which is not immediately released into the atmosphere. Emission were reduced between -114 Mg CO_{2eq} ha^{-1} (T1) and -88 Mg CO_{2eq} ha^{-1} (T2) compared to BAU until end of the century for the both end of life studied (50% BP-Recycling and 50% BP-incineration). A slight increase in emissions occurs after the plantation cycle in year 12 since there are no regrowth effects. This increase is particularly notable in the scenario where the final destination is incineration, highlighting the significance of recycling, despite the relatively small amount of kg PEF considered in this study.

A recent publication by Adler et al. (2022) addresses lignin-first biorefining of poplar plantations to produce textile fibers, with 100% of the harvested biomass being used to produce this bioproduct. This study highlights a new value chain to reduce the environmental footprint of textiles, chemicals, and biofuels. Other studies have emphasized the importance of plantations as feedstocks of lignocellulosic biomass to produce bioproducts providing benefits in terms of climate mitigation, ecosystem enhancement, and wider bioeconomy initiatives (Bishop et al., 2022; Pires et al., 2019; Reshmy et al., 2021; Shrestha et al., 2021).

Global net emissions ought to be reduced at an annual rate of around 7% between 2020 and 2030 to be able to limit global warming to 1.5° (Christensen and Olhoff, 2019). Wood-based products can contribute to climate change mitigation by prolonging the storage of carbon in the anthroposphere (Aryapratama and Pauliuk, 2022). Besides C storage, the replacement of fossil-fuel based products with bioproducts will increase the global warming mitigation potential, was although this aspect was not considered in this study.

5.4. CONCLUSIONS

The above and below-ground C stocks of a standard poplar SRC system under Mediterranean conditions and 12-year plantation length (4 rotations of 3 years each) play an active role in mitigating global warming from the third year of cultivation, both under optimal (17.04 Mg C ha^{-1} yr^{-1}) and restrictive irrigation (13.28 Mg C ha^{-1} yr^{-1}) regimes. This is due to the rapid growth rates achieved in a short period of time. Poplar SRC systems also have a positive impact on soils due to the high amount of C

accumulated in the below-ground fraction (63.75 Mg ha^{-1} and 48.64 Mg ha^{-1} for T1 and T2 respectively), contributing to increased soil C content at the end of the plantation cycle under an appropriate management regime.

The profitability of these plantations is affected by the introduction of an extra payment for C sequestration, thus diversifying the income from the plantation, allowing the initial investment to be recovered one year earlier in both irrigation regimes (T1 and T2), thus making poplar plantations more attractive to investors. The experimental water (irrigation) restriction not only had a negative impact on productivity, which, from the perspective of climate change mitigation, means less C sequestered, but also a notable impact on the profitability of our poplar plantation. However, these planting systems were still found to be profitable under this scheme.

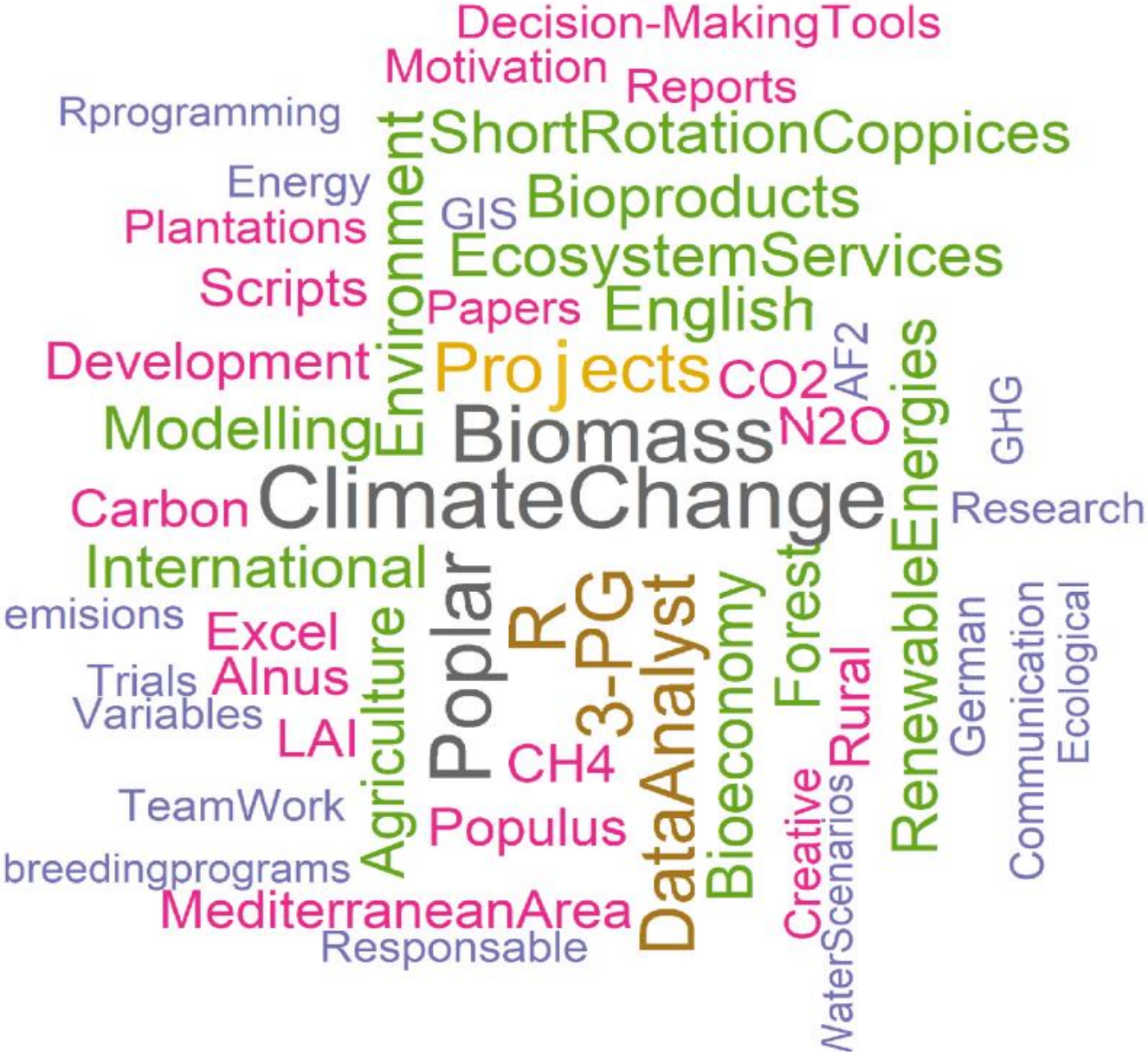
Wood-based products contribute to climate change mitigation by prolonging C storage in the anthroposphere. This alternative end-use of lignocellulosic biomass-based bioproducts makes SRC poplar plantations an even more attractive proposition as part of the development of the bioeconomy, adding greater value to these plantations and providing longer C storage capacity.

This study provides concrete evidence, in environmental and socioeconomic terms, of the need to further our knowledge of the multifaceted benefits of poplar SRC systems, even under conditions of water restriction in the context of climate change. It is therefore crucial to address the existing economic and ecological uncertainties and increase awareness of the potential of poplar SRC systems to contribute to a low-carbon

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA


Decision-MakingTools
Motivation
Reports
Rprogramming
ShortRotationCoppices
Energy
Bioproducts
GIS
Plantations
EcosystemServices
Scripts
Papers
English
Development
Projects
CO2
AF2
Modelling
Environment
Biomass
N2O
RenewableEnergies
GHG
Carbon
ClimateChange
Research
International
Poplar
R
3-PG
DataAnalyst
Bioeconomy
Forest
emisions
Excel
Agriculture
German
Communication
Ecological
Trials
Alnus
Rural
Variables
LAI
CH4
TeamWork
Populus
Creative
breedingprograms
MediterraneanArea
Responsable
WaterScenarios

Chapter 6

General Discussion

"We cannot solve our problems with the same
thinking we used when we created them."

Albert Einstein

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

GENERAL DISCUSSION

This thesis aims to contribute to the broader goal of transitioning towards a more environmentally friendly and sustainable economic model. In order to accomplish this, the use of woody biomass from poplar SRC systems growing under Mediterranean conditions is analysed as a source of energy and/or bioproducts. Improved climate-sensitive biomass prediction tools are proposed in Chapter 3, while economic analyses specific to these plantations are conducted in Chapters 4 and 5, quantifying their carbon sequestration potential in Chapter 4, which highlights the climate mitigation potential of well-managed poplar plantations under Mediterranean conditions.

6.1. IMPROVED BIOMASS PREDICTIONS

The results presented in Chapters 2 and 3 may help to significantly improve our understanding of tree allometry and growth, specifically in poplar SRC systems, taking into account the effects of limited water availability on changes in allometry and physiology in the context of climate change. The productivity of these plantations under Mediterranean conditions is, however, challenged under possible restrictive irrigation scenarios. This applies not only to regions susceptible to summer drought, such as Mediterranean environments, but also to other areas where reduced water availability is anticipated in the foreseeable future. Hence, it is necessary to deepen our understanding of the behaviour of each fraction of the plant and the role they play in the growth of the tree. Specifically, the foliage fraction holds significant importance as it constitutes the primary interface between the trees and their atmospheric environment, thus playing a key role in ecophysiological relationships (Landsberg and Sands, 2011).

In this regard, a comprehensive analysis was conducted (Chapter 2) to examine the monthly changes, over the growing seasons of a complete rotation (3 years), in important leaf-level variables, such as the number and distribution of leaves, foliar biomass, LAI, SLA, leaf macronutrients (NPK and C), and foliar gas exchange parameters. All these variables hold significant importance in numerous ecophysiological models, including the 3-PG model adapted and parameterized in this thesis (Fuertes et al., 2022), which calculates growth based on intercepted radiation, the relationship between leaf area and foliage mass being of central importance (Feikema et al., 2010).

USC DE SANTIAGO DE COMPOSTELA

The results presented in this thesis (Chapter 2) indicate a significant decrease in the number of leaves under the water-restrictive scenario compared to the optimal

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

scenario. However, there was a greater production of branches under water-restricted conditions, with 47% more branches observed in the first year under T2 compared to T1. This increase in branch production, all of which were sileptic in the first year, may have contributed to the successful establishment of the water-restricted plantation. Several authors have highlighted the impact of water availability on poplar foliage production, considering it to be a crucial factor (Anjum et al., 2011; Gao et al., 2017; Gaudillere, 1989; Taiz and Zeiger, 1991). Leaf modifications, such as smaller leaves, were considered adaptive responses under conditions of water stress. Similar observations have been reported by other authors, who point to Mediterranean genotypes of *Populus* developing smaller leaves as an adaptation to drought as well as reduction in leaf biomass production (Cocozza et al., 2010; Viger et al., 2016).

In particular, LAI plays a vital role in the biochemical cycles of ecosystems (Bréda, 2003) and has an important influence on the exchange of energy, gas and water in trees (Johansson and Karačić, 2011). Chapter 2 provides valuable insights into the development of LAI, both under optimal conditions and under water restrictive scenarios, emphasizing the importance of understanding the response of these plantations under current climate change conditions where water availability may decrease, thereby affecting biomass production. Some authors (Barigah et al., 1994; Ceulemans et al., 1990; Verlinden et al., 2013) have suggested that LAI rather than individual leaf area could be a more reliable indicator of biomass productivity, although both leaf characteristics have frequently been found to be positively correlated with biomass production (Marron et al., 2005; Monclus et al., 2009, 2005; Rae et al., 2004). Moreover, SLA shares similar importance to that of LAI as a significant structural parameter in forest ecosystems (Johansson and Karačić, 2011) since it is positively related to net assimilation rate (Korner, 1991).

The individual leaf area in the first year was notably lower in the restricted scenario due to the increased presence of branch leaves. Although no significant differences in the yearly mean leaf area were detected between the two scenarios, these differences were evident in the overall calculation. Furthermore, there was a decrease in the individual leaf area and weight in all years of the study as a result of water stress.

The accuracy of the 3-PG output prediction relies heavily on parameters related to SLA (Esprey et al., 2004; Nouvellon et al., 2010; Pérez-Cruzado et al., 2011). However, detailed information on SLA, specifically tailored to poplar plantations, requires specific parameters values to be obtained (σ_1, σ_0 and t_σ), this information still being limited. Therefore, this study addresses this gap by providing specific parameters for poplar SRC systems. By studying the response of poplar trees under both optimal and water-limited conditions and incorporating these newly determined parameters, we enhance our understanding of the growth patterns of poplar plantations.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

In this context, the adaptation and parameterization of the climate-sensitive, process-based 3-PG model have been undertaken (Chapter 3) 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. This adaptation involves considering the specific processes that are inherent to deciduous species. These processes include simulating annual leaf fall, capturing the litterfall rate as a function of the month, and accounting for monthly variations in LAI throughout the growing season rather than over the entire lifespan of the plantation. Additionally, the model should simulate leaf growth during spring and adapt variables related to allometric relationships and biomass fraction partitioning (foliage, stem, and roots). This adaptation will be based on observing the pattern of monthly variation in the NPP allocation parameters to the different biomass components (W_f, W_s, and W_r) over the first rotation (3 growing seasons) under Mediterranean conditions with optimum irrigation (T1) and 50% irrigation reduction (T2). Furthermore, the model should consider variations in mortality across the growing seasons.

The further development of the 3-PG model needs to build upon the recommendations of Sands and Landsberg (2002a), who suggested considering environmental effects on litterfall, such as water stress.

In relation to leaf fall, some authors applying the 3-PG model to deciduous trees considered null litterfall during the growing season, arguing that litterfall of deciduous tree species is negligible during that period (Nölte et al., 2020). This may be the case under other climatic conditions where growing seasons are shorter. However, under Mediterranean conditions the growing season generally lasts from late March to late November, with the months of active tree growth being from June to September. Low rates of litterfall were even observed in the mid growing season (June to September). Sands and Landsberg (2002b) recommended that monthly litterfall rates should ideally be site dependent, while other authors also highlight variations in litterfall depending on local conditions (Pérez-Cruzado et al., 2011). The results in Chapter 3 revealed seasonal variations in litterfall while no significant variations in response were observed between the irrigation regimes tested.

Furthermore, sensitivity analyses have been performed by other authors to better understand the 3-PG model parameters and identify those that require precise determination (Esprey et al., 2004; Pérez-Cruzado et al., 2011). These analyses revealed that parameters such as canopy quantum efficiency, maximum canopy conductance, LAI, litterfall or SLA of mature trees are highly sensitive. However, information regarding their temporal variability remains limited (Esprey et al., 2004; Nouvellon et al., 2010). Chapters 2 and 3 of this thesis contribute to improving biomass estimates by providing specific results, based on observed data, for a genotype with very high biomass production (AF2) and which belongs to the large group of Euramerican hybrids (*Populus*

× *canadensis* Mönch). Additionally, the thesis proposes an adaptation of the 3-PG model to suit the characteristics of these plantation systems. These advancements are crucial to unlock the full potential of the 3-PG model and improve its precision in accounting for the effects of limited water availability on allometry and physiology, particularly in the context of climate change.

This understanding provides a broad knowledge base on which to develop more accurate predictive management tools, aimed at promoting the establishment of poplar SRC systems, optimizing biomass production and meeting market demands in the transition to a low-carbon bioeconomy.

6.2. ECONOMIC VIABILITY

The results presented in Chapters 4 and 5, reveal the importance of conducting parallel economic analyses that take into account the multifunctionality of these plantations in Mediterranean regions, especially considering the frequent need for irrigation. This is essential to bridge the knowledge gap with regard to the economic viability of poplar SRC systems under Mediterranean conditions. By integrating the results presented in Chapters 2 and 3, which highlight the advancements in biomass prediction tools, with comprehensive economic analyses, this thesis presents robust assessment tools that will aid decision-makers to evaluate and make well-informed choices regarding the implementation of poplar SRC systems.

Realistic yield data is essential in order to evaluate the economic viability of SRC (Hauk et al., 2015). The need for accurate tools to estimate biomass in poplar SRC has been widely addressed (Brahim et al., 2000; Laureysens et al., 2003; Paris et al., 2011; Verlinden et al., 2013) and the importance of carrying out a real economic analysis has also been studied (Fuertes et al., 2021; Hauk et al., 2014).

In Chapter 4, a detailed economic analysis was conducted based on real data under Mediterranean conditions in which the use of irrigation systems is emphasized. The analysis delves into the main costs and divides them into three different categories (cultural operation, land rental and irrigation cost). The goal is to identify the cost factor that has the greatest impact on the profitability of poplar SRC systems. Among the identified cost factors, land rental emerges as the most significant, accounting for 31.88% of the total cost. The second greatest cost factor is that of water and electricity associated with irrigation, which represents 16.61% of the total cost. Lastly, cut-and-chip harvesting accounts for 11.87% of the total cost.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

If the top three costs are examined in more detail, it is evident that land costs are strongly dependent on the location of the SRC plantation, making direct comparisons challenging. Regarding cultural operation costs, these make up a lower percentage of the total than that observed in other studies (Manzone et al., 2014). Total irrigation costs identified in this study have a greater impact than those reported by other authors under similar conditions (Manzone et al., 2014). This discrepancy can be attributed to differences in the irrigation systems used. Many studies have shown that the cut-and-chip harvesting cost has an important impact on the economic feasibility of poplar plantations (Berhongaray et al., 2013; Vanbeveren et al., 2015), and have highlighted the fact that modern technology allows a notable reduction in harvesting cost (Spinelli and Magagnotti, 2011). Collectively, these three factors make up 60.36% of the project's total cost. This highlights the importance of achieving an optimal level of productivity to offset the investment in the plantation.

Alongside achieving optimal productivity, it is important to consider the multifunctionality of poplar SRC systems when evaluating plantation profitability. In this regard, it is of interest to quantify additional inputs, such as ecosystem services, which can contribute to improved returns on investment. One of the main ecosystem services of these plantations is greenhouse gas mitigation (Hillier et al., 2009; Smith, 2004; Walter et al., 2015), although other services include reductions in soil erosion, groundwater nitrate content and surface runoff (Langeveld et al., 2012). SRC also increase the diversity of the agricultural landscape and are a reservoir of different fauna (birds, arthropods, etc.) (Schulz et al., 2009). Additionally, SRC can be used in phytoremediation (Dimitriou et al., 2009). It is therefore necessary to develop systems to quantify ecosystem services and determine a value for them in accordance with market price. These new economic inputs would make poplar SRC investments viable under conditions of average productivity. Ecosystem services are expected to gain greater significance in the coming years, and there is promising potential to enhance the sustainability and profitability of these plantations. Moreover, given the current dynamic development of the bioproduct markets (Budzianowski, 2017), the combination of biomass as a raw material for bioenergy along with the supply of bioproducts could improve the economic and resource-use efficiency of biomass and provide additional revenue.

In Chapter 5, this thesis focuses on quantifying the biomass production of the entire tree, encompassing both above and below-ground biomass, and exploring the carbon sequestration potential of a poplar SRC plantation under regular and water-limited conditions. Additionally, it examines the economic implications associated with offering additional payments for C sequestration. Moreover, it addresses uncertainties related to biomass and C prices, as well as variations in discount rates, offering a practical approach that provides valuable insights for decision-makers to assess the potential economic returns on their investment in poplar SRC plantations. Furthermore, the

USC DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

chapter highlights alternative uses of biomass in long-lasting bioproducts, comparing their potential for climate mitigation with conventional short-lived bioenergy end-use.

The choice of discount rate is a crucial factor when evaluating the value of forests and plantations, as emphasized by various authors (Díaz-Balteiro, 1998; Leech, 2014). Selecting the appropriate discount rate is essential when comparing different scenarios and determining the optimal choice among the alternatives (Díaz-Balteiro, 1998). The choice of discount rate depends on the decision-makers (Díaz-Balteiro et al., 2014) and, as stated by Wagner (Wagner, 2012), there is no single rate which can be applied for all plantations.

Biomass prices are often a source of uncertainty for investors, as they are influenced by various factors such as local demand and supply, proximity to processing facilities, size of the supplier crops, and specific characteristics of the biomass for its intended use. In the case of poplar SRC systems, chip biomass is typically the primary source of income, with additional payments for carbon sequestration often not considered.

Although poplar SRC systems have demonstrated high productivity within a short timeframe, even on marginal agricultural sites (Schweier et al., 2017) , irrigation is crucial to achieve optimal productivity and ensure the survival of trees under Mediterranean conditions as well as in other regions (Padrón and Orensanz García, 1987; Schweier and Becker, 2013; Yan et al., 2016).

The 50% water irrigation restriction applied in the study resulted in a 23 % reduction in above-ground biomass and 22% reduction in below-ground biomass at the end of the lifecycle of the poplar plantation (12 years). This is in line with findings from other studies that have observed reduced productivity in response to water scarcity during the growing seasons (Cañete-Salinas et al., 2019; L. Dimitriou et al., 2009; González-González et al., 2017). Even under the restrictive irrigation regime applied, the rapid growth of trees allows for substantial CO_{2eq} absorption, with an average sequestration rate of 190 and 146 CO_{2eq} ha^{-1} per rotation (3 years) for the different irrigation regimes (T1 and T2, respectively), starting as early as year 3. The effect of including the payment for carbon sequestration diversifies the income from the plantation, leading to earlier investment recovery under both irrigation regimes (T1 and T2), thus making poplar plantations more economically attractive.

In relation to C sequestration potential, the results of this thesis show that poplar SRC plantations not only have a high C sequestration rate but also the potential to further increase soil C stocks through the slow decomposition of remaining stumps and roots while at the same time providing long-term sources of nutrients for the plantation (Alam et al., 2013). A recent study of a poplar SRC plantation in Slovakia revealed that the potential soil organic carbon (SOC) increased on average by 29% during the 20 years of the plantation cycle (considering 5 rotations) (Fürtner et al., 2022), highlighting the

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

importance of taking the environmental benefits of the plantation into account. A carbon certification scheme can thus contribute to improving the climate change mitigation potential and help us move towards a low-carbon bioeconomy by including economic incentives for the incorporation of woody biomass from roots and stumps into soils.

Given the context of climate change, poplar SRC systems have a significant role to play in carbon sequestration, helping alleviate pressure on natural forests and reducing CO_2 levels. With the rising demand for lignocellulosic-based bioproducts, the C absorbed by these plantations remains stored for extended periods in the derived bioproducts. This further amplifies the climate change mitigation potential of poplar SRC plantations.

In summary, by recognizing the value of the ecosystem services provided by poplar SRC systems along with the medium to long-term C storage potential associated with carbon sequestration in below-ground biomass and above-ground biomass-derived bioproducts, these systems could form part of wider strategies to effectively address the challenges of climate change. Moreover, these SRC plantations would play a more prominent role in C sequestration initiatives and sustainability strategies.

6.3. FUTURE PERSPECTIVES

The European Commission has set ambitious goals for developing a competitive, resource-efficient, low-carbon economy by 2050 (EC, 2011). With targets of at least 55% reduction in net greenhouse gases by 2030 and achieving climate neutrality by 2050, it is acknowledged that the forest-based sector will play a significant role in contributing to these objectives. This acknowledgement highlights the positive expectations for the lignocellulosic market given its alignment with the goals of sustainability and climate change mitigation.

The transition towards a bioeconomy-based model involves challenges such as the sustainability of biomass raw material. In this context, other methods of irrigation should be considered, for example, the use of waste water from water treatment plants or industries, which implies the selection of suitable genetic material for these conditions (Pradana et al., 2023). Poplar plantations provide a clear opportunity to use alternative sources of irrigation water, since they have been proposed as an excellent nature-based alternative water treatment solution, given the high phytoremediation capabilities of the genus (Laureysens et al., 2004; Pilipović et al., 2020).

USC DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

By taking advantage of this low cost, nature-based solution, these plantations could play a major role in refilling aquifers with clean water, presenting a sustainable approach to water management, which benefits both ecosystems and communities. Additionally, in the context of water conservation strategies, identifying genotypes with greater hydric stress tolerance would allow the amount of irrigation required to be reduced.

As regards modelling, improving the 3-PG model to include adaptations simulating regrowth after harvesting by sprouting from stumps is of particular interest. This modification would allow the model to better represent the natural regeneration processes of the plantation. In addition, in the context of global warming, it would be of particular interest in poplar SRC biomass prediction to introduce a modification in the 3-PG model to improve leaf cycle processes by including changes in leaf unfolding and leaf senescence dates in relation to monthly average temperatures. This would allow the phenological changes resulting from ongoing climate change to be assessed and quantified. Other potential improvements include parameterizing the model for different genotypes.

In terms of economic viability, the multifunctionality of poplar plantations in Mediterranean regions continues to be an enigma across various sectors. These plantations hold great potential as a powerful mechanism for mitigating climate change, thanks to their ability to store carbon and improve soil quality by enhancing carbon stocks and overall structure. However, a suitable approach to quantify ecosystem services and in particular, quantify their economic impact, is still under development.

In future perspectives of the circular bioeconomy, one challenge lies in developing circular projects that leverage plantations as natural-based solutions for phytoremediation, carbon sequestration and minimal emissions, while also generating sustainable biomass for bioenergy or bioproducts. Thus, this productive biomass system has the dual benefits of meeting market demand for lignocellulosic biomass while providing additional environmental benefits

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



Chapter 7

Conclusions

"Picture a world where renewable energy flows like a river, where forests are our allies, and where carbon emissions are a thing of the past. This vision is not just a dream; it's our potential reality."

Christiana Figueres

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

CHAPTER 7: CONCLUSIONS

This section summarizes the main achievements of the doctoral research. The following conclusions highlight the most significant findings.

Regarding the improvement of predictive tools for biomass in deciduous plantations

1. The 3-PG output prediction is highly sensitive to SLA related parameters. Our results showed SLA follows a similar declining trend over the life span of the leaf in each year of the rotation. It varies markedly from young to mature leaves, exhibiting high variability in the first months of the growing season, probably due to the strong morphological changes that occur at that stage.

2. Small rates of litterfall were even observed in the mid growing season (June to September). Therefore, it is important to consider monthly litterfall rates for poplar leaves, as non-zero litterfall rates were found as soon as late August and lasted until early December. These results are useful to provide realistic predictions of leaf litterfall and nutrient contributions to soil via senescent leaves.

3. No significant differences in SLA and litterfall rates were found between water scenarios, optimal and restrictive (T1 and T2), over the three years of the rotation, so the resulting parameters could be applied to both irrigation scenarios.

4. The monthly oscillations of A and g_s often ran in parallel in both two water scenarios (T1 and T2), with values consistently lower in the restricted water scenario. Gas exchange results show that the selected genotype 'AF2' has tight stomatal control under conditions of water stress, maintaining high photosynthetic levels. This genotype adopts strategies which mitigate losses in production under climate change scenarios, making it a promising candidate not only for modelling biomass production but also for breeding programs.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5. Under restrictive water conditions, IWUE was always significantly higher than under optimal irrigation in all years of the rotation, indicating the genotype's adaptability to prolonged water restrictions. The values obtained in relation to IWUE were indicative of the capacity of the leaf to regulate photosynthesis and stomatal conductance, making the genotype well-suited for adaptation to enduring restrictive water conditions over time.

6. Throughout the three-year rotation, both NPK and PNUE showed strong seasonal variation with decreasing trends observed over the different growing seasons. Under the restrictive scenario (T2), NPK and PNUE decrease particularly, exhibiting a pattern of similar dynamics.

7. The adjustments to the NPP partitioning to the different biomass fractions, with changes along the growing season, effectively handle the changes in carbohydrate distribution by accounting for the annual leaf production characteristic of deciduous species.

8. The proposed parameterization, based on observed data, and adaptation of the 3-PG model structure demonstrated good agreement with the validation dataset, accurately predicting LAI, stem, root, and leaf biomass in the specific dynamics of this type of short-rotation and high-density poplar plantations.

Regarding to the economic analysis of the plantations considering their multifunctionality:

9. The critical cost factors of these plantations under Mediterranean conditions are land rental, water and electricity associated with irrigation and cut-and-chip harvesting. Among the identified costs, land rental is the most crucial factor affecting the profitability of the plantation, accounting for 31.88% of the total cost.

10. This study reveals that economic viability of poplar SRC will be achieved either by ensuring optimum productivity or through an increase in the market prices, associated with more diversified energy use and/or bioproducts, along with the quantification of ecosystem services, which currently do not have a market price.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

11. The above and below-ground C stocks of a standard poplar SRC system under Mediterranean conditions and 12-year plantation length (4 rotations of 3 years each) play an active role in mitigating global warming from the third year of cultivation, both under optimal and restrictive irrigation regimes. This is due to the rapid growth rates achieved in a short period of time.

12. Poplar SRC systems are likely to have a positive impact on soils, primarily attributed to the significant accumulation of C in the below-ground fraction. This accumulation could contribute to an increase in soil carbon content at the end of the plantation cycle, given an appropriate management regime that ensures the carbon in this fraction remains in the soil.

13. Profitability of poplar plantations is influenced by introducing an extra payment for C sequestration, diversifying income and recovering the initial investment a year earlier not only in current scenarios but also under water restriction. Despite the negative impact on productivity due to experimental water restriction, the planting systems remained profitable.

14. Wood-based products contribute to climate change mitigation by prolonging C storage in the anthroposphere. This alternative end-use of lignocellulosic biomass-based bioproducts makes SRC poplar plantations an even more attractive proposition as part of the development of the bioeconomy, adding greater value to these plantations and providing longer C storage capacity.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA



References

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

REFERENCES

Abbas, S.K., Baig, S., Hashmi, I., 2019. Carbon storage and allocation pattern in plant biomass under drought stress and nitrogen supply in *Eucalyptus camaldulensis* and *Populus deltoides*. Pakistan J. Bot. 51, 1605–1614. https://doi.org/10.30848/PJB2019-5(14)

Abràmoff, D., M., Magalhães, P.J., Ram., S.J., 2004. Image processing with ImageJ 11, 36–42.

Adler, A., Kumaniaev, I., Karacic, A., Baddigam, K.R., Hanes, R.J., Subbotina, E., Bartling, A.W., Huertas-Alonso, A.J., Moreno, A., Håkansson, H., Mathew, A.P., Beckham, G.T., Samec, J.S.M., 2022. Lignin-first biorefining of Nordic poplar to produce cellulose fibers could displace cotton production on agricultural lands. Joule 6, 1845–1858. https://doi.org/10.1016/j.joule.2022.06.021

Aerts, R., Chapin, F.S., 2000. The mineral nutrition of wild plants revisited: A re-evaluation of processes and patterns, in: Advances in Ecological Research. pp. 1–67. https://doi.org/10.1016/S0065-2504(08)60016-1

Agreement, P. "United nations," 2015. United nations, unaoc.org.

Al Afas, N., Marron, N., Zavalloni, C., Ceulemans, R., 2008. Growth and production of a short-rotation coppice culture of poplar-IV: Fine root characteristics of five poplar clones. Biomass and Bioenergy 32, 494–502. https://doi.org/10.1016/j.biombioe.2007.11.007

Al Afas, N., Pellis, A., Niinemets, Ü., Ceulemans, R., 2005. Growth and production of a short rotation coppice culture of poplar. II. Clonal and year-to-year differences in leaf and petiole characteristics and stand leaf area index. Biomass and Bioenergy 28, 536–547. https://doi.org/10.1016/j.biombioe.2004.11.010

Alam, A., Kellomäki, S., Kilpeläinen, A., Strandman, H., 2013. Effects of stump extraction on the carbon sequestration in Norway spruce forest ecosystems under varying thinning regimes with implications for fossil fuel substitution. GCB Bioenergy 5, 445–458. https://doi.org/10.1111/gcbb.12010

Alonso, D.M., Hakim, S.H., Zhou, S., Won, W., Hosseinaei, O., Tao, J., Garcia-Negron, V., Motagamwala, A.H., Mellmer, M.A., Huang, K., Houtman, C.J., Labbé, N., Harper, D.P., Maravelias, C.T., Runge, T., Dumesic, J.A., 2017. Increasing the revenue from lignocellulosic biomass: Maximizing feedstock utilization. Sci. Adv. 3. https://doi.org/10.1126/sciadv.1603301

Amichev, B.Y., Johnston, M., Van Rees, K.C.J., 2010. Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG). Biomass and Bioenergy 34, 687–702. https://doi.org/10.1016/j.biombioe.2010.01.012

Anderson, J.A., Luckert, M.K., 2007. Can hybrid poplar save industrial forestry in

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Canada: A financial analysis in Alberta and policy considerations. For. Chron. 83, 92–104. https://doi.org/10.5558/tfc83092-1

Anjum, S.A., Xie, X.Y., Wang, L.C., Saleem, M.F., Man, C., Lei, W., 2011. Morphological, physiological and biochemical responses of plants to drought stress. African J. Agric. Res. 6, 2026–2032. https://doi.org/10.5897/AJAR10.027

Aryapratama, R., Pauliuk, S., 2022. Life cycle carbon emissions of different land conversion and woody biomass utilization scenarios in Indonesia. Sci. Total Environ. 805, 150226. https://doi.org/10.1016/j.scitotenv.2021.150226

Aylott, M.J., 2010. Modelling Climate Change Impacts on the Productivity of Short Rotation Coppice. PhD Thesis Univ. Southampt.

Barigah, T.S., Saugier, B., Mousseau, M., Guittet, J., Ceulemans, R., 1994. Photosynthesis, leaf area and productivity of 5 poplar clones during their establishment year. Ann. des Sci. For. 51, 613–625. https://doi.org/10.1051/forest:19940607

Barrio-Anta, M., Sixto-Blanco, H., Viñas, I.C.R. De, Castedo-Dorado, F., 2008. Dynamic growth model for I-214 poplar plantations in the northern and central plateaux in Spain. For. Ecol. Manage. 255, 1167–1178. https://doi.org/10.1016/j.foreco.2007.10.022

Bastin, J.F., Finegold, Y., Garcia, C., Mollicone, D., Rezende, M., Routh, D., Zohner, C.M., Crowther, T.W., 2019. The global tree restoration potential. Science (80-.). 364, 76–79. https://doi.org/10.1126/science.aax0848

Bellassen, V., Angers, D., Kowalczewski, T., Olesen, A., 2022. Soil carbon is the blind spot of European national GHG inventories. Nat. Clim. Chang. 12, 324–331. https://doi.org/10.1038/s41558-022-01321-9

Benítez-Ponce, P., León-Sicard, T., Jiménez, S., 2018. Double counting in carbon offset projects: A taxonomy and typology of key issues. J. Clean. Prod. 172, 1675–1686.

Bergante, S., Facciotto, G., Minotta, G., 2010. Identification of the main site factors and management intensity affecting the establishment of Short-Rotation-Coppices (SRC) in Northern Italy through stepwise regression analysis. Cent. Eur. J. Biol. 5, 522–530. https://doi.org/10.2478/s11535-010-0028-y

Bergmann, W., 1992. Nutritional disorders of plants: development, visual and analytical diagnosis, Jena, G. F. ed.

Berhongaray, G., El Kasmioui, O., Ceulemans, R., 2013. Comparative analysis of harvesting machines onan operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. Biomass and Bioenergy 58, 333–342. https://doi.org/10.1016/j.biombioe.2013.07.003

Berhongaray, G., Verlinden, M.S., Broeckx, L.S., Janssens, I.A., Ceulemans, R., 2017. Soil carbon and belowground carbon balance of a short-rotation coppice: assessments from three different approaches. GCB Bioenergy 9, 299–313.

https://doi.org/10.1111/gcbb.12369

Berthelot, A., Ranger, J., Gelhaye, D., 2000. Nutrient uptake and immobilization in a short-rotation coppice stand of hybrid poplars in north-west France. For. Ecol. Manage. 128, 167–179. https://doi.org/10.1016/S0378-1127(99)00145-0

Bioplastics, E., 2017. Bioplastics - Furthering efficient waste management 1–4.

Bishop, G., Styles, D., Lens, P.N.L., 2022. Land-use change and valorisation of feedstock side-streams determine the climate mitigation potential of bioplastics. Resour. Conserv. Recycl. 180, 106185. https://doi.org/10.1016/j.resconrec.2022.106185

Blake, T., Tschaplinski, T.J., 1992. Water Relations, in: Ecophysiology of Short Rotation Forest Crops. Mitchell, pp. 66–94.

BOLETÍN OFICIAL DEL ESTADO, 2014. Real Decreto 163/2014, de 14 de marzo, por el que se crea el registro de huella de carbono, compensa-ción y proyectos de absorción de dióxido de carbono. Boletín Oficial del Estado Núm. 77.

Borelli, M., Facciotto, G., 1996. Profitability of off-farm poplar cultivation.

Bradshaw, H.., Ceulemans, R., John Davis, U., Stettler, R., 2000. Emerging model systems in plant biology: poplar (*Populus*) as a model forest tree. J. Plant Growth Regul. 19.3, 306–313.

Brahim, M. Ben, Gavaland, A., Cabanettes, A., 2000. Generalized Allometric Regression to Estimate Biomass of *Populus* in Short-rotation Coppice. Scand. J. For. Res. 15, 171–176. https://doi.org/10.1080/028275800750014975

Bréda, N.J.J., 2003. Ground-based measurements of leaf area index: A review of methods, instruments and current controversies. J. Exp. Bot. 54, 2403–2417. https://doi.org/10.1093/jxb/erg263

Broeckx, L.S., Vanbeveren, S.P.P., Verlinden, M.S., Ceulemans, R., 2015. First vs. second rotation of a poplar short rotation coppice: Leaf area development, light interception and radiation use efficiency. IForest 8, 565–573. https://doi.org/10.3832/ifor1457-008

Broeckx, L.S., Verlinden, M.S., Vangronsveld, J., Ceulemans, R., 2012. Importance of crown architecture for leaf area index of different *Populus* genotypes in a high-density plantation. Tree Physiol. 32, 1214–1226. https://doi.org/10.1093/treephys/tps083

Budzianowski, W.M., 2017. High-value low-volume bioproducts coupled to bioenergies with potential to enhance business development of sustainable biorefineries. Renew. Sustain. Energy Rev. 70, 793–804. https://doi.org/10.1016/j.rser.2016.11.260

Busch, G., 2017. A spatial explicit scenario method to support participative regional land-use decisions regarding economic and ecological options of short rotation coppice (SRC) for renewable energy production on arable land: case study

application for the Göttingen dist. Energy. Sustain. Soc. 7. https://doi.org/10.1186/s13705-017-0105-4

Bustamante, I., Dorado, M., Vera, S., Oliveros, C., 1998. Filtros verdes. Un sistema para la depuración y reutilización de aguas residuales. Tecnoambiente 79, 73–75.

Cañellas, I., Huelin, P., Hernández, M.J., Ciria, P., Calvo, R., Gea-Izquierdo, G., Sixto, H., 2012. The effect of density on short rotation Populus sp. plantations in the Mediterranean area. Biomass and Bioenergy 46, 645–652. https://doi.org/10.1016/j.biombioe.2012.06.032

Cañete-Salinas, P., Zamudio, F., Yáñez, M., Gyenge, J., Valdés, H., Espinosa, C., Jara-Rojas, F., Venegas, J., Retamal, L., Acevedo-Opazo, C., 2019. Responses in growth and physiological traits in two Populus × canadensis clones ('I-214' and 'I-488') submitted to different irrigation frequencies in central Chile. For. Ecol. Manage. 449, 117455. https://doi.org/10.1016/j.foreco.2019.117455

Casella, E., Ceulemans, R., 2002. Spatial distribution of leaf morphological and physiological characteristics in relation to local radiation regime within the canopies of 3-year-old Populus clones in coppice culture. Tree Physiol. 22, 1277–1288. https://doi.org/10.1093/treephys/22.18.1277

Ceulemans, R., 1990. Genetic variation in functional and structural productivity determinants in poplar. Amsterdam: Thesis Publishers.

Ceulemans, R., Isebrands, J.G., 1996. Carbon acquisition and allocation, in: Biology of Populus and Its Implications for Management and Conservation, Part II. pp. 355–399.

Ceulemans, R., Stettler, R.F., Hinckley, T.M., Isebrands, J.G., Heilman, P.E., 1990. Crown architecture of Populus clones as determined by branch orientation and branch characteristics . Tree Physiol. 7, 157–167. https://doi.org/10.1093/treephys/7.1-2-3-4.157

Chapin, F.S., Matson, P.A., Mooney, H.A., 2002. Terrestrial Production Processes, in: Principles of Terrestrial Ecosystem Ecology. Springer New York, pp. 123–150. https://doi.org/10.1007/0-387-21663-4_6

Chaves, M.M., 1991. Effects of water deficits on carbon assimilation. J. Exp. Bot. 42, 1–16. https://doi.org/10.1093/jxb/42.1.1

Christensen, J., Olhoff, A., 2019. Lessons from a decade of emissions gap assessments 1–14.

Chudy, R.P., Busby, G.M., Binkley, C.S., Stanton, B.J., 2019. The economics of dedicated hybrid poplar biomass plantations in the western U.S. Biomass and Bioenergy 124, 114–124. https://doi.org/10.1016/j.biombioe.2019.03.010

CICES, 2018. Common International Classification of Ecosystem Services. European Environment Agency. https://cices.eu/.

Cocozza, C., Cherubini, P., Regier, N., Saurer, M., Frey, B., Tognetti, R., 2010. Early effects of water deficit on two parental clones of Populus nigra grown under different environmental conditions. Funct. Plant Biol. 37, 244–254. https://doi.org/10.1071/FP09156

Commission, E., 2022. European Green Deal : Commission proposes certification of carbon removals to help reach net zero emissions.

Coyle, D.R., Coleman, M.D., 2005. Forest production responses to irrigation and fertilization are not explained by shifts in allocation. For. Ecol. Manage. 208, 137–152. https://doi.org/10.1016/j.foreco.2004.11.022

Cuddington, K., Fortin, M.J., Gerber, L.R., Hastings, A., Liebhold, A., O'connor, M., Ray, C., 2013. Process-based models are required to manage ecological systems in a changing world. Ecosphere 4. https://doi.org/10.1890/ES12-00178.1

Czyzewski, B., Matuszczak, A., 2016. A new land rent theory for sustainable agriculture. Land use policy 55, 222–229. https://doi.org/10.1016/j.landusepol.2016.04.002

D'Amato, D., Korhonen, J., 2021. Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. Ecol. Econ. 188, 107143. https://doi.org/10.1016/j.ecolecon.2021.107143

De Wit, M., Faaij, A., 2010. European biomass resource potential and costs. Biomass and Bioenergy 34, 188–202. https://doi.org/10.1016/j.biombioe.2009.07.011

Delbecq, B.A., Kuethe, T.H., Borchers, A.M., 2014. Identifying the extent of the urban fringe and its impact on agricultural land values. Land Econ. 90, 587–600. https://doi.org/10.3368/le.90.4.587

Delbeke, J., Runge-Metzger, A., Slingenberg, Y., Werksman, J., 2019. The paris agreement. Routledge 24–45. https://doi.org/10.4324/9789276082569-2

Dhillon, A., Sangwan, Malik, Luhach, M.S., 2001. An economic analysis of poplar cultivation. Indian For. 127.1, 86–90.

Di Matteo, G., Nardi, P., Verani, S., Sperandio, G., 2015. Physiological adaptability of Poplar clones selected for bioenergy purposes under non-irrigated and suboptimal site conditions: A case study in Central Italy. Biomass and Bioenergy 81, 183–189. https://doi.org/10.1016/j.biombioe.2015.06.023

Díaz-Balteiro, L., 1998. La tasa de descuento en la gestión forestal. Montes 54, 49–57.

Diaz-Balteiro, L., Rodriguez, L.C.E., 2006. Optimal rotations on Eucalyptus plantations including carbon sequestration-A comparison of results in Brazil and Spain. For. Ecol. Manage. 229, 247–258. https://doi.org/10.1016/j.foreco.2006.04.005

Díaz-Balteiro, L., Romero, C., 2003. Carbon captured as a new instrument in forest management: Some implications. Sci. For. Sci. 103–114.

Díaz-Balteiro, L., Romero, C., Rodriguez, L.C.E., Nobre, S.R., Borges, J.G., 2014. The management of industrial forest plantations. Theoretical foundations and

applications, in: The Management of Industrial Forest Plantations. Springer, pp. 121--170. https://doi.org/10.1007/978-94-017-8899-1

Díaz, E., Roldán, A., 2000. Effects of reafforestation techniques on the nutrient content, photosynthetic rate and stomatal conductance of Pinus halepensis seedlings under semiarid conditions. L. Degrad. Dev. 11, 475–486. https://doi.org/10.1002/1099-145X(200009/10)11:5<475::AID-LDR408>3.0.CO;2-M

Dickmann, D.I., Isebrands, J.G., Eckenwalder, J.E., Richardson, J., 2001. Poplar Culture in North America. NRC Research Press, Ottawa, Ontario, Canada.

Dillen, S.Y., Djomo, S.N., Al Afas, N., Vanbeveren, S., Ceulemans, R., 2013. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass and Bioenergy 56, 157–165. https://doi.org/10.1016/j.biombioe.2013.04.019

Dimitriou, I., Baum, C., Baum, S., Busch, G., Schulz, U., Köhn, J., Lamersdorf, N., L., P., A., P., W., Berndes, M. and, GDimitriou, I., Baum, C., Baum, S., Busch, G., Schulz, U., Köhn, J., Lamersdorf, N., Leinweber, P., Aronsson, P., Weih, G., 2009. The impact of short rotation coppice (SRC) cultivation on the environment., in: Landbauforschung–VTI Agriculture and Forestry. pp. 159-162.

Dimitriou, I., Rosenqvist, H., 2011. Sewage sludge and wastewater fertilisation of Short Rotation Coppice (SRC) for increased bioenergy production-Biological and economic potential. Biomass and Bioenergy 35, 835–842. https://doi.org/10.1016/j.biombioe.2010.11.010

Dimitriou, L., Busch, G., Jacobs, S., Schmidt-Walter, P., Lamersdorf, N., 2009. A review of the impacts of Short Rotation Coppice cultivation on water issues. Agric. For. Res. 59, 197–206.

Djomo, S.N., De Groote, T., Gobin, A., Ceulemans, R., Janssens, I.A., 2019. Combining a land surface model with life cycle assessment for identifying the optimal management of short rotation coppice in Belgium. Biomass and Bioenergy 121, 78–88. https://doi.org/10.1016/j.biombioe.2018.12.010

Dunlap, J., Stettler, R., Heilman, P., 1995. Genetic variation and productivity of Populus trichocarpa and its hybrids. VIII. Leaf and crown morphology of native P. trichocarpa clones from four river valleys in Washington. Can. J. For. Res. 1, 1710–24.

EC, 2018. Europe leads the global clean energy transition: commission welcomes ambitious agreement on further renewable energy development in the EU. Int. Energy Agency. https://doi.org/10.1016/0960-1481(94)90358-1

EC, 2011. A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final.

Eckenwalder, J.E., 1996. Systematics and evolution of Populus. Biology of Populus and its implications for management and conservation. NRC Research Press.

Ehleringer, J.R., 1993. Carbon and Water Relations in Desert Plants: An Isotopic Perspective, in: Stable Isotopes and Plant Carbon-Water Relations. pp. 155–172. https://doi.org/10.1016/b978-0-08-091801-3.50018-0

El Kasmioui, O., Ceulemans, R., 2013. Financial Analysis of the Cultivation of Short Rotation Woody Crops for Bioenergy in Belgium: Barriers and Opportunities. Bioenergy Res. 6, 336–350. https://doi.org/10.1007/s12155-012-9262-7

European Bioplastics, 2018. Bioplastics market development update 2019 2019, 2018–2019.

European Commission, 2018. Land use and forestry regulation for 2021-2030 [WWW Document]. Clim. Action. URL https://ec.europa.eu/clima/eu-action/forests-and-agriculture/land-use-and-forestry-regulation-2021-2030_en (accessed 5.30.22).

European Commission (EC), 2012. Innovating for Sustainable Growth: A Bioeconomy for Europe. COM Final.

Faasch, R.J., Patenaude, G., 2012. The economics of short rotation coppice in Germany. Biomass and Bioenergy 45, 27–40. https://doi.org/10.1016/j.biombioe.2012.04.012

Fang, S., Xue, J., Tang, L., 2007. Biomass production and carbon sequestration potential in poplar plantations with different management patterns. J. Environ. Manage. 85, 672–679. https://doi.org/10.1016/j.jenvman.2006.09.014

FAO (2010) Global forest resources assessment 2010: Main report, FAO Forestry Paper 163, Food and Agriculture Organization of the United Nations Rome 2010

Farago, E., Margaret, E., 2008. Plants and the chemical elements: biochemistry, uptake, tolerance and toxicity. John Wiley & Sons.

Feikema, P., Morris, J., Beverly, C., Baker, T. and Lane, P. 2010 Validation of plantation transpiration in south-eastern Australia estimated using the 3PG+ forest growth model. Forest Ecology and Management, 260, 663–678

Fernández-De-Uña, L., Rossi, S., Aranda, I., Fonti, P., González-González, B.D., Cañellas, I., Gea-Izquierdo, G., 2017. Xylem and leaf functional adjustments to drought in pinus sylvestris and quercus pyrenaica at their elevational boundary. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.01200

Fernàndez-Martínez, J., Joffre, R., Zacchini, M., Fernández-Marín, B., García-Plazaola, J.I., Fleck, I., 2017. Near-infrared reflectance spectroscopy allows rapid and simultaneous evaluation of chloroplast pigments and antioxidants, carbon isotope discrimination and nitrogen content in Populus spp. leaves. For. Ecol. Manage. 399, 227–234. https://doi.org/10.1016/j.foreco.2017.05.041

Fichot, R., Brignolas, F., Cochard, H., Ceulemans, R., 2015. Vulnerability to drought-induced cavitation in poplars: Synthesis and future opportunities. Plant, Cell Environ. 38, 1233–1251. https://doi.org/10.1111/pce.12491

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Forrester, D.I., Guisasola, R., Tang, X., Albrecht, A.T., Dong, T.L., Le Maire, G., 2014. Using a stand-level model to predict light absorption in stands with vertically and horizontally heterogeneous canopies. For. Ecosyst. 1, 1–19. https://doi.org/10.1186/s40663-014-0017-0

Forrester, D.I., Tang, X., 2016. Analysing the spatial and temporal dynamics of species interactions in mixed-species forests and the effects of stand density using the 3-PG model. Ecol. Modell. 319, 233–254. https://doi.org/10.1016/j.ecolmodel.2015.07.010

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., 2007. Changes in atmospheric constituents and in radiative forcing, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change.

Freer-Smith, P., Muys, B., Bozzano, M., Drössler, L., Farrelly, N., Jactel, H., Korhonen, J., Minotta, G., Nijnik, M., Orazio, C., 2019. Plantation forests in Europe: challenges and opportunities. From Science to Policy, Vol. 9. https://doi.org/10.36333/fs09

Fuertes, A., Oliveira, N., Cañellas, I., Sixto, H., Rodríguez-Soalleiro, R., 2021. An economic overview of Populus spp. in Short Rotation Coppice systems under Mediterranean conditions: An assessment tool for decision-making. Renew. Sustain. Energy Rev. 151. https://doi.org/10.1016/j.rser.2021.111577

Fuertes, A., Sixto, H., González, I., Pérez-Cruzado, C., Cañellas, I., Rodríguez-Soalleiro, R., Oliveira, N., 2022. Time-course foliar dynamics of poplar short rotation plantations under Mediterranean conditions. Responses to different water scenarios. Biomass and Bioenergy 159, 106391. https://doi.org/10.1016/j.biombioe.2022.106391

Fürtner, D., Perdomo Echenique, E.A., Hörtenhuber, S.J., Schwarzbauer, P., Hesser, F., 2022. Beyond Monetary Cost-Benefit Analyses: Combining Economic, Environmental and Social Analyses of Short Rotation Coppice Poplar Production in Slovakia. Forests 13. https://doi.org/10.3390/f13020349

Gallardo, D.A., 2014. Standortbasierte Ertragsmodellierung von Pappel- und Weidenklonen in Kurzumtriebsplantagen 1–147.

Gao, F., Catalayud, V., Paoletti, E., Hoshika, Y., Feng, Z., 2017. Water stress mitigates the negative effects of ozone on photosynthesis and biomass in poplar plants. Environ. Pollut. 230, 268–279. https://doi.org/10.1016/j.envpol.2017.06.044

Garavilla, V., 2004. Manual de cultivo de choperas en La Rioja. Gobierno de La Rioja.

Garnica, P., Romero, P., Crespo, O., Garnica, J., 2018. New bioeconomies: exploring the potential role of Salicaceae. 7th International Poplar Symposium, Argentina.

Gasol, C.M., Brun, F., Mosso, A., Rieradevall, J., Gabarrell, X., 2010. Economic assessment and comparison of acacia energy crop with annual traditional crops in Southern Europe. Energy Policy 38, 592–597.

https://doi.org/10.1016/j.enpol.2009.10.011

Gasol, C.M., Martínez, S., Rigola, M., Rieradevall, J., Anton, A., Carrasco, J., Ciria, P., Gabarrell, X., 2009. Feasibility assessment of poplar bioenergy systems in the Southern Europe. Renew. Sustain. Energy Rev. 13, 801–812. https://doi.org/10.1016/j.rser.2008.01.010

Gaudillere, J.P., 1989. Leaf number, water stress and carbon nutrition effects on poplar leaf growth. Ann. des Sci. For. 46.

German Bioeconomy Council, 2018. Global Bioeconomy Summit 2018 - Communiqé.

Gerritse, T., 2019. the Circular Bioeconomy in Practice – Assessing the End-of-Life Options and Its Environmental Impact for Bio-Based Polyethylene Furanoate (Pef).

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, 25–29. https://doi.org/10.1126/sciadv.1700782

Ghezehei, S.B., Nichols, E.G., Maier, C.A., Hazel, D.W., 2019. Adaptability of populus to physiography and growing conditions in the southeastern USA. Forests 10. https://doi.org/10.3390/f10020118

González-González, B.D., Oliveira, N., González, I., Cañellas, I., Sixto, H., 2017. Poplar biomass production in short rotation under irrigation: A case study in the Mediterranean. Biomass and Bioenergy 107, 198–206. https://doi.org/10.1016/j.biombioe.2017.10.004

González, E., Muller, E., Comín, F.A., González-Sanchis, M., 2010. Leaf nutrient concentration as an indicator of Populus and Tamarix response to flooding. Perspect. Plant Ecol. Evol. Syst. 12, 257–266. https://doi.org/10.1016/j.ppees.2010.07.001

González, I., Sixto, H., Rodríguez-Soalleiro, R., Oliveira, N., 2020. Nutrient contribution of litterfall in a short rotation plantation of pure or mixed plots of populus alba l. And robinia pseudoacacia l. Forests 11, 1–19. https://doi.org/10.3390/f11111133

Götze, Uwe, Northcott, Deryl, Schuster, P., 2008. Investment appraisal. Methods and models. Springer.

Gourley, C.J.P., Allan, D.L., Russelle, M.P., 1994. Plant nutrient efficiency: A comparison of definitions and suggested improvement. Plant Soil 158, 29–37. https://doi.org/10.1007/BF00007914

Grafton, B.R.Q., Chu, H.L., Nelson, H., Bonnis, G., 2021. A Global Analysis of the Cost-Efficiency of Forest Carbon Sequestration. OECD Environ. Work. Pap. are 66.

Gregoire, T.G., Valentine, H.T., 2007. Sampling strategies for natural resources and the environment, Sampling Strategies for Natural Resources and the Environment. https://doi.org/10.1201/9780203498880

Gueçaimburu, J.M., Vázquez, J.M., Tancredi, F., Reposo, G.P., Rojo, V., Martínez, M.,

Introcaso, R.M., 2019. Evolución del fósforo disponible a distintos niveles de compactación por tráfico agrícola en un argiudol típico. Chil. J. Agric. Anim. Sci. 35, 81–9. https://doi.org/10.4067/s0719-38902019005000203

Haider, N., Parker, N., Townsend, P.A., 2018. Potential for a hybrid poplar industry using recycled water: an environmental application of the biocycle farm.

Hart, Q.J., Tittmann, P.W., Bandaru, V., Jenkins, B.M., 2015. Modeling poplar growth as a short rotation woody crop for biofuels in the Pacific Northwest. Biomass and Bioenergy 79, 12–27. https://doi.org/10.1016/j.biombioe.2015.05.004

Harvey, H.P., van den Driessche, R., 1999. Poplar nutrient resorption in fall or drought: influence of nutrient status and clone. Can. J. For. Res. 29, 1916–1925. https://doi.org/10.1139/cjfr-29-12-1916

Haughton, A.J., Bohan, D.A., Clark, S.J., Mallott, M.D., Mallott, V., Sage, R., Karp, A., 2016. Dedicated biomass crops can enhance biodiversity in the arable landscape. GCB Bioenergy 8, 1071–1081. https://doi.org/10.1111/gcbb.12312

Hauk, S., Knoke, T., Wittkopf, S., 2014. Economic evaluation of short rotation coppice systems for energy from biomass - A review. Renew. Sustain. Energy Rev. 29, 435–448. https://doi.org/10.1016/j.rser.2013.08.103

Hauk, S., Skibbe, K., Röhle, H., Schröder, J., Wittkopf, S., Knoke, T., 2015. Nondestructive Estimation of Biomass Yield for Short-Rotation Woody Crops Is Reliable and Shows High Yields for Commercial Stands in Bavaria. Bioenergy Res. 8, 1401–1413. https://doi.org/10.1007/s12155-015-9602-5

Headlee, W.L., Zalesny, R.S., Donner, D.M., Hall, R.B., 2012. Using a Process-Based Model (3-PG) to Predict and Map Hybrid Poplar Biomass Productivity in Minnesota and Wisconsin, USA. Bioenergy Res. 6, 196–210. https://doi.org/10.1007/s12155-012-9251-x

Heilman, P.E., Xie Fu Guang, 1994. Effects of nitrogen fertilization on leaf area, light interception, and productivity of short-rotation Populus trichocarpa X Populus deltoides hybrids. Can. J. For. Res. 24, 166–173. https://doi.org/10.1139/x94-022

Hennig, A., Kleinschmit, J.R.G., Schoneberg, S., Löffler, S., Janßen, A., Polle, A., 2015. Water consumption and biomass production of protoplast fusion lines of poplar hybrids under drought stress. Front. Plant Sci. 6, 1–14. https://doi.org/10.3389/fpls.2015.00330

Henri, C.J., Johnson, J.D., 2005. Riparian forest buffer income opportunities: A hybrid poplar case study. J. Soil Water Conserv. 60, 159–163.

Herold, A., Böttcher, H., Gores, S., Urrutia, C., 2021. 2030 Climate Target: Review of LULUCF Regulation 1–23.

Hetemäki, L., Kangas, J., Peltola, H., 2022. Forest Bioeconomy and Climate Change. Springer Nature.

Hillier, J., Whittaker, C., Dailey, G., Aylott, M., Casella, E., Richter, G. m., Riche, A., Murphy, R., Taylor, G., Smith, P., 2009. Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenergy 1, 267–281. https://doi.org/10.1111/j.1757-1707.2009.01021.x

Hinckley, T., Richter, H., Schulte, P., 1991. Water relations. Physiology of trees. Wiley, New York.

Host, G.E., Isebrands, J.G., 1994. An interregional validation of ECOPHYS, a growth process model of juvenile poplar clones. Tree Physiol. 14, 933–945. https://doi.org/10.1093/treephys/14.7-8-9.933

Ibarra, D., Eugenio, M.E., Cañellas, I., Sixto, H., Martín-Sampedro, R., 2017. Potential of different poplar clones for sugar production. Wood Sci. Technol. 51, 669–684. https://doi.org/10.1007/s00226-017-0899-4

Isebrands, J., Nelson, N., 1982. Crown architecture of short-rotation, intensively cultured Populus II. Branch morphology and distribution of leaves within the crown of Populus' Tristis' as related to biomass production. Can. J. For. Res. 12(4), 853–64.

Jégo, G., Thibodeau, F., Morissette, R., Crépeau, M., Claessens, A., Savoie, P., 2017. Estimating the yield potential of short-rotation willow in Canada using the 3PG model. Can. J. For. Res. 47, 636–647. https://doi.org/10.1139/cjfr-2016-0353

Johansson, T., Karačić, A., 2011. Increment and biomass in hybrid poplar and some practical implications. Biomass and Bioenergy 35, 1925–1934. https://doi.org/10.1016/j.biombioe.2011.01.040

Jong, E. de, Visser, H.A., Dias, A.S., Harvey, C., Gruter, G.J.M., 2022. The Road to Bring FDCA and PEF to the Market. Polymers (Basel). 14, 1–32. https://doi.org/10.3390/polym14050943

Jug, A., Hofmann-Schielle, C., Makeschin, F., Rehfuess, K.E., 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. II. Nutritional status and bioelement export by harvested shoot axes. For. Ecol. Manage. 121, 67–83. https://doi.org/10.1016/S0378-1127(98)00557-X

Kaiser, E., Morales, A., Harbinson, J., Kromdijk, J., Heuvelink, E., Marcelis, L.F.M., 2015. Dynamic photosynthesis in different environmental conditions. J. Exp. Bot. 66, 2415–2426. https://doi.org/10.1093/jxb/eru406

Karim, S.A., Hawkins, B.J., 1999. Variation in response to nutrition in a three-generation pedigree of Populus. Can. J. For. Res. 29, 1743–1750. https://doi.org/10.1139/x99-149

Keča, L., Keča, N., Pantić, D., 2012. Net present value and internal rate of return as indicators for assessment of cost-efficiency of poplar plantations: A Serbian case study. Int. For. Rev. 14, 145–156. https://doi.org/10.1505/146554812800923345

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Kira, T., 1975. Primary production of forests, in: Photosynthesis and Productivity in Different Environments. pp. 5–40.

Korner, C., 1991. Some Often Overlooked Plant Characteristics as Determinants of Plant Growth: A Reconsideration. Funct. Ecol. 5, 162. https://doi.org/10.2307/2389254

Lacy, P., 2006. Forest investment: The emergence of timberland as an asset class. Aust. For. 69, 151–155. https://doi.org/10.1080/00049158.2006.10674995

Laina, R., Esteban, E.T., Rodríguez, S.J.H., 2022. Economic and Life Cycle Assessment of integrated wood and chips harvesting from hybrid poplar plantations in the Genil Valley (Spain). Comparison with chips harvesting from Poplar SRCs. From Theory to Pract. Challenges For. Eng. 249.

Landsberg, J., Mäkelä, A., Sievänen, R., Kukkola, M., 2005. Analysis of biomass accumulation and stem size distributions over long periods in managed stands of Pinus sylvestris in Finland using the 3-PG model. Tree Physiol. 25, 781–792. https://doi.org/10.1093/treephys/25.7.781

Landsberg, J., Sands, P., 2011. Physiological ecology of forest production: principles, processes and models., Elsevier/A. ed. London.

Landsberg, J.J., Waring, R.H., 1997. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. For. Ecol. Manage. 95, 209–228. https://doi.org/10.1016/S0378-1127(97)00026-1

Langeveld, H., Quist-wessel, F., Dimitriou, I., Aronsson, P., 2012. Assessing Environmental Impacts of Short Rotation Coppice (SRC) Expansion : Model Definition and Preliminary Results 621–635. https://doi.org/10.1007/s12155-012-9235-x

Laureysens, I., Blust, R., De Temmerman, L., Lemmens, C., Ceulemans, R., 2004. Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: I. Seasonal variation in leaf, wood and bark concentrations. Environ. Pollut. 131, 485–494. https://doi.org/10.1016/j.envpol.2004.02.009

Laureysens, I., Deraedt, W., Indeherberge, T., Ceulemans, R., 2003. Population dynamics in a 6-year old coppice culture of poplar. I. Clonal differences in stool mortality, shoot dynamics and shoot diameter distribution in relation to biomass production. Biomass and Bioenergy 81–95.

Lawson, T., Ere Vialet-Chabrand, S., 2019. Tansley insight Speedy stomata, photosynthesis and plant water use efficiency. Wiley Online Libr. 221, 93–98. https://doi.org/10.1111/nph.15330

Lazdiņa, D., Bardulis, A., Bardule, A., Lazdiņš, A., Zeps, M., Jansons, A., 2014. The first three-year development of ALASIA poplar clones AF2, AF6, AF7, AF8 in biomass short rotation coppice experimental cultures in Latvia. Agron. Res. 12, 543–552.

Le Dantec, V., Dufrêne, E., Saugier, B., 2000. Interannual and spatial variation in

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

maximum leaf area index of temperate deciduous stands. For. Ecol. Manage. 134, 71–81. https://doi.org/10.1016/S0378-1127(99)00246-7

Leech, J., 2014. Rotation length and discount rates. Aust. For. 77, 114–122. https://doi.org/10.1080/00049158.2014.945110

Levasseur, A., Lesage, P., Margni, M., Deschěnes, L., Samson, R., 2010. Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. Environ. Sci. Technol. 44, 3169–3174. https://doi.org/10.1021/es9030003

Li, H., Li, M., Luo, J., Cao, X., Qu, L., Gai, Y., Jiang, X., 2012. N-fertilization has different effects on the growth, carbon and nitrogen physiology, and wood properties of slow- and fast-growing Populus species. J. Exp. Bot. 63, 6173–85. https://doi.org/10.1093/jxb/err313

Liang, B., Ma, C., Zhang, Z., Wei, Z., Gao, T., Zhao, Q., Ma, F., Li, C., 2018. Long-term exogenous application of melatonin improves nutrient uptake fluxes in apple plants under moderate drought stress, Environmental and Experimental Botany. Elsevier B.V. https://doi.org/10.1016/j.envexpbot.2018.08.016

Liang, Z.S., Yang, J.W., Shao, H.B., Han, R.L., 2006. Investigation on water consumption characteristics and water use efficiency of poplar under soil water deficits on the Loess Plateau. Colloids Surfaces B Biointerfaces 53, 23–28. https://doi.org/10.1016/j.colsurfb.2006.07.008

Lindegaard, K.N., Adams, P.W.R., Holley, M., Lamley, A., Henriksson, A., Larsson, S., von Engelbrechten, H.G., Esteban Lopez, G., Pisarek, M., 2016. Short rotation plantations policy history in Europe: Lessons from the past and recommendations for the future. Food Energy Secur. 5, 125–152. https://doi.org/10.1002/fes3.86

Liu, J.F., Arend, M., Yang, W.J., Schaub, M., Ni, Y.Y., Gessler, A., Jiang, Z.P., Rigling, A., Li, M.H., 2017. Effects of drought on leaf carbon source and growth of European beech are modulated by soil type. Sci. Rep. 7, 1–9. https://doi.org/10.1038/srep42462

Liu, T., T Huffman, Kulshreshtha, S., McConkey, B., Du, Y., Green, M., Liu, J., Shang, J., Geng, X., 2007. Bioenergy production on marginal land in Canada: Potential, economic feasibility, and greenhouse gas emissions impacts. Appl. Energy Nov 1, 477–485.

Loomis RS, Williams WA, H.A., 1971. Agricultural productivity. Agric. Ecol. 22(1), 431–68. https://doi.org/10.4324/9781315841168-11

Luukkanen, O., Kozlowski, T., 1972. Gas exchange in six Populus clones. Silvae Genet. 21, 220–229.

Maletta, E., Díaz-Ambrona, C.H., 2020. Lignocellulosic Crops as Sustainable Raw Materials for Bioenergy. Green Energy to Sustain. 1, 489–514. https://doi.org/10.1002/9781119152057.ch20

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Manley, B., 2017. Discount rates used for forest valuation - Results of 2017 survey. New Zeal. J. For.

Manzone, M., Bergante, S., Facciotto, G., 2014. Energy and economic evaluation of a poplar plantation for woodchips production in Italy. Biomass and Bioenergy 60, 164–170. https://doi.org/10.1016/j.biombioe.2013.11.012

Marron, N., Delay, D., Petit, J.M., Dreyer, E., Kahlem, G., Delmotte, F.M., Brignolas, F., 2002. Physiological traits of two Populus x euramericana clones, Luisa Avanzo and Dorskamp, during a water stress and re-watering cycle. Tree Physiol. 22, 849–858. https://doi.org/10.1093/treephys/22.12.849

Marron, N., Villar, M., Dreyer, E., Delay, D., Boudouresque, E., Petit, J.M., Delmotte, F.M., Guehl, J.M., Brignolas, F., 2005. Diversity of leaf traits related to productivity in 31 Populus deltoides x Populus nigra clones. Tree Physiol. 25, 425–435. https://doi.org/10.1093/treephys/25.4.425

Matthews, R., Hogan, G., Mackie, E., 2018. Carbon impacts of biomass consumed in the EU: Supplementary analysis and interpretation for the European Climate Foundation 72.

Mbow, C., Smith, P., Skole, D., 2013. Assessing the role of forests and carbon finance in climate change mitigation. Carbon Management. Carbon Manag. 4(6), 639–653.

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G., Yepez, E. a., 2008. New Ohy 178. https://doi.org/10.1111/j.1469-8137.2008.02436.x

McEwan, A., Marchi, E., Spinelli, R., Brink, M., 2020. Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. J. For. Res. 31, 339–351. https://doi.org/10.1007/s11676-019-01019-3

Medrano, H., Galmes, J., Ribas-Carbo, M., Gulias, J., Bota, J., Pon, A., Moreno, M., Cifre, J., Flexas, J., 2007. Photosynthesis and water use efficiency: improving plant productivity in semi-arid environments, Plant Production.

Meng, S., Zhang, C., Su, L., Li, Y., Zhao, Z., 2016. Nitrogen uptake and metabolism of Populus simonii in response to PEG-induced drought stress. Environ. Exp. Bot. 123, 78–87. https://doi.org/10.1016/j.envexpbot.2015.11.005

Meyer, M., Tavares Wahren, F., Weber, N., Zalesny, R.S., Weih, M., 2021. Sustainable Biomass Value Chains Based on Poplar Plantations in European Rural Areas. Bioenergy Res. 14, 355–356. https://doi.org/10.1007/s12155-021-10275-3

Miguel, A. de, Meffe, R., Leal, M., González-Naranjo, V., Martínez-Hernández, V., Lillo, J., Martín, I., Salas, J.J., Bustamante, I. de, 2014. Treating municipal wastewater through a vegetation filter with a short-rotation poplar species. Ecol. Eng. 73, 560–568. https://doi.org/10.1016/j.ecoleng.2014.09.059

Ministerio de Agricultura, P. y A., 2022. Ecorregímenes. Vida Rural.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Ministerio de Agricultura, P. y A., 2013. Encuesta de Cánones de Arrendamiento Rústico 2012.

Mitchell, Stevens, Watters, 1999. Short-rotation forestry - Operations, productivity and costs based on experience gained in the UK. For. Ecol. Manage. 121, 123–136. https://doi.org/10.1016/S0378-1127(98)00561-1

MITERD, 2019. Guía para la estimación de absorciones de dióxido de carbono. El Minist. para la Transic. Ecológica y el Reto Demográfico.

Monclus, R., Dreyer, E., Delmotte, F.M., Villar, M., Delay, D., Boudouresque, E., Petit, J.M., Marron, N., Bréchet, C., Brignolas, F., 2005. Productivity, leaf traits and carbon isotope discrimination in 29 Populus deltoides x P. nigra clones. New Phytol. 167, 53–62. https://doi.org/10.1111/j.1469-8137.2005.01407.x

Monclus, R., Villar, M., Barbaroux, C., Bastien, C., Fichot, R., Delmotte, F.M., Delay, D., Petit, J.M., Brchet, C., Dreyer, E., Brignolas, F., 2009. Productivity, water-use efficiency and tolerance to moderate water deficit correlate in 33 poplar genotypes from a Populus deltoides × Populus trichocarpa F1 progeny. Tree Physiol. 29, 1329–1339. https://doi.org/10.1093/treephys/tpp075

Motagamwala, A.H., Won, W., Sener, C., Alonso, D.M., Maravelias, C.T., Dumesic, J.A., 2018. Toward biomass-derived renewable plastics: Production of 2,5-furandicarboxylic acid from fructose. Sci. Adv. 4. https://doi.org/10.1126/sciadv.aap9722

Nadal, M., Flexas, J., Gulías, J., 2018. Possible link between photosynthesis and leaf modulus of elasticity among vascular plants: a new player in leaf traits relationships? Ecol. Lett. https://doi.org/10.1111/ele.13103

Nambiar, E.K.S., Fife, D.N., 1991. Nutrient retranslocation in temperate conifers. Tree Physiol. 9, 185–207. https://doi.org/10.1093/treephys/9.1-2.185

Nassi O Di Nasso, N., Guidi, W., Ragaglini, G., Tozzini, C., Bonari, E., 2010. Biomass production and energy balance of a 12-year-old short-rotation coppice poplar stand under different cutting cycles. GCB Bioenergy 2, 89–97. https://doi.org/10.1111/j.1757-1707.2010.01043.x

Navarro, A., Portillo-Estrada, M., Arriga, N., Vanbeveren, S.P.P., Ceulemans, R., 2018. Genotypic variation in transpiration of coppiced poplar during the third rotation of a short-rotation bio-energy culture. GCB Bioenergy 10, 592–607. https://doi.org/10.1111/gcbb.12526

Nelson, N., Burk, T., Isebrands, J., 1981. Crown architecture of short-rotation, intensively cultured Populus.: I. Effects of clone and spacing on first-order branch characteristics. Can. J. For. Res. 1, 73–81.

Niinemets, Ü., Al Afas, N., Cescatti, A., Pellis, A., Ceulemans, R., 2004. Petiole length and biomass investment in support modify light-interception efficiency in dense poplar plantations. Tree Physiol. 24, 141–154. https://doi.org/10.1093/treephys/24.2.141

Nölte, A., Meilby, H., Yousefpour, R., 2018. Multi-purpose forest management in the tropics: Incorporating values of carbon, biodiversity and timber in managing Tectona grandis (teak) plantations in Costa Rica. For. Ecol. Manage. 422, 345–357. https://doi.org/10.1016/j.foreco.2018.04.036

Nölte, A., Yousefpour, R., Hanewinkel, M., 2020. Changes in sessile oak (Quercus petraea) productivity under climate change by improved leaf phenology in the 3-PG model. Ecol. Modell. 438, 109285. https://doi.org/10.1016/j.ecolmodel.2020.109285

OECD, 2009. The Bioeconomy to 2030: Designing a Policy Agenda. OECD Publishing, Paris.

Oliveira, N., 2019. Biometry at individual tree and plot level in short rotation woody crops under Mediterranean conditions (Doctoral dissertation, Universidad de Santiago de Compostela).

Oliveira, N., 2012. Evaluación de la productividad clonal en biomasa, en un cultivo energético experimental de chopo instalado por INIA-ICIFOR en Almazán (Soria). Thesis Master Project.

Oliveira, N., Fuertes, A., González, I., de la Iglesia, Jose Pablo Cañellas, I., Rodríguez-Soalleiro, R., Sixto, H., 2020a. Cultivo de chopo para la producción de biomasa: Estrategia de mitigación mediante la acumulación de Carbono en las diferentes fracciones. Manuscript in preparation for VIII workshop Remedia in Elche, Spain.

Oliveira, N., Pérez-Cruzado, C., Cañellas, I., Rodríguez-Soalleiro, R., Sixto, H., 2020b. Poplar short rotation coppice plantations under mediterranean conditions: The case of Spain. Forests 11, 1–43. https://doi.org/10.3390/f11121352

Oliveira, N., Rodríguez-Soalleiro, R., Hernández, M.J., Cañellas, I., Sixto, H., Pérez-Cruzado, C., 2017a. Improving biomass estimation in a Populus short rotation coppice plantation. For. Ecol. Manage. 391, 194–206. https://doi.org/10.1016/j.foreco.2017.02.020

Oliveira, N., Rodríguez-Soalleiro, R., Pérez-Cruzado, C., Cañellas, I., Sixto, H., 2017b. On the Genetic Affinity of Individual Tree Biomass Allometry in Poplar Short Rotation Coppice. Bioenergy Res. 10, 525–535. https://doi.org/10.1007/s12155-017-9818-7

Oliveira, N., Rodríguez-Soalleiro, R., Pérez-Cruzado, C., Cañellas, I., Sixto, H., Ceulemans, R., 2018. Above- and below-ground carbon accumulation and biomass allocation in poplar short rotation plantations under Mediterranean conditions. For. Ecol. Manage. 428, 57–65. https://doi.org/10.1016/j.foreco.2018.06.031

own unpublished data, n.d. own unpublished data.

Özbucak, T.B., Kutbay, H.G., Kilic, D., Korkmaz, H., Bilgin, A., Yalçin, E., Apaydin, Z., 2008. Foliar resorption of nutrients in selected sympatric tree species in gallery forest (black sea region). Polish J. Ecol. 56, 227–237.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Padrón, A., Orensanz García, J., 1987. El chopo y su cultivo. España.

Pannacci, E., Bartolini, S., Covarelli, G., 2009. Evaluation of four poplar clones in a short rotation forestry in central Italy. Ital. J. Agron. 4, 191–198. https://doi.org/10.4081/ija.2009.4.191

Paris, P., Mareschi, L., Sabatti, M., Pisanelli, A., Ecosse, A., Nardin, F., Scarascia-Mugnozza, G., 2011. Comparing hybrid Populus clones for SRF across northern Italy after two biennial rotations: Survival, growth and yield. Biomass and Bioenergy 35, 1524–1532. https://doi.org/10.1016/j.biombioe.2010.12.050

Pawson, S.M., Brin, A., Brockerhoff, E.G., Lamb, D., Payn, T.W., Paquette, A., Parrotta, J.A., 2013. Plantation forests, climate change and biodiversity. Biodivers. Conserv. 22, 1203–1227. https://doi.org/10.1007/s10531-013-0458-8

Pecchioni, G., Bosco, S., Volpi, I., Mantino, A., Dragoni, F., Giannini, V., Tozzini, C., Mele, M., Ragaglini, G., 2020. Carbon budget of an agroforestry system after being converted from a poplar short rotation coppice. Agronomy 10. https://doi.org/10.3390/agronomy10091251

Pellis, A., Laureysens, I., Ceulemans, R., 2004a. Genetic Variation of the Bud and Leaf Phenology of Seventeen Poplar Clones in a Short Rotation Coppice Culture. Plant Biol. 6, 38–46. https://doi.org/10.1055/s-2003-44746

Pellis, A., Laureysens, I., Ceulemans, R., 2004b. Growth and production of a short rotation coppice culture of poplar I. Clonal differences in leaf characteristics in relation to biomass production. Biomass and Bioenergy 27, 9–19. https://doi.org/10.1016/j.biombioe.2003.11.001

Peltoniemi, M.S., Duursma, R.A., Medlyn, B.E., 2012. Co-optimal distribution of leaf nitrogen and hydraulic conductance in plant canopies. Tree Physiol. 32, 510–519. https://doi.org/10.1093/treephys/tps023

Pérez-Cruzado, C., Muñoz-Sáez, F., Basurco, F., Riesco, G., Rodríguez-Soalleiro, R., 2011. Combining empirical models and the process-based model 3-PG to predict eucalyptus nitens plantations growth in Spain. For. Ecol. Manage. 262, 1067–1077. https://doi.org/10.1016/j.foreco.2011.05.045

Pérez-Cruzado, C., Sanchez-Ron, D., Rodríguez-Soalleiro, R., Hernández, M.J., Mario Sánchez-Martín, M., Cañellas, I., Sixto, H., 2014. Biomass production assessment from Populus spp. short-rotation irrigated crops in Spain. GCB Bioenergy 6, 312–326. https://doi.org/10.1111/gcbb.12061

Pilipović, A., Zalesny, R.S., Orlović, S., Drekić, M., Pekeč, S., Katanić, M., Poljaković-Pajnik, L., 2020. Growth and physiological responses of three poplar clones grown on soils artificially contaminated with heavy metals, diesel fuel, and herbicides. Int. J. Phytoremediation 22, 436–450. https://doi.org/10.1080/15226514.2019.1670616

Pires, J.R.A., Souza, V.G.L., Fernando, A.L., 2019. Valorization of energy crops as a source for nanocellulose production – Current knowledge and future prospects.

Ind. Crops Prod. 140. https://doi.org/10.1016/j.indcrop.2019.111642

Plastics Europe, G.M.R.C.M.& S.G., 2019. An analysis of European plastics production, demand and waste data.

Poorter, H., Niinemets, Ü., Ntagkas, N., Siebenkäs, A., Mäenpää, M., Matsubara, S., Pons, T.L., 2019. A meta-analysis of plant responses to light intensity for 70 traits ranging from molecules to whole plant performance. New Phytol. 223, 1073–1105. https://doi.org/10.1111/nph.15754

Popa, V.I., Volf, I., 2018. Biomass as renewable raw material to obtain bioproducts of high-tech value. Elsevier.

Popović, B.M., Štajner, D., Ždero-Pavlović, R., Tari, I., Csiszár, J., Gallé, Poór, P., Galović, V., Trudić, B., Orlović, S., 2017. Biochemical response of hybrid black poplar tissue culture (Populus × canadensis) on water stress. J. Plant Res. 130, 559–570. https://doi.org/10.1007/s10265-017-0918-4

Potithep, S., Yasuoka, Y., 2011. Application of the 3-PG model for gross primary productivity estimation in deciduous broadleaf forests: A study area in Japan. Forests 2, 590–609. https://doi.org/10.3390/f2020590

Pra, A., Masiero, M., Barreiro, S., Tomé, M., Martinez De Arano, I., Orradre, G., Onaindia, A., Brotto, L., Pettenella, D., 2019. Forest plantations in Southwestern Europe: A comparative trend analysis on investment returns, markets and policies. For. Policy Econ. 109, 102000. https://doi.org/10.1016/j.forpol.2019.102000

Pra, A., Pettenella, D., 2019. Investment returns from hybrid poplar plantations in northern Italy between 2001 and 2016: are we losing a bio-based segment of the primary economy? Invest. returns from hybrid poplar Plant. North. Italy between 2001 2016 are we losing a bio-based Segm. Prim. Econ. 74, 49–71. https://doi.org/10.13128/REA-25479

Pradana, R., Gonzalez, I., Oliveira, N., Gonzalez-Gonzalez, B.D., De Bustamant, I., Sixto, H., 2023. Suitability of Salicaceae genotypes to produce biomass using industrial wastewater. Biomass and Bioenergy 175. https://doi.org/10.1016/j.biombioe.2023.106874

Pradana, R., Sixto, H., González, B., Demaria, I., González, I., Martínez-Hernández, V., De Bustamant, I., n.d. Poplar Vegetation Filters for the beer industry: Wastewater treatment combined with biomass production. InProceedings of the XI Congreso Ibérico de Gestión y Planificación del Agua. Madrid, Spain, pp. 3–5.

Pregitzer, K.S., Dickmann, D.I., Hendrick, R., Nguyen, P. V., 1990. Whole-tree carbon and nitrogen partitioning in young hybrid poplars. Tree Physiol. 7, 79–93. https://doi.org/10.1093/treephys/7.1-2-3-4.79

Pugnaire, F.I., Chapin, F.S., 1992. Environmental and physiological factors governing nutrient resorption efficiency in barley. Oecologia 90, 120–126. https://doi.org/10.1007/BF00317817

R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Rae, A.M., Robinson, K.M., Street, N.R., Taylor, G., 2004. Morphological and physiological traits influencing biomass productivity in short-rotation coppice poplar. Can. J. For. Res. 34, 1488–1498. https://doi.org/10.1139/X04-033

Regier, N., Streb, S., Zeeman, S.C., Frey, B., 2010. Seasonal changes in starch and sugar content of poplar (Populus deltoides × nigra cv. Dorskamp) and the impact of stem girdling on carbohydrate allocation to roots. Tree Physiol. 30, 979–987. https://doi.org/10.1093/treephys/tpq047

Reshmy, R., Thomas, D., Philip, E., Paul, S.A., Madhavan, A., Sindhu, R., Sirohi, R., Varjani, S., Pugazhendhi, A., Pandey, A., Binod, P., 2021. Bioplastic production from renewable lignocellulosic feedstocks: a review. Rev. Environ. Sci. Biotechnol. https://doi.org/10.1007/s11157-021-09565-1

Ridge, C.R., Hinckley, T.M., Stettler, R.F., Van Volkenburgh, E., 1986. Leaf growth characteristics of fast-growing poplar hybrids Populus trichocarpa x P. deltoides. Tree Physiol. 1, 209–216. https://doi.org/10.1093/treephys/1.2.209

Rodríguez-Soalleiro, R., Eimil-Fraga, C., Gómez-García, E., García-Villabrille, J.D., Rojo-Alboreca, A., Muñoz, F., Oliveira, N., Sixto, H., Pérez-Cruzado, C., 2018. Exploring the factors affecting carbon and nutrient concentrations in tree biomass components in natural forests, forest plantations and short rotation forestry. For. Ecosyst. 5. https://doi.org/10.1186/s40663-018-0154-y

Rosenboom, J.G., Hohl, D.K., Fleckenstein, P., Storti, G., Morbidelli, M., 2018. Bottle-grade polyethylene furanoate from ring-opening polymerisation of cyclic oligomers. Nat. Commun. 9, 1–8. https://doi.org/10.1038/s41467-018-05147-y

Ryan, T., 2008. Modern regression methods (Vol. 655). John Wiley & Sons.

Sabatti, M., Fabbrini, F., Harfouche, A., Beritognolo, I., Mareschi, L., Carlini, M., Paris, P., Scarascia-Mugnozza, G., 2014. Evaluation of biomass production potential and heating value of hybrid poplar genotypes in a short-rotation culture in Italy. Ind. Crops Prod. 61, 62–73. https://doi.org/10.1016/j.indcrop.2014.06.043

Sampson, D.A., Ceulemans, R., 1999. SECRETS: simulated carbon fluxes from a mixed coniferous/deciduous Belgian forest. For. Ecosyst. Model. upscaling Remote Sens. 95–108.

San Miguel, G., Corona, B., Ruiz, D., Landholm, D., Laina, R., Tolosana, E., Sixto, H., Cañellas, I., 2015. Environmental, energy and economic analysis of a biomass supply chain based on a poplar short rotation coppice in Spain. J. Clean. Prod. 94, 93–101. https://doi.org/https://doi.org/10.1016/j.jclepro.2015.01.070

Sánchez-Gómez, D., Robson, T.M., Gascó, A., Gil-Pelegrín, E., Aranda, I., 2013. Differences in the leaf functional traits of six beech (Fagus sylvatica L.) populations are reflected in their response to water limitation. Environ. Exp. Bot. 87, 110–119. https://doi.org/10.1016/j.envexpbot.2012.09.011

Sánchez-González, M., Durbán, M., Lee, D.J., Cañellas, I., Sixto, H., 2017. Smooth additive mixed models for predicting aboveground biomass. J. Agric. Biol. Environ. Stat. 22, 23–41. https://doi.org/10.1007/s13253-016-0271-4

Sands, P., 2001. 3PGPJS—a user-friendly interface to 3-PG, the Landsberg and Waring model of forest productivity. Cooperative Research Centre for Sustainable Production Forestry and CSIRO Forestry and Forest Products Technical Report, (29).

Sands, P.J., 2010. 3PG PJS User Manual. Tech. Rep. 16, 1–27.

Sands, P.J., Landsberg, J.J., 2002. Parameterisation of 3-PG for plantation grown Eucalyptus globulus. For. Ecol. Manage. 163, 273–292. https://doi.org/10.1016/S0378-1127(01)00586-2

Sannigrahi, P., Ragauskas, A.J., Tuskan, G.A., 2010. Poplar as a feedstock for biofuels: A review of compositional characteristics. Biofuels, Bioprod. Biorefining. https://doi.org/10.1002/bbb.206

Sardans, J., Peñuelas, J., 2005. Drought decreases soil enzyme activity in a Mediterranean Quercus ilex L. forest. Soil Biol. Biochem. 37, 455–461. https://doi.org/10.1016/j.soilbio.2004.08.004

Sardans, J., Peñuuelas, J., Estiarte, M., Prieto, P., 2008. Warming and drought alter C and N concentration, allocation and accumulation in a Mediterranean shrubland. Glob. Chang. Biol. 14, 2304–2316. https://doi.org/10.1111/j.1365-2486.2008.01656.x

Sarkar, D., Sarkar, M.D., 2007. The lattice Package.

Scarascia-Mugnozza, G., Hinckley, T.M., Stettler, R.F., 1986. Evidence for nonstomatal inhibition of net photosynthesis in rapidly dehydrated shoots of Populus . Can. J. For. Res. 16, 1371–1375. https://doi.org/10.1139/x86-243

Scarascia-Mugnozza, G.E., Hinckley, T.M., Stettler, R.F., Heilman, P.E., Isebrands, J.G., 1999. Production physiology and morphology of Populus species and their hybrids grown under short rotation. III. Seasonal carbon allocation patterns from branches . Can. J. For. Res. 29, 1419–1432. https://doi.org/10.1139/x99-094

Scarlat, N., Dallemand, J.F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environ. Dev. 15, 3–34. https://doi.org/10.1016/j.envdev.2015.03.006

Schiberna, E., Borovics, A., Benke, A., 2021. Economic modelling of poplar short rotation coppice plantations in hungary. Forests 12. https://doi.org/10.3390/f12050623

Schlesinger, W.H., 1997. Biogeochemistry. An Analysis of Global Change, Academic Press. San Diego, CA.

Schulz, U., Brauner, O., Gruß., H., 2009. Animal diversity on short-rotation coppices–a

review., in: Landbauforschung Volkenrode 59.3. pp. 171–181.

Schweier, Becker, 2013. Economics of poplar short rotation coppice plantations on marginal land in Germany. Biomass and Bioenergy 59, 494–502. https://doi.org/10.1016/j.biombioe.2013.10.020

Schweier, J., Molina-Herrera, S., Ghirardo, A., Grote, R., Díaz-Pinés, E., Kreuzwieser, J., Haas, E., Butterbach-Bahl, K., Rennenberg, H., Schnitzler, J.P., Becker, G., 2017. Environmental impacts of bioenergy wood production from poplar short-rotation coppice grown at a marginal agricultural site in Germany. GCB Bioenergy 9, 1207–1221. https://doi.org/10.1111/gcbb.12423

Semerci, A., Semerci, H., Çalişkan, B., Çiçek, N., Ekmekçi, Y., Mencuccini, M., 2017. Morphological and physiological responses to drought stress of European provenances of Scots pine. Eur. J. For. Res. 136, 91–104. https://doi.org/10.1007/s10342-016-1011-6

Shooshtarian, A., 2015. Economics of Hybrid Poplar Plantations in Western Canada for Bioethanol Production.

Shrestha, S., Kognou, A.L.M., Zhang, J., Qin, W., 2021. Different Facets of Lignocellulosic Biomass Including Pectin and Its Perspectives. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-020-01305-w

Silim, S., Nash, R., Reynard, D., White, B., Schroeder, W., 2009. Leaf gas exchange and water potential responses to drought in nine poplar (Populus spp.) clones with contrasting drought tolerance. Trees - Struct. Funct. 23, 959–969. https://doi.org/10.1007/s00468-009-0338-8

Sixto, H., Cañellas, I., van Arendonk, J., Ciria, P., Camps, F., Sánchez, M., Sánchez-González, M., 2015. Growth potential of different species and genotypes for biomass production in short rotation in Mediterranean environments. For. Ecol. Manage. 354, 291–299. https://doi.org/10.1016/j.foreco.2015.05.038

Sixto, H., Gil, P., Ciria, P., Camps, F., Sánchez, M., Cañellas, I., Voltas, J., 2014. Performance of hybrid poplar clones in short rotation coppice in Mediterranean environments: Analysis of genotypic stability. GCB Bioenergy 6, 661–671. https://doi.org/10.1111/gcbb.12079

Sixto, H., Hernández, M.J., Ciria, M.P., Carrasco, J.E., Cañellas, I., 2010. Manual de cultivo de Populus spp. para la producción de biomasa con fines energéticos.

Sixto, H., Hernández, M.J., de Miguel, J., Cañellas, I., 2013. Short-rotation woody crops network, Madrid : Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA).

Smith, P., 2004. Carbon sequestration in croplands: The potential in Europe and the global context. Eur. J. Agron. 20, 229–236. https://doi.org/10.1016/j.eja.2003.08.002

Soliño, M., Oviedo, J.L., Caparrós, A., 2018. Are forest landowners ready for woody

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

energy crops? Preferences for afforestation programs in Southern Spain. Energy Econ. 73, 239–247. https://doi.org/10.1016/j.eneco.2018.05.026

Spinelli, R., Magagnotti, N., 2011. The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the Italian Alps. For. Policy Econ. 13, 520–524. https://doi.org/10.1016/j.forpol.2011.06.009

Spinelli, R., Nati, C., Magagnotti, N., 2009. Using modified foragers to harvest short-rotation poplar plantations. Biomass and Bioenergy 33, 817–821. https://doi.org/10.1016/j.biombioe.2009.01.001

Spinelli, R., Nati, C., Magagnotti, N., 2005. Harvesting and transport of root biomass from fast-growing poplar plantations. Silva Fenn. Monogr. 39, 539–548. https://doi.org/10.14214/sf.365

Stettler, R., Bradshaw, T., Heilman, P., Hinckley, T., 1996. Biology of Populus and its implications for management and conservation.

Štochlová, P., Novotná, K., Costa, M., Rodrigues, A., 2019. Biomass production of poplar short rotation coppice over five and six rotations and its aptitude as a fuel. Biomass and Bioenergy 122, 183–192. https://doi.org/10.1016/j.biombioe.2019.01.011

Surendran Nair, S., Kang, S., Zhang, X., Miguez, F.E., Izaurralde, R.C., Post, W.M., Dietze, M.C., Lynd, L.R., Wullschleger, S.D., 2012. Bioenergy crop models: Descriptions, data requirements, and future challenges. GCB Bioenergy 4, 620–633. https://doi.org/10.1111/j.1757-1707.2012.01166.x

Taiz, L., Zeiger, E., 1991. Plant physiology. Sinauer Associates, Redwood City.

Takashima, T., Hikosaka, K., Hirose, T., 2004. Photosynthesis or persistence: Nitrogen allocation in leaves of evergreen and deciduous Quercus species. Plant, Cell Environ. 27, 1047–1054. https://doi.org/10.1111/j.1365-3040.2004.01209.x

Tallis, M.J., Casella, E., Henshall, P.A., Aylott, M.J., Randle, T.J., Morison, J.I.L., Taylor, G., 2013. Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. GCB Bioenergy 5, 53–66. https://doi.org/10.1111/j.1757-1707.2012.01191.x

Tankersley L., 2006. Hardwood plantations as an investment. University of Tennessee, UT Extension.

Testa, R., Di Trapani, A.M., Foderà, M., Sgroi, F., Tudisca, S., 2014. Economic evaluation of introduction of poplar as biomass crop in Italy. Renew. Sustain. Energy Rev. 38, 775–780. https://doi.org/10.1016/j.rser.2014.07.054

Tripathi, A.M., Klem, K., Fischer, M., Orság, M., Trnka, M., Marek, M. V., 2018a. Water availability influences accumulation and allocation of nutrients and metals in short-rotation poplar plantation. Biomass and Bioenergy 116, 151–160. https://doi.org/10.1016/j.biombioe.2018.06.010

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Tripathi, A.M., Pohanková, E., Fischer, M., Orság, M., Trnka, M., Klem, K., Marek, M. V., 2018b. The evaluation of radiation use efficiency and leaf area index development for the estimation of biomass accumulation in short rotation poplar and annual field crops. Forests 9. https://doi.org/10.3390/f9040168

Tripathi, A.M., Pohankova, E., Pokorny, R., Fischer, M., Orság, M., Torres, C.P.G., Trnka, M., Marek, M. V., 2016. Long term measurement of leaf area index and radiation use efficiency in short rotation coppice poplar cultures and cereal crops. Eur. Biomass Conf. Exhib. Proc. 2016, 83–88.

Tschaplinski, T.J., Blake, T.J., 1989. Water relations, photosynthetic capacity, and root/shoot partitioning of photosynthate as determinants of productivity in hybrid poplar. Can. J. Bot. 67, 1689–1697. https://doi.org/10.1139/b89-213

Vanbeveren, S., I, S.F., Broeckx, L.S., Verlinden, M.S., Zenone, T., Ceulemans, R., 2013. Evolution of leaf area index (LAI) during four years (two rotations) of a SRC poplar plantation, in: Poster. Conference: Integrating biological, environmental and technical aspects for sustainable biomass production with fast growing tree species, Freising, Germany.

Vanbeveren, S.P.P., Ceulemans, R., 2018. Genotypic differences in biomass production during three rotations of short-rotation coppice. Biomass and Bioenergy 119, 198–205. https://doi.org/10.1016/j.biombioe.2018.09.027

Vanbeveren, S.P.P., De Francesco, F., Ceulemans, R., Spinelli, R., 2018. Productivity of mechanized whip harvesting with the Stemster MkIII in a short-rotation coppice established on farmland. Biomass and Bioenergy 108, 323–329. https://doi.org/10.1016/j.biombioe.2017.11.024

Vanbeveren, S.P.P., Schweier, J., Berhongaray, G., Ceulemans, R., 2015. Operational short rotation woody crop plantations: Manual or mechanised harvesting? Biomass and Bioenergy 72, 8–18. https://doi.org/10.1016/j.biombioe.2014.11.019

Vanbeveren, S.P.P., Spinelli, R., Eisenbies, M., Schweier, J., Mola-Yudego, B., Magagnotti, N., Acuna, M., Dimitriou, I., Ceulemans, R., 2017. Mechanised harvesting of short-rotation coppices. Renew. Sustain. Energy Rev. 76, 90–104. https://doi.org/10.1016/j.rser.2017.02.059

Vande Walle, I., Van Camp, N., Van de Casteele, L., Verheyen, K., Lemeur, R., 2007. Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) I-Biomass production after 4 years of tree growth. Biomass and Bioenergy 31, 267–275. https://doi.org/10.1016/j.biombioe.2007.01.019

Verlinden, M.S., Broeckx, L.S., Ceulemans, R., 2015. First vs. second rotation of a poplar short rotation coppice: Above-ground biomass productivity and shoot dynamics. Biomass and Bioenergy 73, 174–185. https://doi.org/10.1016/j.biombioe.2014.12.012

Verlinden, M.S., Broeckx, L.S., Van den Bulcke, J., Van Acker, J., Ceulemans, R., 2013. Comparative study of biomass determinants of 12 poplar (Populus) genotypes in a

USC DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

high-density short-rotation culture. For. Ecol. Manage. 307, 101–111. https://doi.org/10.1016/j.foreco.2013.06.062

Viger, M., Smith, H.K., Cohen, D., Dewoody, J., Trewin, H., Steenackers, M., Bastien, C., Taylor, G., 2016. Adaptive mechanisms and genomic plasticity for drought tolerance identifed in European black poplar (Populus nigra L.). Tree Physiol. 36, 909–928. https://doi.org/10.1093/treephys/tpw017

Wagner, J.E., 2012. Misinterpreting the internal rate of return in sustainable forest management planning and economic analysis. J. Sustain. For. 31, 239–266. https://doi.org/10.1080/10549811.2011.582830

Walter, K., Don, A., Flessa, H., 2015. No general soil carbon sequestration under Central European short rotation coppices. GCB Bioenergy 7, 727–740. https://doi.org/10.1111/gcbb.12177

Weber, J., Stettler, R., Heilman, P., 1985. Genetic variation and productivity of Populus trichocarpa and its hybrids. I. Morphology and phenology of 50 native clones. Can. J. For. Res. 15(2), 376–83.

Wiard, 1987. Growth of selected clones as affected by leaf orientation, light interception and photosyntesis. University of Washington, Seattle.

Wickham, H., 2011. ggplot2. Wiley Interdisciplinary Reviews: Computational Statistics 3.2.

Wilcox, J.R., Farmer, R.E., 1967. Variation and inheritance of juvenile characters of eastern cottonwood. Silvae Genet 16.5–6, 162–165. https://doi.org/10.1017/CCOL9780521870795.005

Wolbert-Haverkamp, M., Musshoff, O., 2014. Is short rotation coppice economically interesting? An application to Germany. Agrofor. Syst. 88, 413–426. https://doi.org/10.1007/s10457-014-9697-2

Wu, Q., Zhang, S., Feng G., Zhu, P., Huang, S., Wang, B., Xu, M., 2020. Determining the optimum range of soil Olsen P for high P use efficiency, crop yield, and soil fertility in three typical cropland soils. Pedosphere 30, 832–843. https://doi.org/10.1016/S1002-0160(20)60040-6

Wullschleger, S.D., Yin, T.M., DiFazio, S.P., Tschaplinski, T.J., Gunter, L.E., Davis, M.F., Tuskan, G.A., 2005. Phenotypic variation in growth and biomass distribution for two advanced-generation pedigrees of hybrid poplar. Can. J. For. Res. 35, 1779–1789. https://doi.org/10.1139/x05-101

Xu, H., Zhang, Z., Xiao, J., Chen, J., Zhu, M., Cao, W., Chen, Z., 2020. Environmental and canopy stomatal control on ecosystem water use efficiency in a riparian poplar plantation. Agric. For. Meteorol. 287, 107953. https://doi.org/10.1016/j.agrformet.2020.107953

Yan, X.L., Dai, T.F., Zhao, D., Jia, L.M., 2016. Combined surface drip irrigation and fertigation significantly increase biomass and carbon storage in a

Populus × euramericana cv. Guariento plantation. J. For. Res. 21, 280–290. https://doi.org/10.1007/s10310-016-0540-7

Zalesny, R.S., Donner, D.M., Coyle, D.R. and Headlee, W.L. 2012 An approach for siting poplar energy production systems to increase productivity and associated ecosystem services. For. Ecol. Manag. 284, 45–58. https://doi.org/10.1016/j.foreco.2012.07.022.

Zhang, C., Zhang, Z., Zhang, L., Li, Q., Li, C., Chen, G., Zhang, S., Liu, Q., Hu, X., 2020. Evolution of the functionalities and structures of biochar in pyrolysis of poplar in a wide temperature range. Bioresour. Technol. 304. https://doi.org/10.1016/j.biortech.2020.123002

Zianis, D., Muukkonen, P., Mäkipää, R., Mencuccini, M., 2005. Biomass and stem volume equations for tree species in Europe, Silva Fennica Monographs. https://doi.org/10.14214/sf.sfm4

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA





Poplar plantations, managed at high density and short rotations, achieve high productivity in a short period, crucial for biomass production and short- to medium-term carbon sequestration, both of which are crucial for advancing the low carbon bioeconomy. This thesis aims to improve climate-sensitive biomass predictions under optimal conditions and water-restricted scenarios. Additionally, it includes economic analysis that quantifies one of today's most demanded ecosystem services: carbon sequestration. These contributions aim to improve plantation efficiency and provide robust solutions adapted to the context of climate change and market needs.