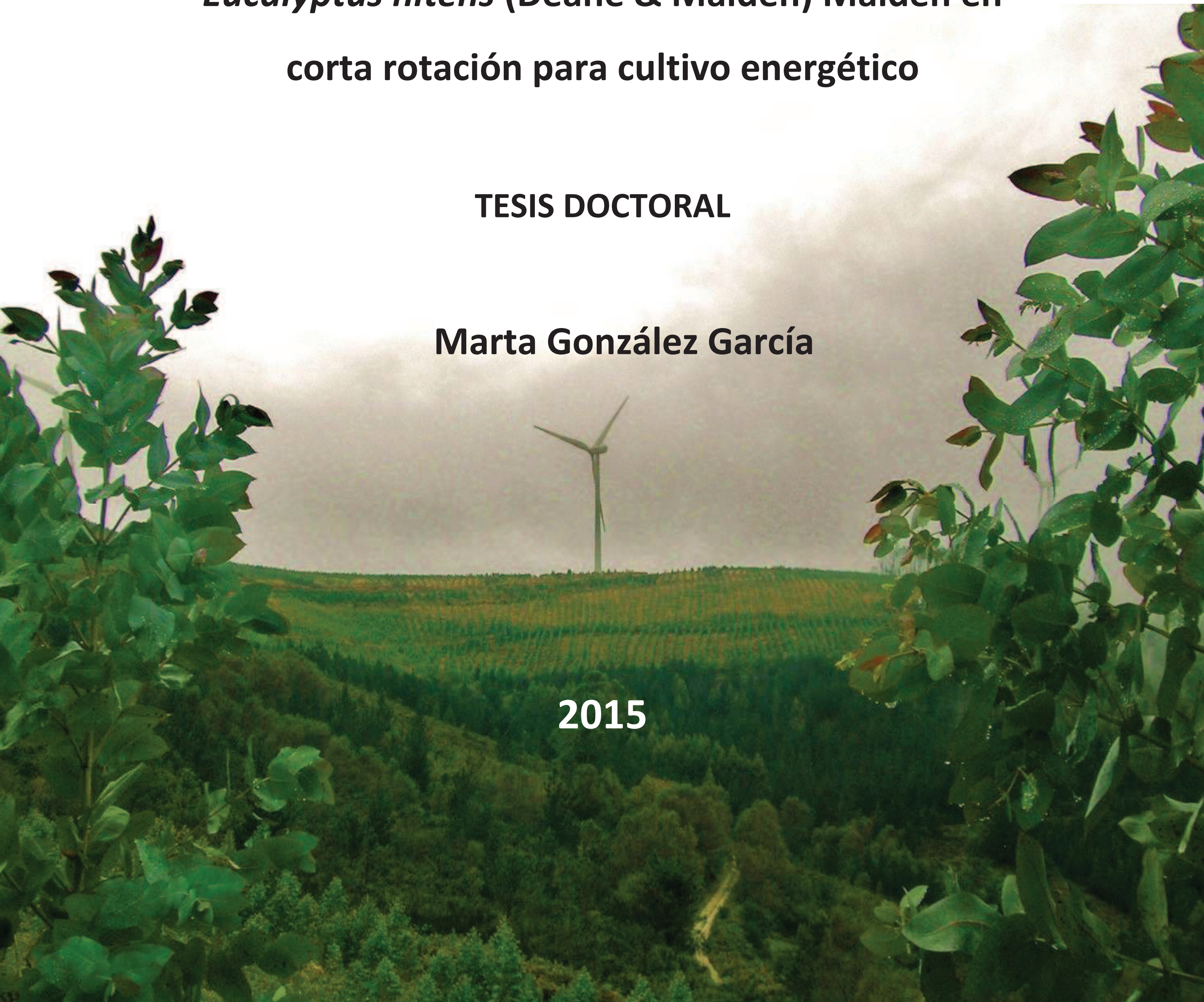
UNIVERSIDAD DE OVIEDO

Programa de Doctorado Recursos Biológicos y Biodiversidad

Modelización de la producción de biomasa de *Eucalyptus nitens* (Deane & Maiden) Maiden en corta rotación para cultivo energético



TESIS DOCTORAL

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RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis	
Español: Modelización de la producción de biomasa de *Eucalyptus nitens* (Deane & Maiden) Maiden en corta rotación para cultivo energético.	Inglés: Modelization of *Eucalyptus nitens* (Deane & Maiden) Maiden short rotation woody crops for bioenergy production.

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RESUMEN (en español)

La biomasa forestal es una fuente de energía renovable cuyo uso genera beneficios de tipo ambiental, económico y social. En los últimos años el cultivo de *Eucalyptus nitens* (Deane & Maiden) Maiden para producción de biomasa se han extendido por el Noroeste de España.

Los objetivos de esta Tesis Doctoral se centran en la modelización forestal de plantaciones energéticas de esta especie con el fin de estimar su productividad y proporcionar las herramientas para optimizar la producción mediante una gestión forestal sostenible.

La información utilizada en esta Tesis procede de una red experimental de 40 parcelas permanentes ubicadas en el área de distribución de las plantaciones bioenergéticas localizada en Galicia, en el noroeste de España. La recogida de datos en las plantaciones incluyó mediciones dasométricas, muestreo destructivo de la biomasa aérea, análisis de suelos y de nutrientes en los distintos componentes de la biomasa, evaluación energética y monitorización de la humedad edáfica entre otros parámetros.

Los modelos de crecimiento y producción son herramientas esenciales para predecir la productividad de las plantaciones bioenergéticas. La precisión, el comportamiento y la flexibilidad de dichos modelos varían dependiendo de la metodología de ajuste y del tipo de ecuación. En esta Tesis se emplearon diferentes metodologías de ajuste y distintos modelos para el desarrollo de las funciones de crecimiento y producción.

Se desarrollaron distintas herramientas predictivas tanto a nivel de árbol como a nivel de masa para la estimación de la biomasa de la copa, del fuste y la biomasa aérea: ecuaciones de biomasa, factores de expansión de la biomasa (*BEF*s) y ecuaciones de *BEF*. Las ecuaciones ajustadas explicaron un alto porcentaje de la variabilidad de los datos mientras que los *BEF*s constantes proporcionaron estimaciones menos precisas para todos los componentes, por ello se recomienda evitar su uso siempre que sea posible al menos para la fracción de copa y la biomasa aérea.

Se desarrolló un modelo dinámico de crecimiento compuesto por dos funciones de transición (altura dominante y área basimétrica) que proporcionó un alto grado de precisión. Las curvas de crecimiento obtenidas para el índice de sitio fueron 5, 8, 11 y 14 m para una edad de referencia de 4 años. El incremento medio anual de biomasa aérea varió entre 3,25 y 18,45 Mg ha^{-1} año^{-1} para un turno óptimo proyectado entre 6 y 12 años en función de la calidad de estación. La introducción de variables ambientales en los modelos aportó una mayor robustez y flexibilidad frente a pequeños cambios ambientales.

Se parametrizó y se calibró el modelo de procesos 3-PG para estudiar la producción de estas plantaciones a nivel de masa. Adicionalmente se aplicó a nivel espacial en el área de distribución de las plantaciones donde se exploró su productividad potencial y se evaluaron distintos escenarios de gestión mostrando que inferiores densidades de plantación (3000 pies ha^{-1}) y turnos entre 6 y 8 años pueden ser los más adecuados para fines bioenergéticos. Complementariamente se concluyó que conviene evitar el uso de datos climáticos medios ya que sobrestima la producción al no tener en cuenta eventos climáticos extremos.

La información relacionada con los nutrientes, el carbono y el potencial energético de la biomasa es esencial en las plantaciones energéticas desde el punto de vista ambiental y económico. Las hojas y la corteza de *E. nitens* fueron los componentes con mayor concentración de nutrientes. Sin embargo, al calcular el contenido a nivel de masa, la madera, componente mayoritario al final del turno, fue la fracción con mayor contenido de carbono y la mayor parte de los nutrientes estudiados. El poder calorífico en la fracción de madera así como el resto de las propiedades de la combustión resultaron constantes.

Los resultados obtenidos en esta tesis proporcionan información esencial en la gestión forestal de las plantaciones energéticas de *E. nitens* en el noroeste de España.

RESUMEN (en inglés)

Forest biomass is a renewable energy which generates environmental, economic and social benefits. In recent years the use of *Eucalyptus nitens* (Deane & Maiden) Maiden woody crops for bioenergy has extended across Northwest Spain.

The objectives of this Thesis are focused on modeling *E. nitens* bioenergy plantations to predict biomass productivity and provide useful tools in order to implement the most appropriate management of plantations.

The information used in this work came from an experimental network of 40 permanent plots located across the distribution area of the bioenergy stands in Galicia in Northwest Spain.

Data collection included stands measurements, destructive sampling of trees, soil and biomass nutritional analysis, energy evaluation and soil moisture monitoring, among other parameters.

Growth and yield models are essential tools for predicting productivity of these bioenergy stands. The accuracy, behaviour and flexibility of the model vary depending on the fit methodology and the equation type. In this Thesis different methodologies were used to develop growth and yield models.

Above-ground biomass prediction tools were developed at tree and stand level for crown, stem and above-ground biomass: constant Biomass Expansion Factors (*BEF*s), biomass and *BEF* equations. The models explained a high percentage of data variability, although constant *BEF*s resulted in the worst estimations for all components and should thus be avoided whenever possible, at least for crown and above-ground biomass.

A dynamic stand growth model formed by two transition functions (dominant height and basal area) was developed and it reached high values of accuracy. The site index growth curves had values of 5, 8, 11 and 14 m for a base age of 4 years. Biomass Mean Annual Increment varied from 3.25 to 18.45 Mg ha^{-1} y^{-1} at the end of the rotation which was projected from 6 to 12 years according to site quality. The inclusion of environmental variables in the models provided more robustness and flexibility under slightly changing conditions.

The 3-PG process-based model was parameterised and calibrated at plot scale for *E. nitens* plantations to estimate stand production. In addition, the model was also applied at spatial level in a selected area in Northwest Spain to quantify potential productivity and to evaluate different management scenarios. The results showed that lower stockings (3000 trees ha^{-1}) and shorter rotations, from 6 to 8 years, are more suitable for bioenergy production. Complementarily the use of mean climate data should be avoided because it produces overestimation in productivity predictions.

Information related to nutrients, carbon and energy potential is essential in bioenergy plantations, both from the environmental and economics point of view. Leaves and bark were the *E. nitens* tree components with the highest nutrient concentration although stemwood, the principal tree component at the end of the rotation, had the highest carbon and nutrient content, except for N and Ca where leaves and bark were, respectively, the most important components. Wood calorific value and combustion properties were quite constant showed low ash content.

The results obtained in this Thesis provide valuable information for the optimization of sustainable forest management in *E. nitens* woody crop plantations in Northwest Spain.

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STRUCTURE OF THE THESIS

This doctoral Thesis, which is focused on modeling the bioenergy production of *Eucalyptus nitens*, is divided into 6 chapters, which are summarised as follows:

Chapter 1, General introduction and objectives. The section includes the background and justification of the Thesis followed by the defining of the stated aims.

Chapter 2, Estimation of above-ground biomass at tree and stand levels. Different methodologies to estimate biomass and volume were analysed, and their accuracies compared.

Chapter 3, Development of a dynamic growth model which includes environmental factors to predict stand growth and define site quality.

Chapter 4, Prediction of bioenergy productivity using a process-based model, considering different management strategies.

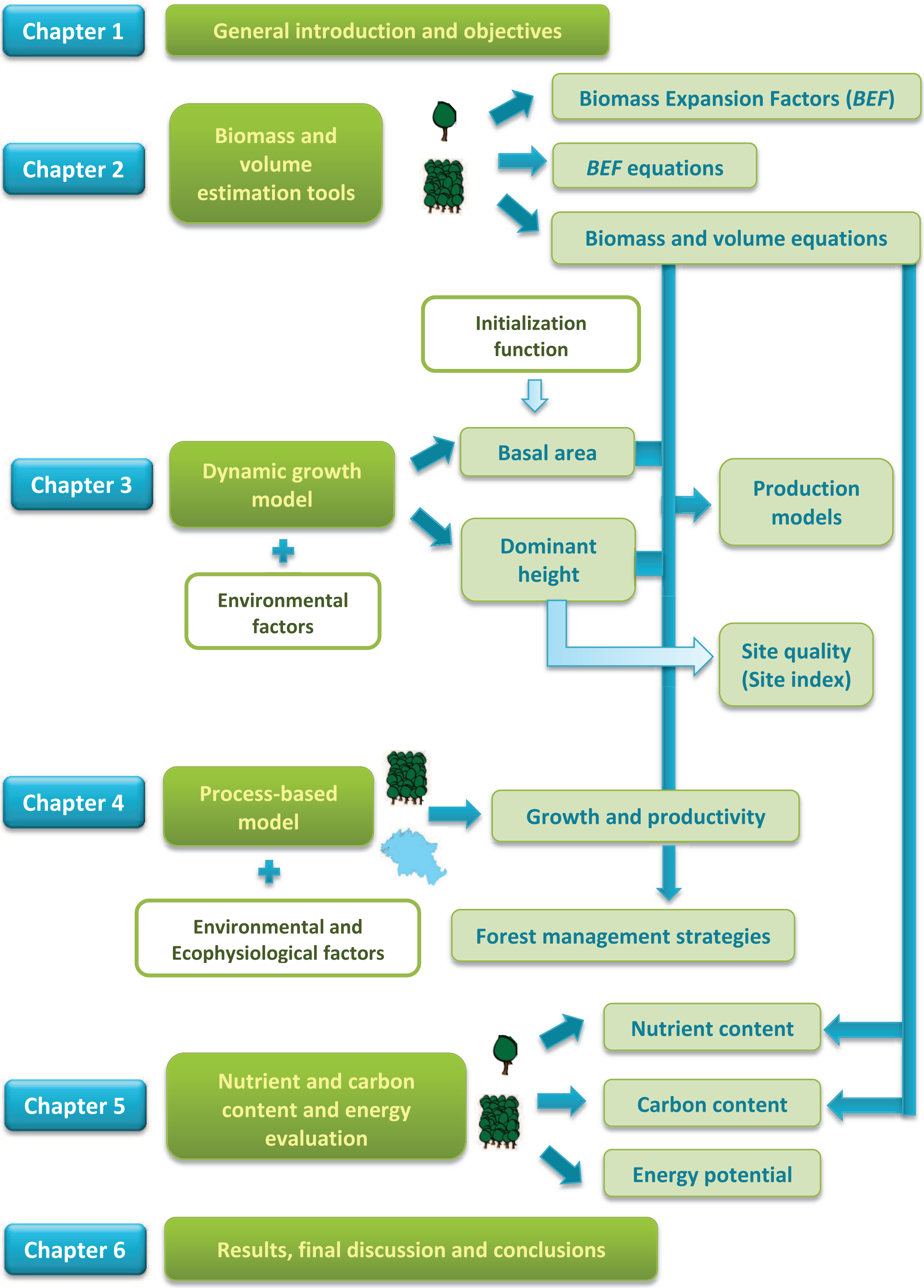
Chapter 5, Characterization of nutrient and carbon content and energy potential of above-ground biomass according to site quality.

Chapter 6, General results and discussion of the studies performed and final conclusions.

Bibliography references in this Thesis are included at the end of each chapter to facilitate the literature search.

Note: *This Thesis had been written in a bilingual format Spanish-English to aspirate to the International PhD Mention.*

GRAPHICAL ABSTRACT



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Biomass and volume equations

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CHAPTER 1

General introduction and objectives

CHAPTER 1. General introduction and objectives

1.1. Justification of the Thesis

Eucalyptus nitens (Deane & Maiden) Maiden, is a suitable species for bioenergy production in Northwest Spain. Galicia, in the far Northwest of Spain, has a large unproductive surface area which is covered by bush species and abandoned land of low ecological interest (DGCN, 2012). Moreover, *Eucalyptus* plantations in the area have contributed to the development of rural areas (Vázquez et al., 1997).

The interesting possibilities of renewable energies to mitigate climate change and reduce energy dependence, in addition to their associated social benefits, have resulted in *Eucalyptus* bioenergy stands being extended across the Northwest of Spain during the lasts years.

This Doctoral Thesis is focused on the study of these bioenergy plantations to provide information and useful tools which model biomass productivity and facilitate sustainable forest management.

1.2. Background

1.2.1. *Eucalyptus* as woody crops to produce energy

European governments made an agreement to increase the amount of renewable energies in final energy consumption to 20 % by 2020 in order to fight global warming and climate change, in addition to reducing dependence on non-renewable energy sources (Klessmann, 2013). In Spain, the National Action Plan for Renewable Energy and the Plan for Renewable Energies (Spanish initials, PER) set these targets at 22.7 % and 20.8 % respectively. Although the renewable energy sector has shown great development in the last decades and is expected to continue increasing over the next few years (Hoefnagels et al., 2014), recent reports have predicted a negative trend towards meeting these

European objectives by 2020, and more specifically, in Spain the best case scenario anticipates energy reduction to be 12.6-17.1 %, below the agreed target (Montoya et al., 2014).

In 2011 (the latest year for which data are currently available), 11.6 % of Spain's primary energy consumption came from renewable energy, where wind, solar, hydropower and biomass are the main energy sources. Spain has great potential to produce biomass, and it has been estimated that the combined potential of agriculture and forestry residues in the country is 11.25 % of the net electrical energy generated in the country in 2008 (Gómez et al., 2010). Nevertheless, wind and solar power are in reality the most significant energy sources and at the present time only 636 MW of the total of renewable energy installed in Spain, 32.47 GW, comes from biomass energy (Montoya et al., 2014).

Biomass is the biological material derived and stored in plants, including trees, crops or algae, through the process of photosynthesis whereby carbohydrates are produced (Saxena et al., 2009). Biomass is composed of varying quantities of cellulose, hemicellulose and lignin, the main components of which are carbohydrates, and small quantities of other components such as lipids, proteins, simple sugars and starches (Pant and Monhanty, 2014; Saidur et al., 2011). The combination of cellulose, hemicellulose, and lignin are referred to as 'lignocellulose' and it comprises around half the total mass of plant material. When plants are employed for energy purposes or simply die, the energy stored in carbohydrates is released as carbon dioxide back into the atmosphere. Additionally, biomass contains inorganic constituents and a percentage of water. The specific composition of different biomass materials is decisive in selecting appropriate species for the processes of fuel generation and derived products (Demirbas, 2004; Yaman, 2004).

Biomass can be classified according to various criteria. One of the most common is by the nature of the species such that biomass is divided into different types of herbaceous plants and grasses, woody plants (lignocellulosic biomass), aquatic plants or algae and manures produced by animals (McKendry, 2002).

Lignocellulosic biomass refers to plants with a major cellulose and lignin component (Shelly, 2008). One example is woody biomass, which is the solid material derived from trees, including tree components such as limbs, tops, branches and leaves (Smith et al., 2009). This lignocellulosic biomass can further be classified into two main categories: productive biomass, which is obtained with the sole purpose of obtaining energy, i.e. energy crops, or residual biomass obtained from a variety of activities such as forest residues from thinnings, prunnings or clear cuttings or wastes from wood manufacturing (Long et al., 2013).

Residual biomass has great potential since in some areas there is a huge quantity of this resource available and it has a relatively low cost to energy producers or even a negative cost if there is an obligation on plantation owners to remove such material from the forest after harvesting. Furthermore, the extraction of residual biomass has the positive effect of reducing wildfire hazard and also contributes to preventing the spread of diseases in the forest (Shelly, 2008; Soliño, 2010). However, when tree wastes are collected a large quantity of nutrients and organic matter are extracted from the forest, resulting in soil degradation if these elements are not replaced (Bosco et al., 2004; Raulund-Rasmussen et al., 2008).

Although energy can be produced using residues obtained from forest wastes, they may be insufficient to support the energy demand in some regions. In addition, residual biomass is often a low quality fuel, is dispersed across a wide area and is always dependent on other forest activities to obtain the product. As such, the establishment of woody biomass sources to produce quality fuel located close to biomass demand points, which reduces transportation costs and fossil fuel consumption and lowers the carbon footprint of energy production, is therefore a valuable complementary strategy to maximise energy production from woody biomass (Field et al., 2007; Leslie et al., 2012).

Woody crops are fast growing tree species with special characteristics for energy fuels, which are generally managed at high stocking and short rotations in order to provide relatively high yields over short time frames (Mckay, 2011). Generally the biomass obtained from these crops is used to produce heat and electricity in combustion or for second generation biofuels like bioethanol (McKendry, 2002; Romaní et al., 2013).

Woody crops are also known as Short Rotation Forestry (*SRF*), Short Rotation Woody Crops (*SRWC*) or Short Rotation Coppice (*SRC*). The latter refers to the regrowth of trees following harvesting and therefore new planting is not necessary in the next rotation.

SRWC plantations may go some way to meeting the energy demands currently met by fossil fuels in addition to contributing to the mitigation of climate change due to the great potential of young or middle-aged stands to sequester carbon, especially if they can be intensively managed (Zhang et al., 2012). Bioenergy stands can be planted on forest or on agricultural lands (Hoogwijk et al., 2009; Perlack et al., 2005), the latter have high potential due to the increased incidence of abandoned agricultural land in some developed countries in recent years.

Biomass production using *SRWC* involves a high level of management inputs. However, in general, principles of plantation establishment and management are common to all types of short rotation plantations, although the details vary between different species or clones, soils, and countries (Mitchell et al., 1995). Some of the key management factors in promoting a high bioenergy production are plant stocking, rotation length, cultivation techniques such as fertilization, irrigation and weed control, and site and species selection (González-García, 2015).

Plant stockings in *SRWC* are generally from 1000 to 20000 trees ha^{-1} (Hauk et al., 2014; Sims et al., 2001) depending on the species and the rotation length, which is between 1 and 15 years (Drew et al., 1987). The longer the rotation, the wider the spacing required between plants to promote higher production and avoid plant competition and mortality due to high self-thinning rate (Mitchell, 1995). In addition, the rotation period depends on site quality, because crops planted on more productive terrain reach optimum growth at a younger age, and also on harvesting logistics (Castaño-Santamaría et al., 2013; Hartsough and Cooper, 1999). Weed control is important to the success of the plantation, especially in the first growth stage until the crop foliage shades out weeds (Tubby and Armstrong, 2002). Moreover, fertilization generally increases tree growth especially in poor sites with a low nutrient availability where application of nutrients may be necessary to maintain productivity.

The most suitable species and material (mainly clones) to be used as woody crops may be either site specific, which may produce higher yields under particular conditions, or those which can adapt to a wider range of soil and climatic conditions, i.e. which have high potential productivity and suitability for different sites, and are therefore a safer option for new sites (Mitchell et al., 1995). The most usual woody crops species are hybrid poplars (*Populus* spp.), willows (*Salix* spp.) and *Eucalyptus* spp. due to their good growth rates and their characteristics suitable for bioenergy production (Armstrong et al., 1999; Sims et al., 2001; Sixto et al., 2007; Sochacki et al., 2007).

Eucalyptus spp. come mainly from Australia with a few species also native to Indonesia and Papua New Guinea and it is one of the fastest growing hardwood plantation genus in the world (Evans, 1980). While there are more than 700 species, only a few of these species have been widely planted outside their native range for commercial uses. The most widespread species used worldwide are *E. camadulensis*, *E. dunnii*, *E. globulus, E. grandis*, *E. nitens*, *E. pellita, E. saligna*, *E. terenicornis* and *E. urophylla*. These species together with their hybrids account for more than 90 % of planted *Eucalyptus* forests (Stanturf et al., 2013). *Eucalypt* plantations are grown extensively in tropical and subtropical regions throughout Africa, South America, Asia, and Australia, and, in more temperate regions of Europe, South America, North America, and Australia (Rockwood et al., 2008).

Eucalyptus seed movement in the world became important in the 19th century due to the need for timber in mines and industries as well as the use of wood for combustion. Genetic improvement has been carried out since then in several countries to obtain species and provenances with good adaptation and high productivity (Campbell and Sederoff, 1996; Griffin, 1989; Hamilton et al., 2008; Potts, 2004; van Wyk, 1990). It is estimated that the first *Eucalyptus* were planted in Northwest Spain in 1863 (Rigueiro-Rodríquez, 1993).

Although *Eucalyptus* production has been focused on pulp and paper manufacturing as well as on solid products for a long time, in recent decades the use of *Eucalyptus* for bioenergy production has increased around the world (Rockwood et al., 2008; Stanturf et al., 2013) and the experience of several countries such as Australia, New Zealand, South Africa, Brazil, Chile and the United States have been reported (Betters et al., 1991; Buchholz et al., 2013; González et al., 2011; Keith et al., 1999; Leslie et al., 2012; Luger, 1999; Sanhueza Silva, 2009; Sims et al., 1999; Sochacki et al., 2007). In Northwest Spain, due to its climatic characteristics, *Eucalyptus* is the fast-growing species with the highest productivity and it has begun to be planted as energy crops in recent years due to growing societal interest in biomass energy (Pérez et al., 2011).

Eucalyptus exhibits the key factors needed for use as fuel feedstock. They have rapid growth and can tolerate a wide range of soils, obtaining high productivity on marginal sites because they are able to adapt to low nutrient conditions, and have great potential over short rotations (González et al., 2011; Leslie et al., 2012; Luger, 1999; Mughini et al., 2014; Rockwood et al., 2008;

Searle and Malins, 2014; Stanturf et al., 2013). In addition, they have high wood density (mean values of 400-600 kg m^{-3}) and a calorific value higher than other *SRWC* species (Hicks and Clark, 2001; Senelwa and Sims, 1999). Moreover, unlike many trees, they do not have a true dormant period and retain their foliage, which enables growth during warm winter periods (Leslie et al., 2012).

1.2.2. *Eucalyptus nitens*, the tree species studied

Eucalyptus nitens (Deane & Maiden) Maiden from the *Eucalyptus* subgenus *Symphyomyrtus*, whose common name is Shining Gum, came from the Tablelands of New South Wales and Victoria (Australia) at latitude 30-38° S and elevation range of 600 to 1500 m (Dutkowski et al., 2001; FAO, 1981; Tibbits et al., 1997). In natural stands it grows in association with *Eucalyptus regnans* and *Eucalyptus delegatensis*.

E. nitens has a straight trunk which can reach 60-70 m in height and 1.8 m in diameter (Nicholls and Pederick, 1979). The crown covers in general one third of the total tree height while the bark is basically smooth, although husking into strips (FAO, 1981). Dead branches are generally at right angle to the stem and are not as easily removed as in other *Eucalyptus* species (FAO, 1981). Seed supply in this species can be problematic due to the fact that seed yield is low and is generally concentrated around the individual tree. Hence, it is thought there is a high degree of self-fertilization (FAO, 1981).

Although the parent material of the soils across its distribution area has great variability, in general all the soils have high organic matter content in the upper stratums and are always well drained (FAO, 1981). Climates are wet with a precipitation range of 750-1500 mm and a dry season of up to 3 months (Booth and Pryor, 1991; FAO, 1981) and the growth temperature range is from 2°C to 32°C (Pérez-Cruzado et al., 2011b; Rodríguez et al., 2009).

E. nitens started to be used commercially in Spain in the 1990s as an alternative to *Eucalyptus globulus* Labill. in inland areas with low winter temperatures due to this latter species not being able to survive in these areas due to the frosts. *E. nitens,* on the other hand, has good cold hardiness (Booth and Pryor, 1991; Schönau and Gardner, 1991; Tibbits and Reid, 1987), tolerating temperatures as low as -12°C and more than 100 frost events per year as well as snow (Booth and Pryor, 1991; González-Río et al., 1997). The tolerance rate depends not only on the Australian provenance but also on individual differences within provenance (Tibbits and Hodge, 2003). Additionally *E. nitens* has higher resistance than *E. globulus* to the *Eucalyptus* pests and illness which have been observed to exist in Spain (Aguín et al., 2013).

The regrowth ability of *Eucalyptus* spp. is frequently exploited for the reestablishment of the next rotation following harvesting. However, the main disadvantage for the commercial use of *E. nitens* is its low coppice regrowth capacity (Little et al., 2002; Little and Gardner, 2003). Some of the regrowth problems can be associated with harvesting technique, and with a little more care recovery rates improve, but the largest contributing factor lies in the nature of the species and even though careful harvesting is carried out, regeneration is not guaranteed as the ability to regrow after harvesting depends on the Australian origin. It is possible to find vigorous regrowth in some areas for a species which is totally unable to regrow in others (Pérez et al., 2011). Some experiences in Chile have shown a coppice capacity > 80 % (Muñoz and Espinosa, 2001) which greatly reduces re-establishment costs and enhances stand profitability. However, the most common provenance used in reforestation in the north of Spain, McAlister, has little resprouting ability (Sims et al., 2001, 1999) and nowadays the use of other provenances in this region for regrowth is under study (Pérez-Cruzado et al., 2011b).

E. nitens shows high productivity in the north of Spain (Pérez-Cruzado et al., 2011a,b; Pérez-Cruzado and Rodríguez-Soalleiro, 2011), which varies with site characteristics, management and stand stocking. It shows a superiority in production when compared with other *Eucalyptus* species such as *E. globulus*, *E. viminalis* or *E. regnans* in high stocking (2000 trees ha^{-1}) and short rotation (6 years) or other species such as poplars (Pérez et al., 2011). Moreover, it has good energy potential due to the high calorific value of its biomass (Pérez et al., 2006, 2008, 2011).

1.2.3. Modeling bioenergy plantations

1.2.3.1. Above-ground biomass prediction tools

Tools which quantify forest biomass production are essential in forest management and for scientific purposes. Studies of ecosystem productivity, energy and nutrient flows, and carbon cycles all require the ability to assess forest biomass (Burkhart and Tomé, 2012).

Biomass prediction is essential in bioenergy stands where the aerial components of the tree are harvested and therefore, crown and bark fraction must be also quantified, together with stemwood and in such cases total biomass is the main variable for predicting plantation yield. Several biomass studies have been carried out previously in *Eucalyptus* bioenergy plantations to quantify production and select the most appropriate species (Botman, 2010; Buchholz et al., 2013; Guo et al., 2006; Senelwa and Sims, 1997; Sims et al., 1999; Sochacki et al., 2007).

Despite ground components being taken into account in some cases (Misra et al., 1998; O'Grady et al., 2006; Razakamanarivo et al., 2012), roots are not usually removed from the ground because it complicates and considerably increases the harvesting costs. Biomass prediction therefore generally focuses on the estimation of above-ground biomass.

Tree biomass is commonly estimated using fitted regression relationships which relate data from the dimensions of standing trees and the dry weights of the components and whole tree. Thus, tree biomass is calculated directly using data from easily collected tree characteristics (e.g. diameter at breast height or total height) at tree level or variables derived from inventories (e.g. basal area or dominant height) at stand level.

1.2.3.2. Growth and yield models

Growth functions describe the change in size of an individual or stand population over time. They are very useful to predict forest development and so select the best management strategies to implement in plantations. Yield models predict the size of the tree or population at a certain point in time and hence they can be used in association with growth functions to predict production at a given time of plantation development.

The selection of appropriate growth functions is an important aspect in the development of growth and yield models because their behaviour when extrapolated may be quite different depending on the underlying mathematical properties involved (Burkhart and Tomé, 2012).

Models can be classified as empiric or mechanistic. The empirical approach is based on experimental data while mechanistic models include the physiological process involved in tree growth.

Empirical models are used most frequently for studying issues related to forest management (Pretzsch, 2010). However, although they can accommodate slight changes in environmental conditions their applicability is limited in a range of variability (Fontes et al., 2010). Therefore, environmental factors can be included in the model to make it more flexible use where there are small changes in conditions (Nunes et al., 2011).

Process based models are promising tools for understanding present and future forest growth because they take into account the physiological processes that control plant growth, such as photosynthesis and respiration, which depend on environmental conditions (Landsberg and Sands, 2010). Advocates of this approach often justify it stating that the predictive capability of models is improved through the incorporation of mechanisms associated with plant development. However, these models are often regarded as overly complex, requiring too many estimates of parameter values and variables for model initialization to be used as forest management tools (Bartelink and Mohren, 2004).

1.2.3.3. Nutritional and carbon content and energy potential

Bioenergy plantations where high plant stockings and short rotations are used and all tree components are harvested extract more biomass than conventional forests for pulp or wood and therefore they have a higher mineral export (Nguyen Thé et al., 2010). This has an environmental impact in terms of soil impoverishment because extraction may compromise the agricultural or forestry potential of the land in the future (Raulund-Rasmussen et al., 2008). A nutritional evaluation of the plantations is therefore essential to generate information on rotation nutrient extraction depending on site production and thus perform sustainable forest management in bioenergy stands.

In recent years, the estimation of forest carbon stocks has gained prominence due to the role of forests in the mitigation of global climate change through carbon storage in biomass and soil (Ruiz-Peinado et al., 2012). CO_2 capture to reduce global warming is one of the incentives of promoting bioenergy stands and hence the quantification of carbon stocks in energy crops is important to incorporate this aspect into forest management and planning.

The study of biomass energy properties provides essential information on the use and transformation of woody crops as biofuels. Calorific value, which is specific to a species, and other stand characteristics are necessary due to energy potential being an important issue from an economic perspective.

1.3. Experimental design

The information used in this Thesis came from an experimental network of 40 permanent plots designed exclusively for the study of the plantations, located in the distribution area of the *E. nitens* bioenergy stands in the Spanish Atlantic Arc, in Galicia (Figure 1.1). This network covers the environmental variability of the existing bioenergy stands in the region and the range of stockings used for this species as energy crops (Sims et al., 1999a, 2001).

Further information about the experimental design and the stands characteristics as well as data collection is fully explained in Chapters 2-5.

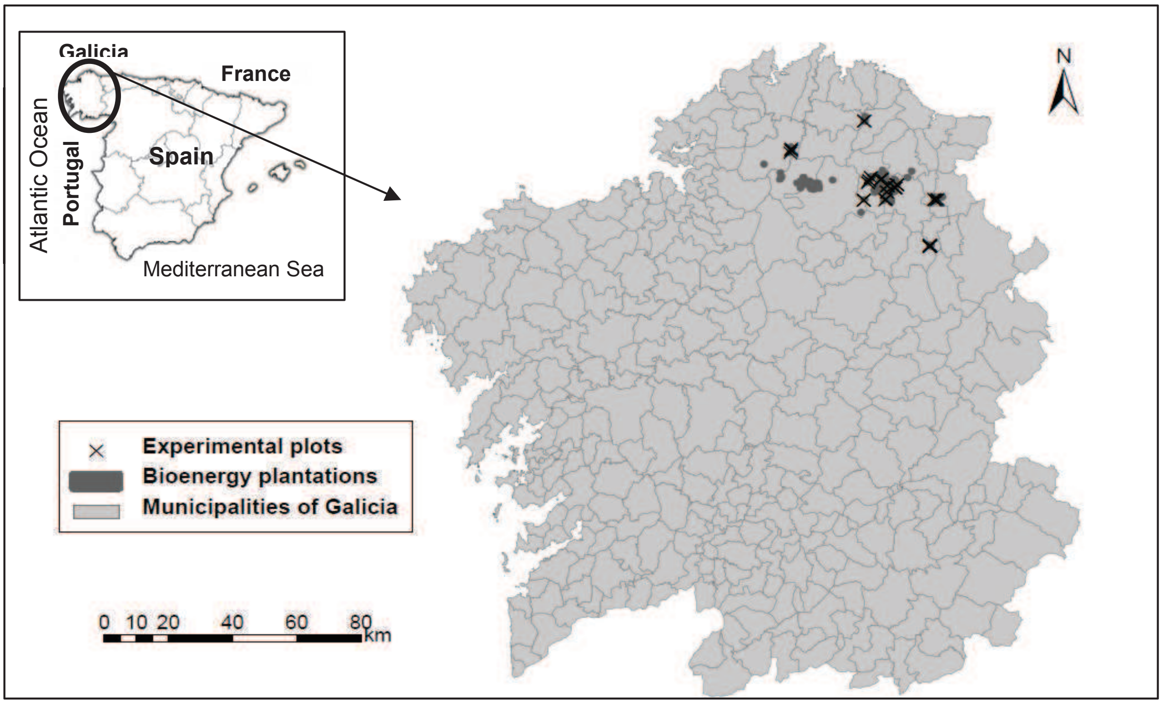

Figure 1.1. Distribution of *Eucalyptus nitens* bioenergy stands in the region of Galicia and location of the network of permanent plots used in this Doctoral Thesis.

1.4. Objectives

The main objective of this Doctoral Thesis was to assess the productivity of short rotation *Eucalyptus nitens* plantations for the generation of biomass and renewable energy targets in Northwest Spain.

The specific goals were the following:

- To develop prediction tools for estimating above-ground biomass and volume at tree and stand level (**Chapter 2**).
- To study stand growth and productivity considering the influence of environmental factors and management strategies, addressed through different modeling approaches: A dynamic growth and yield model (**Chapter 3**) and a process-based model (**Chapter 4**).
- To evaluate the nutritional and carbon content of above-ground biomass according to site productivity as well as the energy potential (**Chapter 5**).

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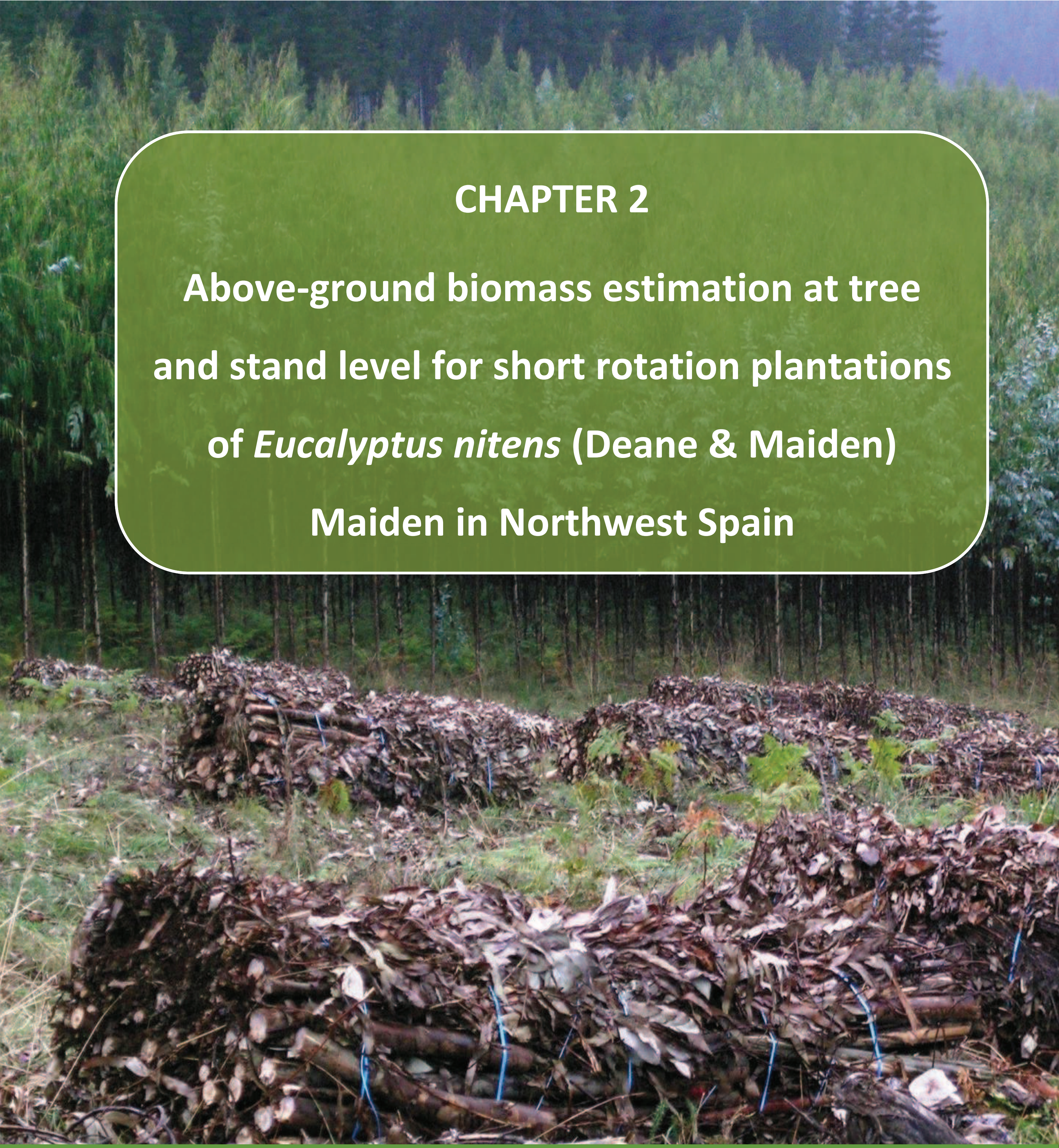

CHAPTER 2

Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain

Article reference

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CHAPTER 2. Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain

2.0. Abstract

Above-ground allometric biomass and Biomass Expansion Factor (*BEF*) equations were developed in *Eucalyptus nitens* crops, in age sequence from 2 to 5 years and densities between 2300 and 5600 trees ha^{-1}. All models were fitted for crown, stem and above-ground biomass at tree and stand level and explained a high percentage of data variability ($R^2_{adj} > 0.90$). *BEF*s were calculated for all categories and showed great variation, mainly for crown and above-ground biomass. *BEF*s and stand-tree variable behaviour was analysed to develop *BEF* models to improve the predictions of constant *BEF* calculated here.

Although all studied variables had significant relationships with *BEF*, dominant height showed the closest correlation with the crown and above-ground biomass, the equations explaining 99 % of biomass variability. Quadratic mean diameter, basal area and age were selected for the stem model. They explained more than 87 % of the stem biomass variability. The comparison of the three approaches, biomass and *BEF* equations and constant *BEF*s, showed that biomass equations provided the most accurate predictions for stem and total components, followed by *BEF* equations. Constant *BEF*s proved the least accurate method for estimating biomass and only provided satisfactory results in relation to stem biomass. In contrast, for the crown component, *BEF* equations provided slightly more accuracy predictions than biomass equations.

The best methodology for biomass production estimation depends on available resources and the level of required accuracy; however, our results suggest that constant *BEF* should be avoided whenever possible, at least for crown and above-ground biomass.

Keywords: Above-ground biomass equations, Biomass expansion factor (*BEF*), Woody crops.

2.1. Introduction

Short Rotation Forestry (*SRF*) refers to fast growing tree species with special characteristics which enable high biomass yields to be produced in a short period of time. Generally this biomass is used to obtain heat and electricity in combustion or second generation biofuels like bioethanol (McKendry, 2002).

SRF may go some way to meeting energy demands currently met by fossil fuels in addition to contributing to the mitigation of climate change due to the great potential of young or middle-aged stands to sequester carbon and avoid fossil fuel emissions through bioenergy use, especially if they can be intensively managed (Zhang et al., 2012).

Eucalyptus species are commonly used nowadays as woody crops because of their fast growth and high productivity. Furthermore, they adapt well to various sites and their management is simple compared with other common forest species. Consequently, *Eucalyptus* spp. is one of the most important commercial species in Spain and its principal use is in pulpwood production. In Galicia, the region of the country with the highest surface area covered by these species, *Eucalyptus* stands comprise 18 % of the total forests cover (DGCN, 2012).

Eucalyptus nitens (Deane & Maiden) Maiden began to be used in reforestation in Spain in the nineties, expanding into northern inland areas where the most widespread *Eucalyptus* species (*Eucalyptus globulus* Labill) was not able to survive due to the low temperatures (Neilsen, 1990). In addition to frost resistance (FAO, 1981; Prado and Barros, 1989), *E. nitens* has great potential as an energy crop due to its fast development, high yields and resistance to pests and diseases. A regional study in the north of Spain showed a greater energy potential in the various tree components of *E. nitens* compared to *E. globulus* when forest waste was used for biomass production (Pérez et al., 2006). This is very interesting due to *E. nitens* wood value is lower than *E.*

globulus due to the higher specific consumption for pulp production so it is a promising species for energy use and market price stability. Hence the establishment of this species in Northwest Spain as short rotation plantations for energy production.

Biomass estimation methods are very important for quantifying the energy potential or carbon stock in forests in order to meet the Kyoto Protocol objectives as well as for other environmental and nutritional stability studies. The most important tools for this are biomass equations and biomass expansion factors (*BEF*s). Biomass equations are mathematical relations which transform tree or stand variables (e.g. diameter at breast height, total height, basal area, dominant height etc.) into biomass estimates. *BEF*s on the other hand, are multipliers that enable the expansion of the growing stock (i.e., the stem volume of living trees) to be calculated, for total or component biomass, at tree or stand level (Lehtonen et al., 2004; Somogyi et al., 2007; Wirth et al., 2004).

Most of the available *BEF*s are constant and only volume data are required for biomass calculation. However, these constant *BEF* values for each species are average values which, it is widely acknowledged, are sometimes inaccurate because they depend on the age and plant density of the stand and site quality (Black et al., 2004; Kauppi et al., 1995; Lehtonen et al., 2004; Pajtík et al., 2008; Peichl and Arain, 2007), something which is even more marked in young stands because they change so rapidly over time (Pajtík et al., 2008; Skovsgaard and Nord-Larsen, 2012). To reduce the inaccuracy of constant *BEF* values, *BEF* equations have been developed recently in specific studies, including stand variables as predictors (Faias et al., 2009; Guo et al., 2010; Soares and Tomé, 2012; Teobaldelli et al., 2009). In Spain, Castedo-Dorado et al. (2012) developed different biomass and *BEF* equations for the major commercial species in the Northwest of the country. With regard to *E. nitens*, a recent study to quantify biomass using equations was carried out by (Pérez-Cruzado and Rodríguez-Soalleiro, 2011) in traditional pulp production plantations with tree stocking densities between 500 and 1600 ha^{-1}. However for short rotation (2-5 years) and high tree density (2300-5600 ha^{-1}) plantations there are no estimation tools available at the moment. Such methods would be of great value for forest management decisions in addition to quantifying biomass and carbon stock. Therefore, the objective of this work is to develop biomass prediction tools at tree and stand level (equations and constant *BEF*s) for *E. nitens* short rotation plantations in Northwest Spain and to carry out a comparison of the accuracy of each approach.

2.2. Material and methods

2.2.1. Material

2.2.1.1. Study area

The study was carried out in Galicia, in the northwest of Spain. The area has a temperate Atlantic climate with mean temperatures of the warmest and the coldest month of 19°C and -5°C respectively, and an annual precipitation of 1000-1500 mm, distributed throughout the year with the lowest monthly rainfall during summer. The inland areas generally have periods of frost (up to 50 days per year in total) from December to February. According to FAO (1991) the soils in this region are Rankers and Humic Cambisols. The coordinates of the plots were 43° 10’ 27”- 43° 32’ 56”N and 7° 48’ 39”- 7° 14’ 10”W.

2.2.1.2. Characteristics of the stands and data collection

Forty square experimental plots of 400 m^2 size were identified and selected in the study area. They were subjectively chosen to represent the existing range of ages, stand densities and site conditions. The tree stocking ranged from 2300 to 5500 ha^{-1} in either single or double row and plantation age from 2 to 5 years. Due to the young stage of the plantations, less than 5 years, and the importance of planting time for the initial growth of the tree in the first year, the exact stands age was calculated. For this purpose, the difference between the plantation and the measurement date in addition to the length of vegetative growth period were taken into account. The elevation ranged between 450 and 700 m above sea level. Soils were acid (pH (H_2O) < 5) with a high content of organic matter and an effective average depth of 0.43 m. The average slope of the plots was 13 %. Most of the stands were flat, an important characteristic which facilitates mechanization activities in this type of plantation (Defra, 2004). The following silvicultural treatments were carried out in the stands; fertilization in the first stage and chemical and mechanical weed control when needed to avoid competition problems.

Two inventories were carried out in all the experimental plots of the study area in the winter of two consecutive years, the second being just prior to the destructive biomass sampling. Table 2.1 presents the descriptive statistics of the main tree and stand variables of the plots used in this study.

Table 2.1. Summary statistics of the main plots variables of the two inventories.

Variable	Inventory	Min.	Max.	Mean	Std. Dev.
Age – t (years)	1	1.56	3.56	2.35	0.74
	2	2.56	4.56	3.35	0.74
N° of trees per hectare – N (trees ha^{-1})	1	2375	5600	3664	834
	2	2375	5550	3641	826
Basal area – G (m^2 ha^{-1})	1	0.46	14.28	4.18	3.56
	2	1.97	29.30	9.38	4.67
Dominant height – H_0 (m)	1	2.39	9.75	5.07	1.87
	2	4.28	13.35	7.71	2.07
Total height – h (m)	1	0.46	10.40	3.78	1.79
	2	1.00	14.16	6.00	2.03
Diameter at breast height – d (cm)	1	0.15	10.27	3.42	1.86
	2	0.30	13.30	5.35	2.12

Diameter at breast height, dbh (d), total height (h) and height of the live crown (h_v) were measured in all trees within the plots using callipers and digital hypsometer, respectively. The information about diameter and height distribution was used to select the tree sample for developing biomass and volume models. At the end of the study, a total of 120 trees covering, as far as possible, the variation in tree height for a given diameter, were selected for destructive sampling. All selected trees were taken from the middle of the plantations to avoid the edge effect on the tree variables (Verwijst and Telenius, 1999). Figure 2.1 shows the relationship between height and diameter of the selected trees.

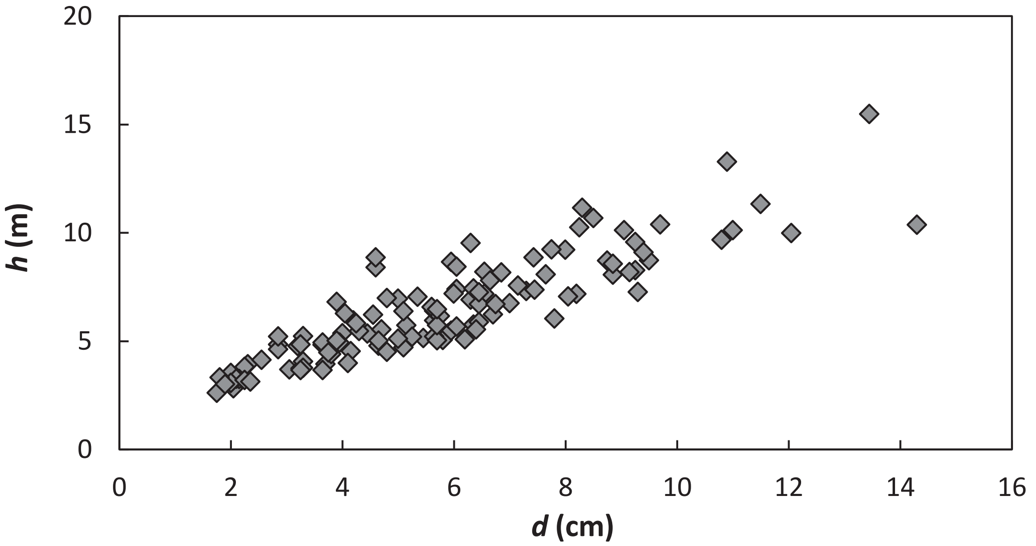

Figure 2.1. Scatter plot of the total tree height (*h*) against diameter at breast height (*d*) for the sample of trees destructively sampled.

The classic destructive sampling methodologies used for conventional forestry (i.e. for timber purposes) is not appropriate for short woody crops (Senelwa and Sims, 1997; Verwijst and Telenius, 1999) due to the small tree sizes because young age of the trees and the high stocking used to produce biomass as quickly as possible. In addition, *Eucalyptus* bioenergy plantations employ a whole tree harvester and all tree biomass is used to produce energy hence the calculation of the biomass of individual tree components (i.e. leaves, thick branches, thin branches, dead branches, bark, wood, etc.) is not a priority for the user. Therefore, in this study as well as above-ground tree biomass, only crown and stem components were considered to estimate above-ground biomass, which is more appropriate and useful.

After each tree was felled, diameters at breast height, total height, and height of the live crown were measured using callipers and measuring tape, to the nearest 0.1 cm and 1 cm respectively. Above-ground tree biomass was separated into crown biomass and stem (barked logs with a thin-end diameter of 2 cm). The fresh weight of the crown was measured to the nearest 50 g and representative subsamples were selected and weighted in the field. The crown subsamples were an estimation of the proportion of sample fresh weight, approximately 25 %, over the total fraction fresh weigh. The stem was divided into logs of 0.5 m long and subsequently weighted to the nearest 100 g. Three wood disks were cut from each stem at regular intervals. These disks together with the crown subsamples were weighted fresh in the field and taken to the laboratory to oven-dry at 65°C to a constant weight. Based on the ratio of dry biomass to fresh biomass, the biomass of each component was calculated and then summed to obtain the above-ground biomass of each tree. Table 2.2 lists the descriptive statistics of the sampled trees.

Table 2.2. Descriptive statistics of sampled trees for fitting of the biomass and volume equations.

Variable	**Min.**	**Max.**	**Mean**	**Std. Dev.**
h (m)	2.61	15.48	6.43	2.33
h_v (m)	0.40	7.40	2.69	1.38
d (cm)	1.75	14.30	5.77	2.58
W_{Crown} (kg)	0.19	12.17	2.72	2.30
W_{Stem} (kg)	0.30	34.79	4.90	5.27
W_{AGB} (kg)	0.58	45.87	7.60	7.44
V (dm^3)	1.26	137.71	19.76	21.95

2.2.2. Methods

2.2.2.1. Above-ground biomass models and fit

Allometric equations are widely used for forest biomass assessment (Cannell, 1984; Kauppi et al., 1992; Nelson et al., 1999) and relate the growth of one part of an organism to another part or to the tree as a whole (Keith et al., 1999). Hence, the above-ground biomass and its components were regressed on tree or stand variable using the following power function:

$$W_i = \beta_0 \cdot X^{\beta_1} + e_i \qquad (2.1)$$

where W_i represents the biomass of each tree component (i=stem, crown or above-ground) at tree level (kg) or at stand level (Mg ha^{-1}), X denotes the independent tree or stand variable, β_0, and β_1 are parameters and e_i is the model error.

The equations were fitted individually and the heterocedasticity, inherent to biomass or volume equations, was corrected by weighted regression. Weighting factors were obtained using the method proposed by Harvey (1976). The homocedasticity of the residues was checked by White´s Test (*WT*) (White, 1980). Collinearity among variables may produce errors in parameters or in regression coefficients (Kleinbaum et al., 1988; Myers, 1986). Its presence was evaluated with the condition number (*IC*). According to Belsey (1991) and Draper and Smith (1981) an *IC* in the range of 30-100, is indicative of problems associated with collinearity, and if *IC* is above 1000 it suggests the problems are serious.

Finally a nonlinear simultaneous equation system at each level (tree and stand) was fitted, considering the above-ground biomass equation as a sum of the stem wood and crown biomass equations in order to ensure additivity for biomass estimation (Parresol, 2001). Parameter estimation of the models was accomplished by Seemingly Unrelated Regression (SUR), using SAS/ETS® Model Procedure (SAS Institute Inc., 2004a).

The complete process was implemented for two systems of equations depending on the included variables at tree and stand level. At tree level, one of the equation systems was fitted using exclusively diameter as predictor variable to simplify the model while in the other system all the tree variables were taken into account to find out the most accurate system. The independent variables were total height (*h*), live crown height (h_v) and diameter at breast height (*d*) (Table 2.2). On the other hand, using the same strategy that at tree level, two families of equations were obtained for the stands, one of them using only basal area and the other including the best explanatory variables. At this level, the studied variables were age of the stand (*t*), number of trees per hectare (*N*), basal area (*G*), dominant height (H_0) and quadratic mean diameter (*dg*) (Table 2.1).

2.2.2.2. Biomass expansion factor (*BEF*) models and fit

Volume data are necessary to obtain *BEF*s. For this purpose, tree volume over bark was calculated as the sum of the individual log volumes estimated with the Smalian formula considering the top section of the tree as a cone. *BEF*s at tree level were calculated with sample trees volume and biomass in order to study the allometry of the species and to provide a constant value for each component of the tree.

Since volume equations are not available for short rotation plantations of *E*. *nitens* so they were developed in this work. Thereafter, allometric equations were fitted at tree and stand level using weighted regression to account for heterocedasticity in a similar way to in the biomass models. In addition, depending on the explanatory variables included in the equations two types of models were developed with the same objectives and characteristics than in the biomass functions. A correlation analysis was carried out to select the best variables of the listed in the previous section to be used as independent variables for the most accurate volume model at tree and stand level. Finally

*BEF*s were computed for all the plots using stand biomass and volume. *BEF* was calculated with the following equation:

$$BEF_i = \frac{W_i}{V_i} \qquad (2.2)$$

where BEF_i represents the biomass expansion factor (tree level: kg m^{-3}; stand level: Mg m^{-3}), W_i is dry weight of above-ground biomass (tree level: kg; stand level: Mg ha^{-1}) and V_i is the total volume over bark (tree level: dm^3; stand level: m^3 ha^{-1}).

Although this work focuses on predicting *BEF* equations, a constant value of *BEF* at stand level was calculated as the average value of all plot *BEF*s so that it could be compared with the values obtained from the equations.

Several stand variables were computed for each plot: age of the stand (t), number of trees per hectare (N), basal area (G), dominant height (H_0) and quadratic mean diameter (dg).

A correlation analysis was carried out to study the possible relationship between *BEF* and the main variables at tree and at stand level. For this purpose a lineal model was considered and the Corr Procedure of SAS/STAT® (SAS Institute Inc., 2004b) was used. Positive correlation means that one variable increases, when the other tends to increase and negative correlation implies the opposite trend. Complementarily coefficients close to ±1 show a strong correlation and a t-test is utilized to determine if the correlation coefficient is significant (p-value < 0.05) or not.

Finally, the selection of the best stand variables for use in the *BEF* equations was decided by correlation analysis results and graphs.

2.2.2.3. Model evaluation and comparison

The performance of the biomass, volume and *BEF* equations was assessed through graphical analysis and goodness of fit statistics. The comparison statistics used were the adjusted coefficient of determination (R^2_{adj})

and the root mean square error (*RMSE*). The adjusted coefficient of determination measures the amount of observed variability explained by the model and the *RMSE* provides a measure of the precision of the estimates in the same units as the dependent variable. Calculations were made following the formulas:

$$R^2_{\text{adj}} = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \cdot \frac{n-1}{n-p} \qquad (2.3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-p}} \qquad (2.4)$$

where Y_i is the real value, $\hat{Y}_i$ is the value predicted by the model, $\bar{Y}$ is the average value, all of which refer to the dependent variable under study, *n* is the total number of observations and *p* represents the number of parameters included in the model.

The use of a new independent dataset is the only method that can be regarded as a truly appropriate validation for a new model (Vanclay and Skovsgaard, 1997). Alternative approaches can be employed for this purpose, like splitting the dataset into two portions or double cross-validation, although, they do not provide any additional information about the predictive ability of the models (Kozak and Kozak, 2003; Yang et al., 2004). Unfortunately, in this work no validation dataset was available and therefore it was decided that the best strategy was to use all the datasets to fit the best and strongest model.

Finally, a comparison of the three approaches of above-ground stand biomass estimation (biomass and *BEF*s equations and constant *BEF*) was carried out. In this comparison, the errors for the different methods were calculated as the difference between the stand biomass obtained with the aggregation of the biomass of all trees in the plot (by applying the tree biomass equations) and the biomass estimated at stand level using the three analysed approaches.

A schematic representation of the complete process with all the specific phases at tree and stand level is shown in Figure 2.2.

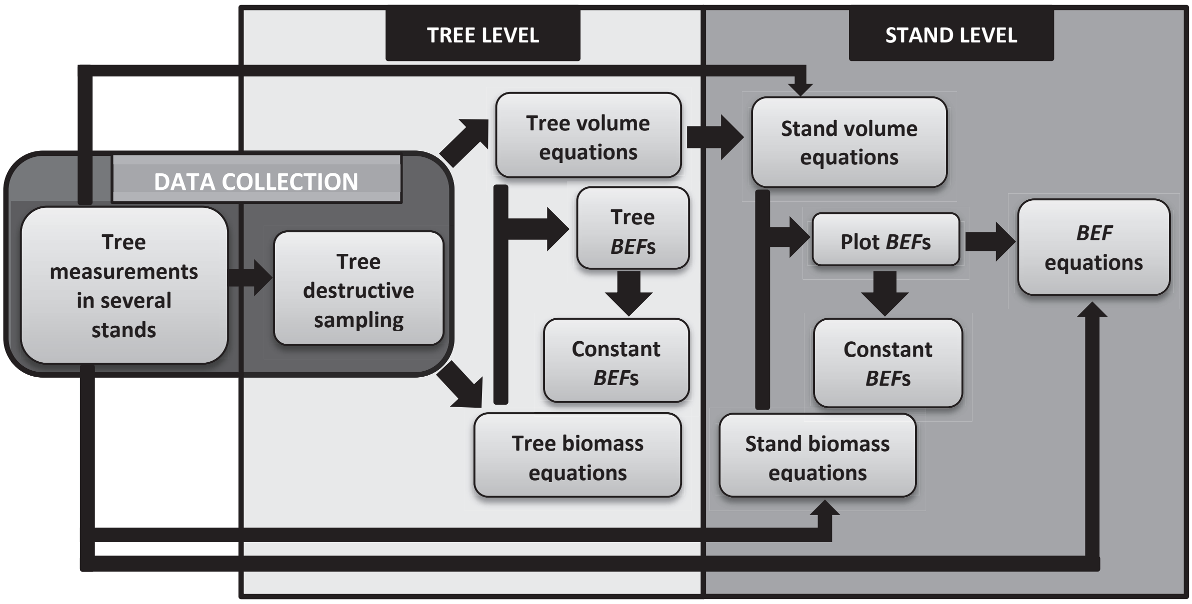

Figure 2.2. Scheme of the process followed in the three approaches of above-ground biomass estimation used in this work.

2.3. Results and discussion

2.3.1. Above-ground biomass equations

Information about tree and stand biomass equations is given in Table 2.3. Diameter was the main predictor tree variable because it shows a high correlation with all tree biomass components (Antonio et al., 2007; Pajtík et al., 2008; Razakamanarivo et al., 2012; Sochacki et al., 2007). In addition, measuring diameters is easier and cheaper than other tree variables. Hence, a biomass equation system using only diameter as explanatory variable is provided in this work. However the combination of diameter with other tree variables, e.g. total height, generally improve the accuracy of the biomass equations (Antonio et al., 2007; Sochacki et al., 2007; Zewdie et al., 2009). Hence, all possible combinations of the variables were tested and the most accurate equation system was developed to obtain the best fit. Finally, for this system, together with diameter, live crown height for the crown component and total height for the stem were selected to introduce in the models. These models explain between 92 % and 98 % of tree sample variability compared with the simplified models whose results range from 90 % to 94 %.

The best predictor variable at stand level for crown and stem components was basal area. The simplified equation system reached accurate results with R^2_{adj} approximately between 96 and 99 %. However the inclusion of dominant height in the equations considerably improved R^2_{adj} and *RMSE* decreased. Hence, both variables were selected to be used in the most accurate biomass stand system. All the estimate parameters for the two levels, tree and stand, were highly significant at p-value < 0.0001. As expected, the best coefficients of determination were obtained for equations at stand level with values close to 1. However all the values were above 0.9, indicating a high degree of accuracy for the above-ground biomass estimation. White´s Test and predicted residue graphs showed that heterocedasticity was corrected by weighted regression for all the functions. The values of the condition numbers (*IC*) were in all the systems fewer than 40, indicating that there were no serious collinearity problems. Taken together, the results suggest that the equations developed are suitable for application to stands with similar characteristics to those analyzed here.

Table 2.3. Estimated parameters and statistical values for dry weight biomass equations and for overbark volume functions at tree and stand level.

Level	**Equation**	**Type**	**Component**	**Equation**	***RMSE***	R^2_{adj}	***WT***
Tree	**Biomass**	Simplified	Crown	$W_{\text{Crown}} = 0.113 \cdot d^{1.742}$	0.6875	0.9116	0.2601
			Stem	$W_{\text{Stem}} = 0.081 \cdot d^{2.201}$	1.6229	0.9059	0.7642
			Above-ground	$W_{\text{AGB}} = W_{\text{Crown}} + W_{\text{Stem}}$	1.8577	0.9382	0.6109
		Accurate	Crown	$W_{\text{Crown}} = 0.090 \cdot d^{2.012} \cdot {h_V}^{-0.276}$	0.6369	0.9242	0.2470
			Stem	$W_{\text{Stem}} = 0.040 \cdot d^{1.580} \cdot h^{0.945}$	0.8040	0.9769	0.9690
			Above-ground	$W_{\text{AGB}} = W_{\text{Crown}} + W_{\text{Stem}}$	1.2356	0.9727	0.5741
	Volume	Simplified	Stem	$V = 2.990 \cdot 10^{-4} \cdot d^{2.240}$	0.0053	0.9432	0.0642
		Accurate	Stem	$V = 1.571 \cdot 10^{-4} \cdot d^{1.775} \cdot h^{0.772}$	0.0022	0.9903	0.8091
Stand	**Biomass**	Simplified	Crown	$W_{\text{Crown}} = 1.446 \cdot G^{0.810}$	0.8120	0.9592	0.6074
			Stem	$W_{\text{Stem}} = 0.887 \cdot G^{1.211}$	1.3651	0.9737	0.3748
			Above-ground	$W_{\text{AGB}} = W_{\text{Crown}} + W_{\text{Stem}}$	1.1069	0.9919	0.6831
		Accurate	Crown	$W_{\text{Crown}} = 2.525 \cdot Ho^{-0.465} \cdot G^{0.982}$	0.6378	0.9748	0.5934
			Stem	$W_{\text{Stem}} = 0.429 \cdot Ho^{0.589} \cdot G^{0.998}$	0.7036	0.9930	0.2739
			Above-ground	$W_{\text{AGB}} = W_{\text{Crown}} + W_{\text{Stem}}$	0.8485	0.9952	0.9229
	Volume	Simplified	Stem	$V = 3.292 \cdot G^{1.248}$	4.477	0.9825	0.0505
		Accurate	Stem	$V = 1.808 \cdot Ho^{0.504} \cdot G^{1.055}$	2.1872	0.9958	0.2102

where W is individual tree (kg) or stand (Mg ha^{-1}) biomass and V is individual tree volume (m^3) or stand volume (m^3 ha^{-1}) depending on the level of the equation, d represents diameter at breast height (cm), h is total height (m), h_v denotes height of the live crown (m), G is the basal area (m^2 ha^{-1}), H_0 represents dominant height (m), *RMSE* is the root mean square error for the tree (kg) or the stand equation (Mg ha^{-1}), R^2_{adj} is the adjusted coefficient of determination of the model and *WT* is the result of heterocedasticity White´s Test ($\alpha < 0.05$).

2.3.2. Biomass expansion factors

The first step to calculate *BEF*s is to develop tree volume equations. These equations were fitted firstly at tree level to estimate, then at stand level. The goodness of fit statistics (Table 2.3) and the graphical analysis showed the models to be good.

Biomass components demonstrate various natural changes depending on site index and the tree development phase (Satoo and Madgwick, 1982). The wood proportion increases with age while that of leaves and branches decrease (Aparicio, 2001; Bonomelli and Suárez, 1999; Peichl and Arain, 2007). Therefore, constant values of biomass expansion factors are highly variable and generally inaccurate (Faias et al., 2009; Lehtonen et al., 2004; Soares and Tomé, 2012, 2004; Somogyi et al., 2007). This leads to biomass underestimations in young or poor quality stands and, on the contrary, overestimations in mature or highly productive stand (Brown and Schroeder, 1999; Fang et al., 1998; Schroeder et al., 1997).

Constant *BEF*s (average values) of 0.43 and 0.50 were obtained at tree and stand level respectively from the above-ground biomass data. Table 2.4 shows *BEF* values for both studied levels and in general for crown and above-ground *BEF*s. The values ranged widely because they are dependent on age and other tree or stand characteristics. In contrast, stem *BEF*s were very constant which could be due to the fact that the variables used to calculate stem *BEF*, volume and biomass, whose relation is the basic density of wood, are obviously proportional.

Table 2.4. Constant (average value) and extremes values of *BEF* calculated at tree (kg dm^{-3}) and stand level (Mg m^{-3}).

		BEF			
Level	**Component**	**Constant**	**Min.**	**Max.**	**Std. Dev.**
Tree	**Crown**	0.17	0.06	0.38	0.06
	Stem	0.25	0.20	0.34	0.03
	Above-ground	0.43	0.26	0.82	0.09
Stand	**Crown**	0.25	0.09	0.62	0.12
	Stem	0.25	0.24	0.27	0.01
	Above-ground	0.50	0.35	0.89	0.13

Apart from the stem component, it seems that use of constant *BEF* values may induce serious errors in biomass or carbon estimation such that the development of *BEF* equations is the recommended approach when the data are available (Faias et al., 2009; Guo et al., 2010; Jalkanen et al., 2005; Sabaté, et al., 2005; Sanquetta et al., 2011; Tobin and Nieuwenhuis, 2007). *BEF*s are age dependent because tree allometry and biomass partitioning varies as a function of age (Kauppi et al., 1995; Lehtonen et al., 2004; Pajtík et al., 2008). It is important to highlight that in this study, it is considered that tree age is the same variable as stand age because it is forest plantations that are under consideration.

All coefficients of correlation for crown and above-ground *BEF* were significant (p-value < 0.0001) and negative, decreasing with tree size and increasing age. The correlation analysis indicates that total height is the tree variable most closely associated with these *BEF*s, followed by diameter and age. Total height has also been found to be the most accurate explanatory variable to estimate tree *BEF* in other studies (Levy et al., 2004; Sanquetta et al., 2011). On the other hand, stem *BEF* had no significant relationships with the main tree variables in this study for the reasons previously explained. Figure 2.3 shows the graphs which relate *BEF* values and tree variables. The graph lines represent the constant *BEF* for each studied category (stem, crown or whole tree) and p-value is the value of the significance test of the correlation analysis.

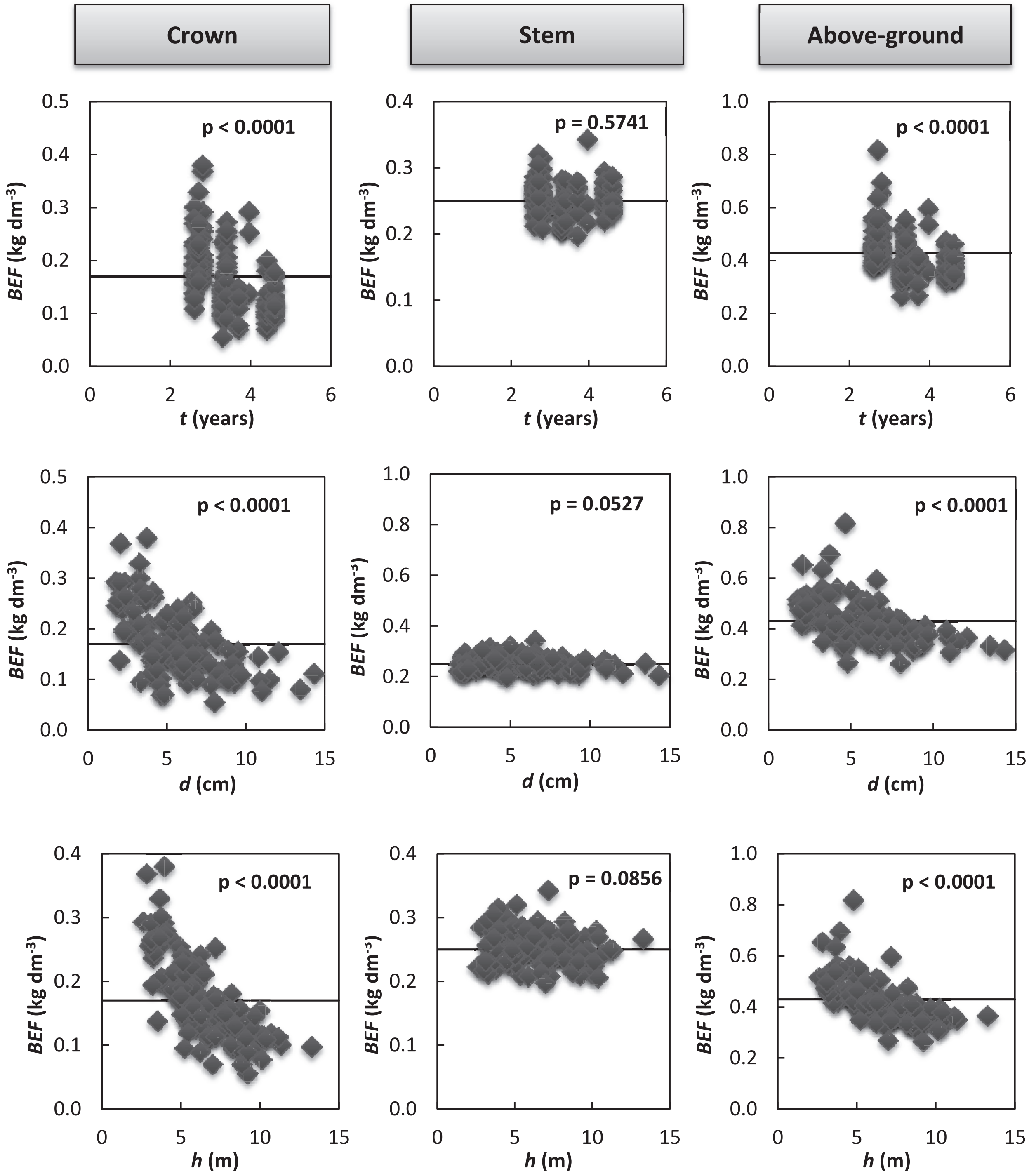

Figure 2.3. Relation between tree *BEF*s and tree variables: age (*t*), diameter at breast height (*d*) and total tree height (*h*) for crown, stem and whole tree. The graph lines represent the constant *BEF* (average) for each category and p (p-value) is the results of the test of significance in the correlation analysis.

The changes in the main tree components during stand development are shown in Figure 2.4. When plantations are very young, less than two years of age, crown biomass constitutes the main component of the tree. This is due to the fact that in the first stand stage, maximum foliage development is likely to be crucial for survival under competition conditions (Peichl and Arain, 2007). However, this changes when crown closure is achieved and stem growth is accentuated to ensure tree stability. As a result, in young stands *BEF* is highly variable because trees are in a vigorous growth phase which produces great changes in biomass partitioning (Black et al., 2004; Pajtík et al., 2008). However, this behaviour changes in older stands, where *BEF* presents an asymptotic behaviour due to the stabilization of growth rate (Sanquetta et al., 2011) and therefore, most of the tree biomass is allocated to the stem (Black et al., 2004; Pajtík et al., 2008; Peichl and Arain, 2007).

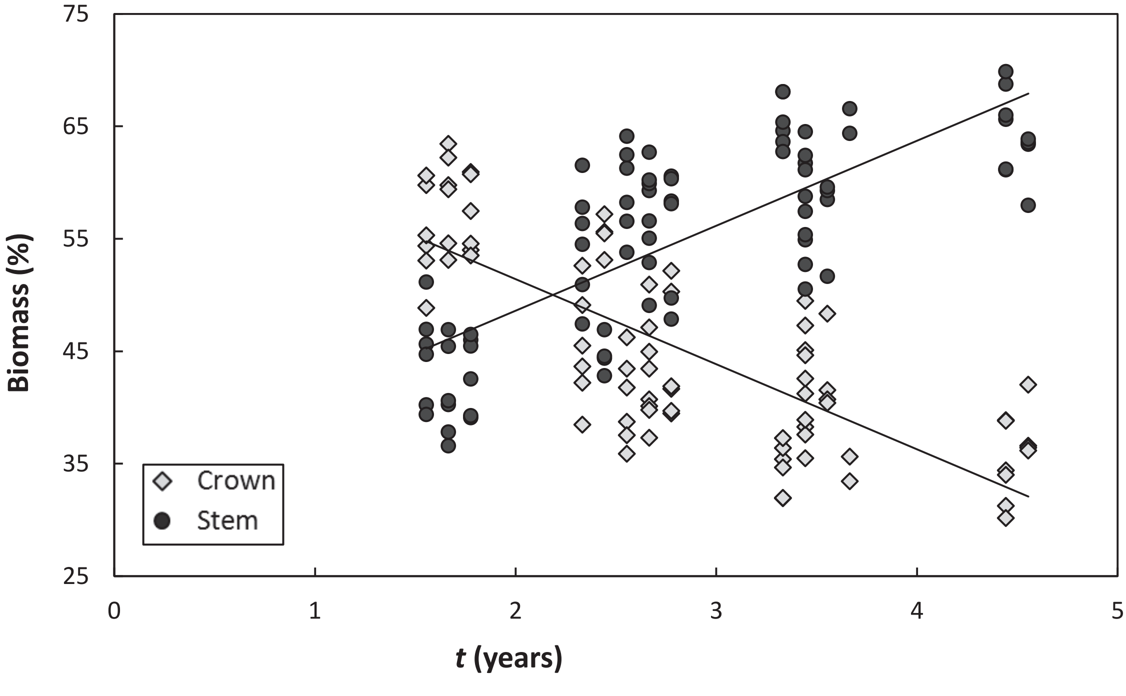

Figure 2.4. Relationship between crown and stem biomass as trees age in *E. nitens* short rotation plantations. Lines are non-parametric average lines of each tree component.

The analysis of the relationships between crown, stem and above-ground *BEF*s and stand variables showed highly significant correlations (< 0.001) for the variables age, basal area, dominant height and quadratic mean diameter and, additionally, the correlation with stocking was significant at the 0.05 % level (Figure 2.5). The analysed variables show a decreasing pattern over time, presenting a strong initial tendency which becomes almost negligible beyond a certain point (Lehtonen et al., 2004). This trend is clearest with dominant height, quadratic mean diameter and basal area (Castedo-Dorado et al., 2012; Soares and Tomé, 2004, 2012), and it tends to stabilize with the growth of the stand (Sanquetta et al., 2011). In addition, these results highlight the fact that when a constant *BEF* is used, estimations may have serious errors (Faias et al., 2009; Guo et al., 2010; Jalkanen et al., 2005; Sabaté, et al., 2005; Sanquetta et al., 2011; Tobin and Nieuwenhuis, 2007). However some studies have determined a limit for the use of constant *BEF* from a certain value of the predictor variable since when *BEF* is stabilized, the biomass estimation errors are minimised (Brown and Schroeder, 1999; Soares and Tomé, 2012). This could be a good way to simplify the calculations in mature stands where volume information is highly accessible. Nevertheless, it is not possible to apply this criterion in very young stands such as those studied here since there is not a clear constant value of *BEF*, although the tendency to stabilization does exist. Moreover, other error associated with volume estimation in small trees must be considered, since ratio between independent variables error mensuration and the average value of independent variables is very high on these small trees.

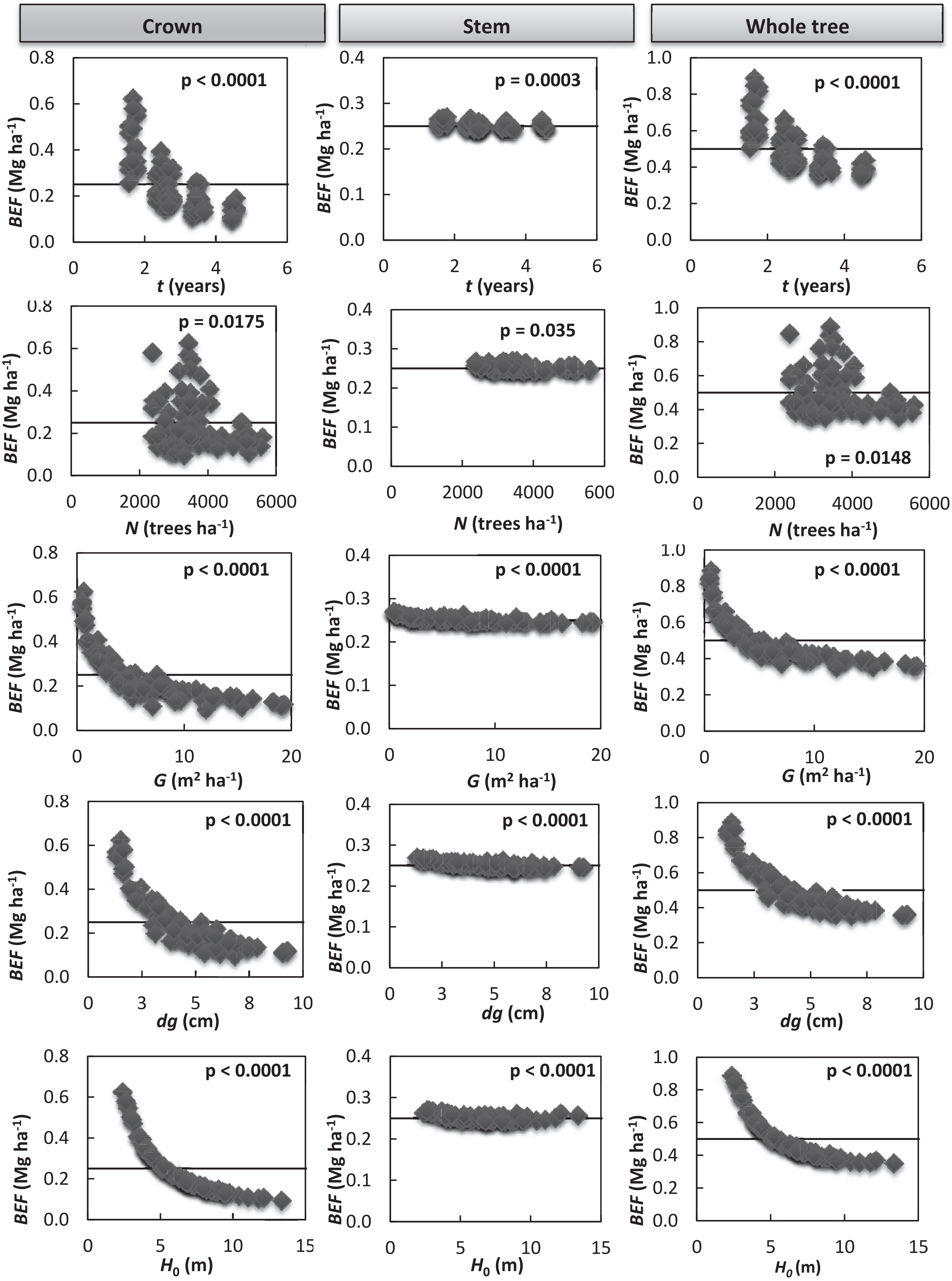

Figure 2.5. Relationship between stand *BEF*s and stand variables: age (*t*), number of trees per hectare (*N*), basal area (*G*), quadratic mean diameter (*dg*) and dominant height (H_0); for crown, stem and whole tree. The lines represent the constant *BEF* (average) or each category. p-value is the results of the test of significance in the correlation analysis.

BEF stand models were developed at three components (crown, stem and whole tree). Dominant height was the selected variable for crown and above-ground *BEF* models (Table 2.5) since it is the best variable to explain *BEF* conduct in other apically dominant species (Castedo-Dorado et al., 2012; Faias et al., 2009; Soares and Tomé, 2012). The dominant height function fitted in this study is the Schumacher's equation (Sit and Poulin-Costello, 1994) which was developed to modeling volume yield of even-aged timber stands. It has been used previously by Teobaldelli et al. (2009) in a *BEF* study with different conifers and broadleaved species. In this equation a new parameter was incorporated to improve the accuracy of the model, which reaches an R^2_{adj} of 0.99 in both levels. The selected model for stem *BEF*, however, was an allometric equation (2.1) combining the best explanatory variables, quadratic mean diameter, basal area and age.

Table 2.5. Estimated parameters and statistical values for *BEF* stand equations.

Component	Variable	Equation	*RMSE*	R^2_{adj}
Crown	H_0	$BEF_{\text{Crown}} = e^{-18.165+\left(18.812/Ho^{0.069}\right)}$	0.0062	0.9974
Stem	*dg, G, t*	$BEF_{\text{Stem}} = 0.250 \cdot dg^{0.040} \cdot G^{-0.052} \cdot t^{0.038}$	0.0025	0.8718
Above-ground	H_0	$BEF_{\text{AGB}} = e^{-1.622+\left(2.647/Ho^{0.622}\right)}$	0.0113	0.9921

where *BEF* is stand biomass expansion factor (Mg m^{-3}), H_0 is the dominant height (m), *G* denotes the basal area (m^2 ha^{-1}), *dg* is the quadratic mean diameter (cm), *t* is the stand age (years), *RMSE* is the root mean square error of the model (Mg m^{-3}) and R^2_{adj} is the adjusted coefficient of determination of the model.

2.3.3. Comparison of biomass estimation

In general, biomass prediction with allometric equations is considered to be the most realistic reference values for calculating biomass. For the stem component in this study, this is true, because the biomass equation (R^2_{adj}= 0.9930) with fewer dependent variables is more accurate than the *BEF* equation (R^2_{adj}= 0.8718) and volume equation (R^2_{adj}= 0.9903). Furthermore, constant *BEF* behaves well for this tree component due to the low variation in the value range of the plots. For the above-ground biomass, in contrast, the percentage of variability explained by the biomass equation (R^2_{adj}= 0.9952) was almost the same as that explained by the *BEF* equation including dominant height as stand variable (R^2_{adj}= 0.9921). In addition, the crown component R^2_{adj} increased from 0.9748 to 0.9974 when comparing biomass and *BEF* equations respectively, but showed a poor predictive capacity when constant *BEF* was tested.

The graphical comparison between the observed and the predicted biomass by the studied methods showed a good trend in the most of the situations. Nevertheless, bias was detected for the crown and the above-ground biomass when constant *BEF* was used, and the same tendency was also obtained using *BEF* equations with above-ground biomass (Figure 2.6).

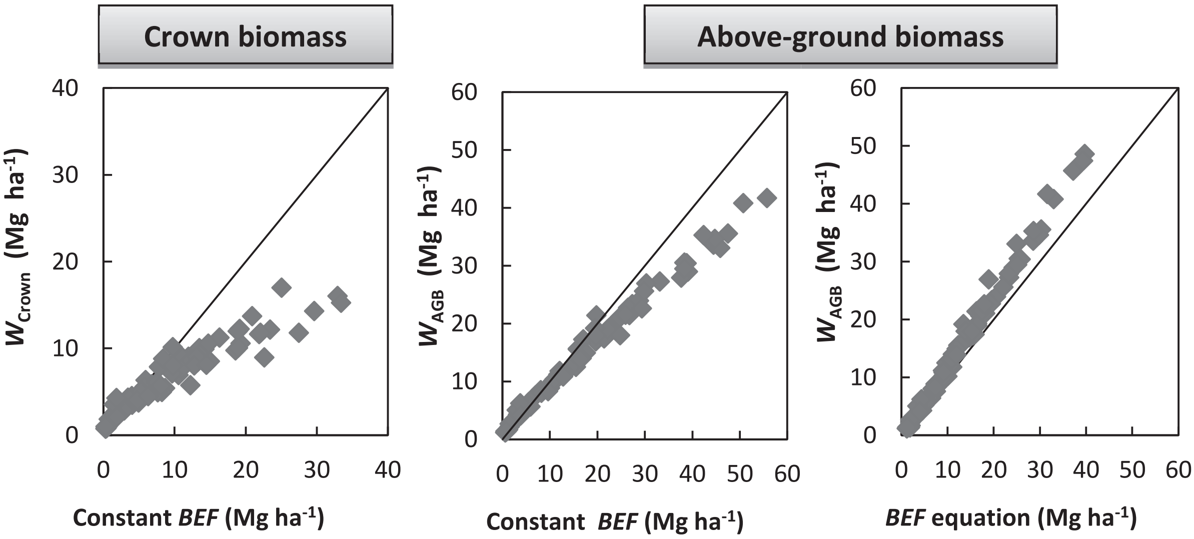

Figure 2.6. Observed biomass *vs*. biomass predicted by constant *BEF* for crown and by constant *BEF* and *BEF* equations for whole tree. The graph lines represent a line with slope of 1:1.

Applying biomass equations the general mean error was 0.04 Mg ha^{-1} for the crown and the above-ground biomass and 0.01 Mg ha^{-1} for the stem. It was found to be the most accurate methodology to calculate biomass for stem and total tree. However, for the crown biomass, the best results were obtained using the *BEF* equation (0.01 Mg ha^{-1}), although they are very similar to those of biomass equation, which could be the best method if volume errors had been considered. The constant *BEF* value approach was the least accurate method for all three levels, generally resulting in underestimation. Figure 2.7 shows the mean errors obtained with the different methods by stand age class.

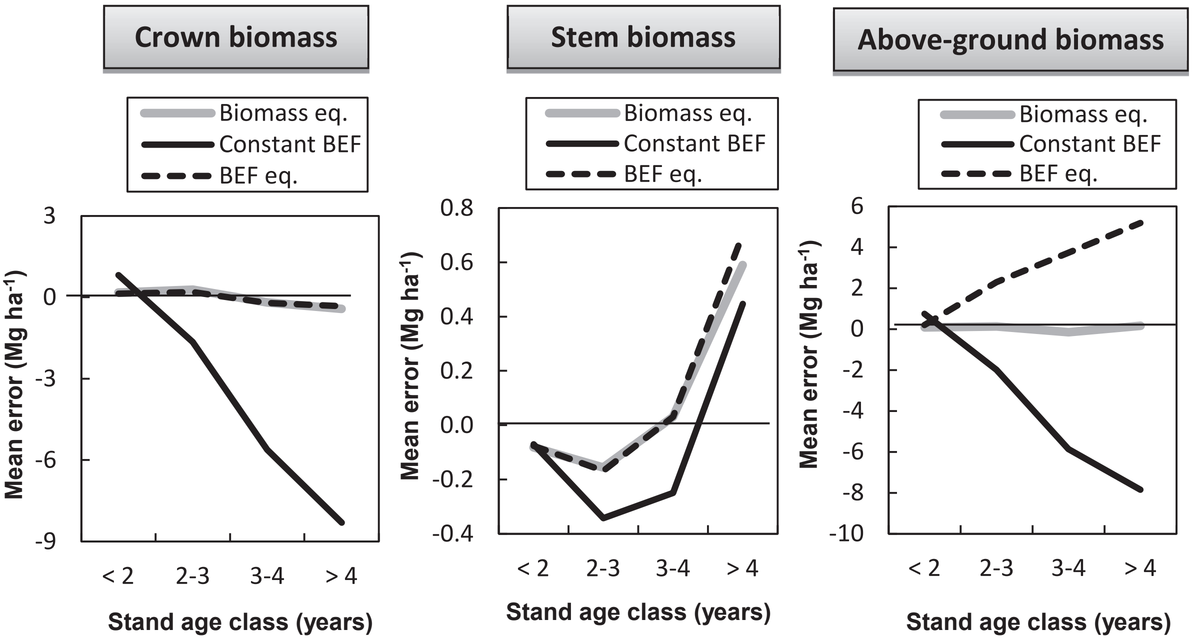

Figure 2.7. Mean errors of biomass estimations using allometric equations, constant *BEF*s and *BEF* equations by stand age class for crown, stem and above-ground biomass.

It particularly highlights the ranges of age for which the models provide especially poor or good predictions. As expected, constant *BEF* showed the greatest error in most variables and categories compared to biomass and *BEF* equations. However, this error is not very important in stem component where, although the other methods are more accurate in stands younger than 4 years, the mean error of constant *BEF* by age class did not reach 0.5 Mg ha^{-1}. For estimating crown component, as indicated above, either biomass or *BEF* equations could be used as their degree of accuracy is very similar in all stand classes, but constant *BEF* should be avoided because it produce an increasing level of bias as stand age increases. Finally, for above-ground estimations, biomass equation is seen to be the best methodology since with the stand growth model *BEF* tends to produce overestimations, and constant *BEF* underestimations, with a maximum mean error of 5.18 and 7.86 Mg ha^{-1} respectively.

2.4. Conclusions

In general *BEF*s had a good correlation with stand variables because they are age and site dependent. Dominant height, mean quadratic diameter, basal area and age had the strongest relationship with *BEF*. The *BEF* model, followed by biomass equation, provided the best predictions for the crown component even though the error in the intermediate step of volume estimation must be considered. On the other hand, although the best results for the stem fraction were obtained with biomass equations, biomass can be calculated with any of the studied methodologies because all of them provided good predictions. The biomass equation is the most accurate method for above-ground biomass followed by *BEF* function. Constant *BEF* value used as default underestimated biomass production and its use is not recommended when other methods are available except in stem component where it does not produce a high degree of errors.

The inclusion of variation in stand size and quality means that the biomass estimation methods which have been developed in this work can be used in other *E. nitens* woody crop plantations with similar characteristics. The user's selection of one of these methods over the other will depend on the available data and the accuracy required in the study.

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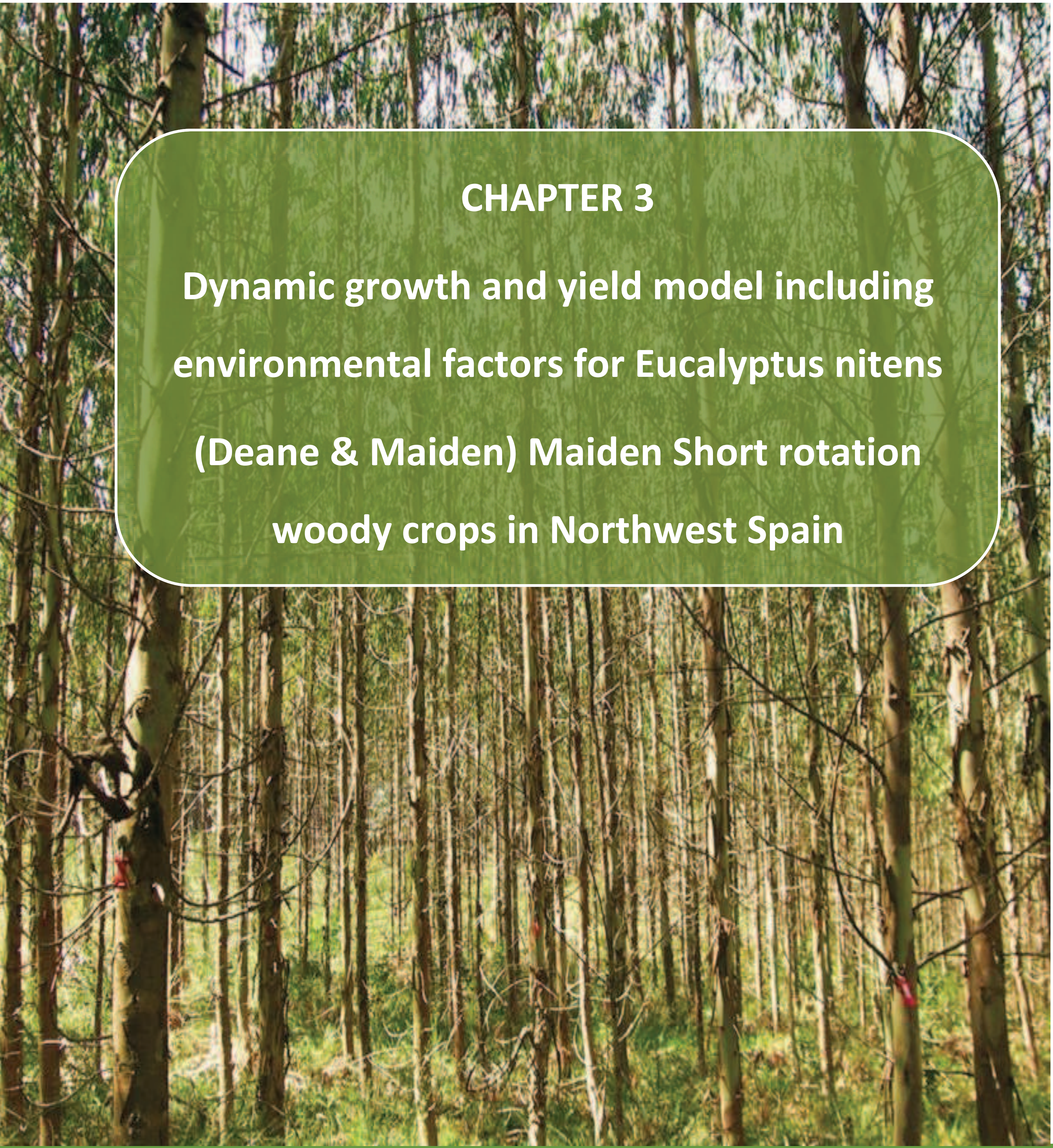

CHAPTER 3

Dynamic growth and yield model including environmental factors for Eucalyptus nitens (Deane & Maiden) Maiden Short rotation woody crops in Northwest Spain

Article reference

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CHAPTER 3. Dynamic growth and yield model including environmental factors for *Eucalyptus nitens* (Deane & Maiden) Maiden Short rotation woody crops in Northwest Spain

3.0. Abstract

A dynamic model consisting of two projection functions, dominant height and basal area, was developed for the prediction of stand growth in *Eucalyptus nitens* bioenergy plantations aged 2 to 6 years and with tree densities of 2300 and 5600 trees ha^{-1}. The data came from 40 permanent sample plots, representing site quality variability across the distribution area of *E. nitens* crops. Three inventories were carried out to collect tree data and determine stand variables. Additionally, edaphic, physiographic and climatic information were obtained and included in the model. For both functions, an ADA growth model was selected, which achieved high accuracy. The corresponding growth curves developed in this study had values of 5, 8, 11 and 14 m for dominant height and 4, 14, 24 and 34 m^2 ha^{-1} for basal area at the base age of 4 years. The inclusion of environmental factors (i.e. soil and climatic variables) as parameters in the model resulted in good estimations and increased the model's flexibility to adapt to small variations in site conditions. The model developed here is thus shown to be useful for simulating the growth of *E. nitens* crops when environmental information is available. A prediction function was fitted for use in stands without diameter inventories or not previously occupied by *E. nitens*, and including environmental variables improved its accuracy. Biomass Mean Annual Increment (*MAI*) varied from 3.25 to 18.45 Mg ha^{-1} y^{-1} at the end of the rotation, projected as between 6 and 12 years depending on site quality.

Keywords: *Eucalyptus,* site quality, bioenergy, Algebraic Difference Equations, climate, soil.

3.1. Introduction

In recent years, society's concerns about climate change and rises in the price of fossil fuels have increased interest in bioenergy production, particularly short rotation plantations. These produce high biomass yields in a short period of time using fast-growing species such as poplar, willow or eucalyptus, which are used extensively in several countries around the world with a wide range of climates and soils (Wright, 2006).

The first *Eucalyptus nitens* (Deane & Maiden) Maiden plantations in the northwest of Spain were established in the early 20th century, principally for pulp production. Even though early studies on the potential use of residual biomass from forest activities, i.e. thinnings and clear cuttings, suggested that it would be insufficient to cover future demand for bioenergy (Pérez et al., 2006), the huge increase in the land area planted with this species in the northwest of Spain in the last decade suggests that this situation has most likely changed. This success of the species is due to the a number of advantages it presents, such as its high energy potential (Pérez et al., 2006), its good resistance to fungus and insects such as *Gonipterus scutellatus* Gyll., and its tolerance of low temperatures (FAO, 1981).

Prediction tools are essential in forestry to forecast development and so decide the best management strategies. In relation to energy crops, comprehensive planning is crucial in order to supply biomass when it is required and, furthermore, it is necessary to know the evolution and availability of the stock in a given plantation at a given time. At the same time, it is important that the models used are able to adapt to changing environmental conditions (Fontes et al., 2010).

Dynamic growth models are mathematical equations developed to predict past or future stand states from a given known past or present state (Cieszewski, 2003). As such, they can be developed using appropriate data, such as information from inventoried taken at any time, from permanent sample plots or stem analyses. Whole stand models are especially suitable for bioenergy plantations because they are homogeneous, even-aged pure stands where the trees have broadly similar characteristics (García, 1988; Vanclay, 1994). Such stand models are generally simple due to the fact that they predict forest state using aggregate and stand variables such as basal area, stems per hectare or dominant height.

Dynamic growth models provide a better description of the development of the stand over the time than static models (García, 1988) although it is necessary to have more than one measurement over time (longitudinal data) to develop them. The general mathematical expression of these models is $Y = f(t, t_0, Y_0)$, where Y is the value of the function at age t, and Y_0 is the reference variable defined as the value of the function at age t_0.

The use of algebraic difference equations, obtained through the derivation of dynamic equations, has given rise to the “algebraic difference approach” (ADA) when one parameter is site-specific (Bailey and Clutter, 1974) or the “generalized algebraic difference approach” (GADA) when more than one parameter depends on the site (Cieszewski and Bailey, 2000). The models derived by ADA and GADA are base age and path invariant and they are widely used to develop dominant height and basal area models in even-aged stands (e.g. Bravo et al., 2011; Cieszewski, 2001).

GADA requires an explicit definition of how the site-specific parameters change across different sites by replacing them with explicit functions of X (one unobservable independent variable that describes site productivity as a summary of management regimes and ecological factors) and new parameters, while ADA is based on a solution using a single base model parameter (Bailey and Clutter, 1974; Cieszewski and Bailey, 2000). In this way, the initial selected two-dimensional base equation $\left(Y = f(t)\right)$ is expanded into an explicit three dimensional site equation $\left(Y = f(t, X)\right)$ describing both cross sectional and longitudinal changes with two independent variables, t and X. Since X cannot be reliably measured or even functionally defined, the final step involves the substitution of X by equivalent initial conditions t_0 and Y_0 ($Y = f(t, t_0, Y_0)$) so that the model can be implicitly defined and practically useful (Cieszewski, 2002; Cieszewski and Bailey, 2000).

In Spain, there are several dynamic growth models developed for different forest species and these have recently been collected together (Bravo et al., 2011). For *E. nitens* short rotation woody crops, two management tools, a static model and a process based model, have been developed recently (Pérez-Cruzado et al., 2011a,b). However, they are not dynamic equations and their stand density rates do not go as high as 2300 trees ha^{-1} (the lowest stocking used in this study). For these reasons, and given the advantages described above for these types of models, dynamic growth models based on algebraic difference equations were developed in this study.

Stand dynamics depend on the productive capacity of the site, which is usually related to climate and soil characteristics, as has been shown in several studies (Bravo-Oviedo et al., 2008; 2011; Nunes et al., 2011). Hence it follows that if this relationship between growth and site parameters is analysed, and the corresponding site variability explained by this analysis is included in growth models, it could help to make the models more flexible with respect to environmental variations and thus improve their accuracy (Bravo-Oviedo et al., 2008; Nunes et al., 2011). This is clearly very important in terms of responding to climate change.

The objective of this study was to develop a dynamic whole-stand model for predicting biomass growth and yield for bioenergy plantations of *E. nitens* across its distribution area in Spain. This model comprised two projection functions, dominant height (allowing site quality classification) and basal area. Soil, climatic and physiographic variables were subsequently included in the model to explore the possibility of improving predictions under a climate change scenario. In addition, a stand basal area prediction function was fitted to provide an initial value of basal area at a given age, when this information is not available.

3.2. Material and methods

3.2.1. Material

The data used to develop the stand model were obtained from 40 permanent sample plots of *Eucalyptus nitens,* McAlister provenance, located in Galicia, in Northwest Spain (coordinates, 43º 10’ 27”- 43º 32’ 56”N and 7º 48’ 39”- 7º 14’ 10”W). The plots were subjectively chosen from a number of homogenous energy stands in order to represent the range of ages and site conditions existing in the area, and can therefore be considered appropriate for developing growth models.

The stands were planted between 2007 and 2009, and 400 m^2 experimental plots were established in the middle of the stands to avoid edge effects at the end of 2010. The tree stocking density ranged from 2300 to 5600 trees ha^{-1} and trees were planted in either single or double lines, depending on the sample plot. The physiography of the plots was characterized by slopes of between 0 and 38% (mean 13%) and an elevation ranging from 400 to 700 m above sea level.

In this region, soils are Rankers and Humic Cambisols, according to FAO (1991). Soil depth to bed rock was determined for each plot in three randomly selected points using a Dutch auger, and ten soil sub-samples from depths of between 0 and 20 cm were taken to determine edaphic characteristics.

The pH was measured using both KCl (1:2.5) and H_2O (1:2.5,) and the latter (diluted 1:5) was also used to analyse electrical conductivity. Organic matter content was determined by the dichromate oxidation method. Total N was determined by Kjeldahl digestion and available P was measured by colorimetry using Mehlich reagent (Mehlich, 1953). Exchangeable cations (K, Mg, Na and Ca) were extracted with 1 M NH_4Cl (Peech, 1947), and exchangeable Al was extracted with 1 M KCl and analysed by atomic absorption. The sum of cation exchange and effective cation exchange capacity (sum of exchangeable cations and exchangeable Al) were calculated. Finally, particle size distribution, to determine soil texture, was analysed by the pipette method using sodium hexametaphosphate and Na_2CO_3 as dispersant (Gee and Bauder, 1996).

Plot climatic variables were interpolated using the model proposed by Sánchez-Palomares et al. (1999) which employs the data of the hydrographical basin and the elevation and coordinates of the plots. The estimated variables were mean annual and seasonal precipitation, mean annual temperature, mean temperature in the warmest and coldest months, maximum and minimum mean temperature in the warmest and coldest months, mean summer and winter temperature, annual potential evapotranspiration, annual moisture surplus and deficit and annual water reserve index.

An inventory was carried out in the winters of three consecutive years between 2010/2011 and 2012/2013. In short rotation plantations used for bioenergy it is important to reduce the intervals between measurements as much as possible as there is faster growth and shorter rotations than for other common forest species. Therefore, in this case three annual measurements were considered enough to develop the growth model. The first and the second inventories were carried out in all the plots, while the final inventory only comprised a sub-set of the 40 plots which, however, fully represented the variability of ages and site qualities for the species in the area.

For the inventories, two measurements of diameter at breast height (1.3 m above-ground level) were made, at right angles to each other and to the nearest 0.1 cm, using callipers, and the arithmetic mean of the two measurements was calculated. Total height was also measured for all trees; to the nearest 0.1 m using a digital hypsometer, or to the nearest 0.01 m using a telescopic measuring pole in the smaller stands. Finally, descriptive variables for each tree were also collected (e.g. if they were alive or dead).

Due to the early stage of the plantations (age less than 6 years) and the importance of time of planting for the initial growth of trees in the first year, the exact stand age was estimated for each plot. For this purpose, the difference between the planting and the measurement date, in addition to the length of the vegetative growth period in each plot, were taken into account.

Following the taking of the inventory, number of trees per hectare, quadratic mean diameter (*dg*), basal area (*G*) and dominant height (*Ho*) – taken as the mean height of the 100 thickest trees per hectare – were calculated for each plot and inventory.

Table 3.1 presents summary statistics of the stands: the physiographic, edaphic and climatic variables used for model development, including the mean, minimum, maximum and standard deviation.

3.2.2. Methods

3.2.2.1. Model structure

The model uses stand variables to characterize the system at an initial stage, and projection or transition functions to project stand growth in the future. Any model selected must satisfy the desirable attributes of growth functions (Bailey and Clutter, 1974; Cieszewski, 2003; Parresol and Vissage, 1998): (1) polymorphism, (2) sigmoid growth pattern with an inflexion point, (3) horizontal asymptote at old ages, (4) logical behaviour (height should be zero at age zero and equal to site index at the base age), (5) parsimony and absence of trends in residuals, (6) base-age invariance, and (7) path invariance.

For unthinned stands, a dimensional vector which includes dominant height and basal area as explanatory variables can be enough to describe the state of the stand at a given time (Pienaar and Turnbull, 1973). However, although the plantations studied here had not been thinned, tree density may well have decreased over time due to competition. For permanent sample plots, a suitable combination of short and long intervals between measurements is considered necessary in order to study and calculate tree mortality (Tewari et al., 2014). However, this study only considered a short period of time and the mortality rate detected over the three years was very low (< 7.5 %, Table 3.1) and thus changes in plantation density were not considered to be of any great significance for the study. The status of the stands was therefore characterized using only dominant height and stand basal area as state variables.

Table 3.1. Main variable statistics of the stands studied.

Variable	Min.	Max.	Mean	Std. Dev.
Age (years)	1.56	5.56	3.22	1.16
N° of trees per hectare	2375	5600	3697	851
Mortality rate (%)	0.00	7.44	1.65	1.97
Basal area (m^2 ha^{-1})	0.46	31.88	9.02	7.06
Quadratic mean diameter (cm)	1.31	12.21	5.16	2.30
Dominant height (m)	2.39	15.68	7.40	3.13
Above-ground biomass (Mg ha^{-1})	1.20	84.85	22.51	18.91
Stem over-bark volume (m^3 ha^{-1})	1.51	253.15	57.48	55.28
Physiographic				
Slope (%)	0.00	37.90	13.40	9.74
Elevation (m)	447.00	697.00	608.53	64.71
Edaphic				
pH (H_2O 1:2.5)	3.90	5.27	4.46	0.29
pH (KCl 1:2.5)	3.19	4.43	3.85	0.29
Electrical conductivity (dS m^{-1})	0.02	0.19	0.06	0.03
Organic matter (%)	7.90	22.27	12.49	3.07
Total N (%)	0.10	0.40	0.22	0.07
C/N ratio	15.79	71.77	35.30	12.66
Available $P^{(a)}$ (mg kg^{-1})	10.20	18.13	14.60	2.10
$Ca_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.04	0.88	0.16	0.15
$Mg_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.06	0.51	0.20	0.09
$Na_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.09	0.45	0.17	0.06
$K_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.12	0.85	0.27	0.13
$Al_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	1.96	14.82	6.64	2.44
Sum of base cations ($cmol_c$ kg^{-1})	0.45	1.40	0.81	0.25
Effective cation exchange capacity ($cmol_c$ kg^{-1})	2.84	15.60	7.44	2.43
Sand (%)	13.00	71.72	42.31	14.92
Clay (%)	2.70	39.61	11.87	7.49
Silt (%)	17.17	73.10	45.83	14.04
Soil depth (m)	0.20	0.94	0.43	0.15
Climatic				
Annual total precipitation (mm)	1171	1345	1244.1	39.02
Spring precipitation (mm)	292	338	311.85	10.35
Summer precipitation (mm)	140	156	146.83	4.17
Autumn precipitation (mm)	320	369	340.05	11.32
Winter precipitation (mm)	418	481	445.30	13.94
Mean annual temperature (°C)	10.30	11.50	10.71	0.30
Mean temperature of the warmest month (°C)	16.10	17.40	16.69	0.33
Mean temperature of the coldest month (°C)	5.00	6.60	5.52	0.44
Mean summer temperature (°C)	15.10	16.50	15.74	0.36
Mean winter temperature (°C)	5.60	7.10	6.05	0.42
Maximum mean temperature of the warmest month	20.70	23.60	22.14	0.81
Minimum mean temperature of the coldest month (°C)	1.20	3.40	1.98	0.54
Evapotranspiration (mm)	633	664	643.83	7.42
Annual moisture surplus (mm)	665	827	736.45	37.58
Annual moisture deficit (mm)	117	153	136.05	9.50
Annual water reserve index	88.20	119.20	101.78	7.44

Methods: (a) Method described in Mehlich (1953), (b) Method described in Peech (1947).

Dominant height and basal area growth functions are two of the most important components of whole-stand models since they are directly related to productive variables such as biomass or volume. In addition, dominant height is the most widely used method for evaluating site quality in pure even-aged stands (Bravo et al., 2011).

In this study two projection functions, dominant height and basal area, were therefore developed.

3.2.2.2. Models considered

The following base growth models were used to describe dominant height and basal area projection functions: Korf-Lundqvist, Hossfeld and Bertalanffy-Richards. The integral form of each growth function was converted into algebraic difference equations; that is, ADA models when one parameter of the equation was free, or GADA models in the case of two free parameters, resulting in a total of twelve models being fitted. Table 3.2 shows the basic and the algebraic difference equation (ADA or GADA) forms for the functions considered, as well as references for the various models. Following general notational convention, a_1, a_2, and a_3 are used to denote parameters in base models, whereas b_1, b_2, and b_3 are employed for global parameters in ADA and GADA formulations.

Table 3.2. Models considered for dominant height and basal area projection functions.

Base function	Site	Solution for *X* with initial values (t_0, Y_0)	Dynamic equation	Reference	Model
Lundqvist-Korf (1957): $Y = a_1 \cdot \exp(-a_2 \cdot t^{-a_3})$	$a_1 = X$	$X_0 = \frac{Y_0}{exp(-b_2 \cdot {t_0}^{-b_3})}$	$Y = Y_0 \cdot \frac{exp(-b_2 \cdot t^{-b_3})}{exp(-b_2 \cdot {t_0}^{-b_3})}$	Bailey and Clutter (1974)	M1
	$a_2 = X$	$X_0 = -Ln\left(\frac{Y_0}{b_1}\right) \cdot t_0^{b_3}$	$Y = b_1 \left(\frac{Y_0}{b_1}\right)^{\left(\frac{t_0}{t_1}\right)^{b_3}}$	Bailey and Clutter (1974)	M2
	$a_3 = X$	$X_0 = \frac{-Ln\left(\frac{Y_0}{b_1}\right)/-b_2}{Ln\ t_0}$	$Y = b_1 \cdot \exp(-b_2 \cdot t^{X_0})$	Ni and Liu (2008)	M3
	$a_1 = \exp(X)$ $a_2 = b_1 + b_2/X$	$X_0 = \frac{1}{2}\left(b_1 \cdot t_0^{-b_3} + Ln(Y_0) + \sqrt{4 \cdot b_2 \cdot t_0^{-b_3} + \left(b_1 \cdot t_0^{-b_3} + Ln(Y_0)\right)^2}\right)$	$Y = \exp(X_0) \cdot \exp\left(-(b_1 + b_2/X_0)\right) \cdot t^{-b_3})$	Cieszewski (2004)	M4
Hossfeld (1822): $Y = \frac{a_1}{1 + a_2 \cdot t^{-a_3}}$	$a_1 = X$	$X_0 = Y_0 \cdot \left(1 + b_2 \cdot t^{-b_3}\right)$	$Y = Y_0 \cdot \frac{1 + b_2 \cdot {t_0}^{-b_3}}{1 + b_2 \cdot t^{-b_3}}$	Cieszewski and Bella (1989)	M5
	$a_2 = X$	$X_0 = {t_0}^{-b_3}\left(\frac{b_1}{Y_0} - 1\right)$	$Y = b_1/(1 - (1 - b_1/Y_0) \cdot (t_0/t)^{b_3})$	McDill and Amateis (1992)	M6
	$a_3 = X$	$X_0 = -\frac{Ln\left(\frac{(b_1/Y_0 - 1)}{b_2}\right)}{Ln(t_0)}$	$Y = \frac{b_1}{1 + b_2 \cdot t^{-X_0}}$	Ni and Liu (2008)	M7
	$a_1 = b_1 + X$ $a_1 = b_2/X$	$X_0 = \frac{1}{2}\left(Y_0 - b_1 \pm \sqrt{(Y_0 - b_1)^2} + 4 \cdot b_2 \cdot Y_0 \cdot t_0^{-b_3}\right)$	$Y = \frac{b_1 + X_0}{1 + b_2/X_0 \cdot t^{-b_3}}$	Cieszewski and Bella (1989)	M8
Bertalanffy-Richards (Bertalanffy 1949;1957; Richards 1959): $Y = a_1 \cdot (1 - \exp(-a_2 \cdot t))^{a_3}$	$a_1 = X$	$X_0 = \frac{Y_0}{(1 - \exp(-b_2 \cdot t_0)^{b_3})}$	$Y = Y_0 \cdot \frac{\left(1 - exp(-b_2 \cdot t)\right)^{b_3}}{\left(1 - exp(-b_2 \cdot t_0)\right)^{b_3}}$	Clutter et al. (1983)	M9
	$a_2 = X$	$X_0 = -Ln\left(1 - (Y_0/b_1)^{1/b_3}\right)/t_0$	$Y = b_1 \left(1 - \left(1 - \left(\frac{Y_0}{b_1}\right)^{1/b_3}\right)^{t/t_0}\right)^{b_3}$	Clutter et al. (1983)	M10
	$a_3 = X$	$X_0 = \frac{Ln\left(\frac{Y_0}{b_1}\right)}{Ln\left(1 - exp(-b_2 \cdot t_0)\right)}$	$Y = b_1 \left(\frac{Y_0}{b_1}\right)^{\frac{Ln\left(1 - exp(-b_2 \cdot t)\right)}{Ln\left(1 - exp(-b_2 \cdot t_0)\right)}}$	Newnham (1988)	M11
	$a_1 = \exp(X)$ $a_2 = b_2 + b_3/X$	$X_0 = \frac{1}{2}\left((Ln(Y_0) - b_2 \cdot L_0) \pm \sqrt{(Ln(Y_0) - b_2 \cdot L_0)^2 - 4 \cdot b_3 \cdot L_0}\right)$ with $L_0 = Ln\left(1 - exp(-b_1 \cdot t_0)\right)$	$Y = Y_0 \cdot \left(\frac{1 - exp(-b_1 \cdot t)}{1 - exp(-b_{12} \cdot t_0)}\right)^{(b_2 + b_3/X_0)}$	Cieszewski (2004); Krumland and Eng (2005)	M12

3.2.2.3. Development of growth models including environmental data

Stand productivity depends on basal area and site quality, which in turn depends on climate, soil and physiography; these site factors can thus be used to predict the growth capacity of forests (Oliver and Larson, 1996). In this study, the relationship between the basal area and dominant height projection functions and the site variables described in Table 3.1 were evaluated. For this purpose, linear, allometric and logarithmic structures (3.1-3.3) were tested, incorporating a single environmental variable in each parameter in order to reduce multicollinearity (Pérez-Cruzado et al., 2014):

$$b_i = c_{i1} + c_{i2} \cdot Z_i \qquad (3.1)$$

$$b_i = c_{i1} \cdot ln\, Z_i + c_{i2} \qquad (3.2)$$

$$b_i = c_{i1} \cdot Z_i^{c_{i2}} \qquad (3.3)$$

where b_i is the expansion of the parameter of the previous model (Table 3.2: b_1, b_2, or b_3 in ADA and GADA formulations), c_{i1} and c_{i2} are the new model parameters and Z_i is the environmental variable (Table 3.1) which is being incorporated in the model.

3.2.2.4. Stand basal area initialization function

The basal area dynamic equation requires a value of basal area at a given age in order to be used for prediction. When this variable is unknown, a prediction function is needed to predict basal area from other stand variables such as plantation age, stand density and site productivity. The basal area growth model of this study is therefore composed of two equations: one for stand basal area projection (as explained in a previous section) and another for prediction.

To ensure compatibility between basal area projection and prediction functions: (1) the prediction function used should be obtained from the base growth model from which the projection function is derived, (2) the site-specific parameter of the prediction function should be related, in linear or non-linear form, to stand variables that do not vary over time (e.g. site index) and (3) the non-site-specific parameters of the base equation must have the same value for both the initialization and projection functions. Compatibility implies that, for a given stand basal area curve obtained from the prediction function, irrespective of which point on the curve is used as the initial condition value in the projection function, the estimated stand basal area will always be a point on that curve.

Additionally, this work also tests the inclusion of environmental factors (climate, soil and physiography variables) in both basal area prediction and projection functions. This is carried out by relating some parameters in linear or non-linear form with environmental variables, in order to explore the possibility of developing a site-dependent function with increased robustness.

3.2.2.5. Model fitting

The fitting of both projection functions was accomplished using the base-age invariant dummy variables method proposed by Cieszewski et al. (2000) which estimates site-specific effects under the assumption that data measurements always contain measurement and environmental errors (on both the left- and right-hand sides of the model) that must be modelled. Autocorrelation among residuals in the projection functions was expected to be very low in this work because only three inventories were carried out, therefore they were not modelled. This absence of autocorrelation was confirmed by graphical inspection and using the Durbin and Watson´s test (1951).

Dominant height and basal area projection functions were fitted simultaneously using the seemingly unrelated regression technique for non-linear models (NSUR) implemented in Model Procedure of SAS/ETS® (SAS Institute Inc., 2004a). This method allows the correlation between residuals of both variables to be taken into account − correlation between both variables being expected since it is reasonable to assume that trees within a plot are ecologically interdependent − which usually results in an increase in parameter estimation efficiency and consistency. The method was accomplished in two steps: (1) separate fitting of each of the two projection functions and selection of the best models, (2) simultaneous re-fitting of the two best equations from the previous step.

In order to maintain compatibility between basal area projection and prediction functions, each parameter estimated in the projection equation (non-site-specific parameters) was substituted into the prediction equation and the latter then fitted individually to obtain estimates of the remaining parameters (site specific parameters). This methodology was selected because it gives priority to the projection function, it being the parameter which is most frequently used to project basal area when initial stand condition can be obtained from a forest inventory (Barrio-Anta et al., 2006; Castedo-Dorado et al., 2007; Tomé et al., 2001).

In addition, several models which included other stand variables and parameters in the base function, and various other growth models were also tested so as to determine the most accurate basal area prediction equation. The best predictor stand variables of basal area for inclusion in the model were found through correlation analysis using Corr Procedure of SAS/STAT® (SAS Institute Inc., 2004b). The presence of heterocedasticity was checked graphically, as well as using specific tests (Breusch and Pagan, 1979; White, 1980), and was corrected by weighted regression (Harvey, 1976).

3.2.2.6. Model evaluation

The fitted models were graphically and numerically evaluated. Numerical analysis consisted in the calculation of goodness-of-fit statistics, the adjusted coefficient of determination (R^2_{adj}) and the root mean square error (*RMSE*) based on *PRESS* residuals. The expressions of the statistics are the following:

$$R_{adj}^2 = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \cdot \frac{n-1}{n-p} \quad (3.4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n-p}} \quad (3.5)$$

where Y_i and $\hat{Y}_i$ are the observed and predicted values of the dependent variable respectively, $\bar{Y}$ is the average value, *n* is the total number of observations and *p* represents the number of parameters included in the model.

The *PRESS* residual is the difference between the observed value and the predicted value where the observation in question is omitted and hence error prediction is more realistic (Myers, 1986). The resulting statistics were designated as $R^2_{adj}{}^P$ and $RMSE^P$.

Graphical analysis was accomplished by visual inspection of the observed residuals against estimated values for the detection of possible systematic discrepancies, and graphical overlaying of the curves of the projection functions on the observed trajectories was used to ensure the logical behaviour of models.

Practical use of dominant height projection function to estimate site quality from any given height-age pairing requires the selection of a base age to which site index will be referenced. The selection of a base age therefore becomes an important issue when only one observation of a new individual stand is available. The base age should be selected so that it is a reliable predictor of height at other ages. To address this consideration, different base ages and their corresponding observed heights were used to estimate heights at other ages (both forward and backward) for each plot. The results were compared with the observed values in each plot and the relative error in predictions (*RE*) was then calculated as follows:

$$RE(\%) = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2/(n-p)}{\bar{Y}}} \cdot 100 \quad (3.6)$$

where $\mathrm{Y_i}$ and $\hat{\mathrm{Y}}_\mathrm{i}$ are the observed and predicted values of the dependent variable respectively, $\bar{\mathrm{Y}}$ is the average value, *n* is the total number of observations and p represents the number of parameters included in the model.

3.3. Results and Discussion

3.3.1. Dominant height and basal area projection functions

The estimated parameters and goodness-of-fit statistics based on *PRESS* residuals for individually-fitted dominant height and basal area projection functions are shown in Table 3.3. In the selection process, the models for both variables were analysed and compared using the statistical results, residuals analysis and the biological behaviour shown in the graphs of the model curves in relation to the observed plot data. Most of the models explained more than 90 % of the total variation although some resulted in no significant parameters, even after testing a wide range of initial values of the parameter in the fitting process of the model. With regard to dominant height, convergence was not found in the parameter estimation process with the GADA models M4 and M8.

Finally, in accordance with the established criteria, the model formulation M10 (Clutter et al., 1983), with a_2 as a specific site parameter, was selected for the two projection functions; dominant height and basal area. This model has also been found to be one of the best in other similar studies, for example, Barrio-Anta et al. (2008). A simultaneous fit of both models was carried out and the fitting statistics and parameter estimates are shown in Table 3.4. The models selected were ADA and polymorphic equations, albeit with a constant single asymptote (b_1 parameter), which is not a problem as long as growth curve behaviour is appropriate for the age range for which the model will be used (Bailey and Clutter, 1974). In the resulting projection functions, all parameters were significant at the 1% level. Dominant height and basal area models explained 98.37 % and 96.08 % of observed variability respectively, while their respective $RMSE^{P}$ values were 0.41 m and 1.43 m^2 ha^{-1}. The results of the specific tests and graphical analysis showed that there were no heterocedasticity problems, nor trends in residues against estimated value graphs, and confirmed the absence of autocorrelation in the models.

Table 3.3. Parameters estimated and their approx. p-values, results of Durbin-Watson's test (*D-W*), p-value for testing positive (Pr<DW) and negative autocorrelation (Pr>DW) and fit statistics based on *PRESS* residuals $^{(P)}$ for dominant height and basal area projection functions tested. Non-convergent models are not included in the Table.

	Model	b_1	b_2	b_3	***D-W***	***Pr<D-W***	***Pr>D-W***	$RMSE^P$	$R^2_{adj}{}^P$
H_0	M1	---	10.382 (0.1277)	0.128 (0.0924)	2.809	0.742	0.258	0.4415	0.9812
	M2	1478.38 (0.5589)	---	0.220 (0.0035)	2.866	0.810	0.190	0.4097	0.9838
	M3	202.635 (0.3311)	4.834 (<0.0001	---	2.591	0.441	0.559	0.7289	0.9488
	M5	---	42.786 (0.0716)	1.267 (<0.0001)	2.810	0.741	0.259	0.4454	0.9809
	M6	47.024 (<0.0001)	---	1.401 (<0.0001)	2.840	0.760	0.240	0.4025	0.9844
	M7	33.099 (<0.0001)	18.159 (<0.0001	---	2.584	0.430	0.571	0.7456	0.9464
	M9	---	0.071 (0.1079)	1.290 (<0.0001)	2.810	0.740	0.260	0.4451	0.9809
	M10	35.988 (<0.0001)	---	1.460 (<0.0001)	2.842	0.763	0.237	0.4026	0.9844
	M11	566.892 (0.5795)	0.008 (0.5492)	---	2.979	0.935	0.065	0.4354	0.9817
	M12	0.114 (0.0105)	-1.131 (0.4544)	9.441 (0.0966)	2.891	0.831	0.169	0.4106	0.9837
G	M1	---	7.646 (<0.0001	0.492 (0.0003)	2.203	0.012	0.9879	1.7253	0.9425
	M2	380.456 (0.1741)	---	0.609 (<0.0001)	2.484	0.220	0.780	1.3281	0.9659
	M3	107.58 (0.0029)	6.925 (<0.0001	---	2.291	0.078	0.922	2.2906	0.8983
	M4	-17.213 (0.2774)	126.554 (0.1311)	0.764 (<0.0001)	2.423	0.152	0.848	1.4448	0.9596
	M5	---	111.770 (<0.0001	2.569 (<0.0001)	2.256	0.023	0.977	1.8236	0.9358
	M6	61.984 (<0.0001)	---	2.695 (<0.0001)	2.494	0.245	0.755	1.4921	0.9570
	M7	42.129 (<0.0001)	112.26 (<0.0001	---	2.388	0.223	0.777	2.3190	0.8960
	M8	7.1970 (0.7762)	4331.18 (0.1472)	2.847 (<0.0001)	2.369	0.088	0.912	1.6531	0.9472
	M9	---	0.247 (0.0002)	3.297 (<0.0001)	2.226	0.016	0.984	1.7805	0.9388
	M10	66.052 (<0.0001)	---	3.667 (<0.0001)	2.490	0.236	0.764	1.4162	0.9612
	M12	0.388 (<0.0001)	-1.823 (0.4885)	24.453 (0.0348)	2.441	0.164	0.837	1.4904	0.9570

Table 3.4. Parameters estimated and their approx. p-values, results of Durbin-Watson's test (*D-W*), p-value for testing positive (Pr<DW) and negative autocorrelation (Pr>DW) and fit statistics based on *PRESS* residuals $^{(P)}$ of the simultaneous fit for the model selected.

Variable	Model	b_1	b_3	*D-W*	*Pr<D-W*	*Pr>D-W*	$RMSE^P$	$R^2_{adj}{}^P$
H_0	M10	48.056 (<0.0001)	1.357 (<0.0001)	2.841	0.771	0.230	0.4109	0.9837
G	M10	67.281 (<0.0001)	3.616 (<0.0001)	2.497	0.250	0.750	1.4247	0.9608

With respect to base age, it was observed that the age range from 3.5-4.5 years had the lowest relative error. Therefore, the age of 4 years was proposed as the base age to classify site productivity for this type of stand. At this reference age, the values of 5, 8, 11 and 14 m were established for the dominant height growth curves and 4, 14, 24 and 34 m^2 ha^{-1} for basal area growth curves, depending on site quality. Figure 3.1 shows the projection functions for dominant height (a) and basal area (b) based on the data in Table 3.4.

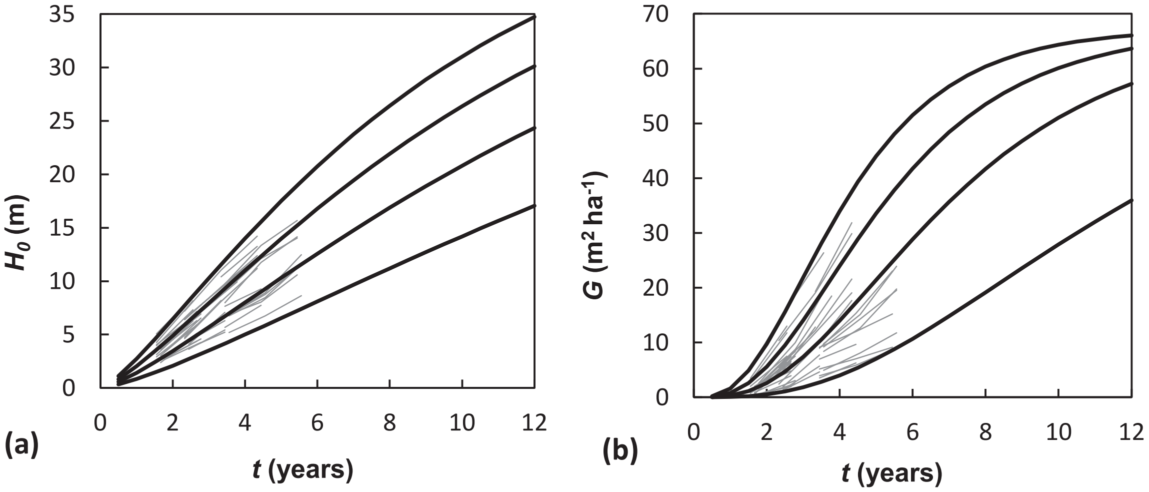

Figure 3.1. (a) Dominant height (H_0) growth curves for values of 5, 8, 11 and 14 m for dominant height and (b) basal area (*G*) growth curves for values of 4, 14, 24 and 34 m^2 ha^{-1} for basal area, (both in bold) at a base age of 4 years, overlaid on the observed values over time (in grey).

3.3.2. Development of growth models including environmental data

The individual projection functions (M10) were expanded using structures 3.1-3.3 and the different environmental variables (Table 3.1) producing good results in some cases. Finally, after simultaneous fitting of the basal area and the dominant height functions, five models which included the expansion of parameter b_3 (Table 3.5) were selected as the best models, in accordance with the criteria explained in the prevision section for projection functions.

The climate variables incorporated in the models are associated with warm temperatures - mean temperature (*TMW*) and mean of maximum temperatures (*TMAX*) both for the warmest month and mean summer temperature (*TSU*) – as well as summer precipitation (*PS*). The inclusion of these parameters confirms the fact that *E. nitens* growth is affected by climate factors in summer: Although annual total precipitation in the area is approximately 1250 mm, well within the requirements for the species, which have been established as between 750 and 1750 mm per year (FAO, 1981; Booth and Pryor, 1991), rainfall in the study area is in fact considerably reduced in summer, which can affect tree growth, as has been shown in another study on the same permanent sample plots (González-García et al., 2015). Moreover, higher summer temperatures increase tree evapotranspiration, which together with the reduction in soil water content, means that growth is likely to be negatively affected in this season.

The soil variables included in the models were organic matter content (*OM*) and sand content (*SAND*), which emphasizes the significance of these variables for this kind of plantation in the distribution area, and confirming the soil requirements of the species, which shows better development in well drained loamy soils (FAO, 1981). The high values of organic matter content in our soils (8-22 %) is the result of complex interactions between vegetation, soil use and climate, which makes it difficult to determine a direct relationship between organic matter content and stand productivity.

Table 3.5. Parameters estimated, results of Durbin-Watson's test (*D-W*), p-value for testing positive (Pr<DW) and negative autocorrelation (Pr>DW) and fit statistics based on *PRESS* residuals $^{(P)}$ for dominant height and basal area models including soil and climate variables.

Model	Variable	Parameters	*D-W*	*Pr<D-W*	*Pr>D-W*	$RMSE^P$	$R^2_{adj}{}^P$
OM	H_0	b_1=22.638 b_3=0.152·*OM*	2.553	0.360	0.640	0.5329	0.9726
	G	b_1=55.786 b_3=8.534-0.359·*OM*	2.711	0.420	0.580	1.2199	0.9712
SAND	H_0	b_1=21.716 b_3=0.043·*SAND*	2.580	0.161	0.839	0.6779	0.9557
	G	b_1=57.152 b_3=2.420+0.035·*SAND*	2.416	0.106	0.894	1.3836	0.9630
TMW	H_0	b_1=38.438 b_3=0.086·*TMW*	2.861	0.800	0.200	0.4110	0.9837
	G	b_1=66.646 b_3=39.929-2.176·*TMW*	2.482	0.207	0.793	1.3503	0.9648
TMAX	H_0	b_1=35.191 b_3=0.066·*TMAX*	2.873	0.818	0.182	0.4120	0.9836
	G	b_1=58.427 b_3=30.268-1.185·*TMAX*	2.342	0.061	0.939	1.2588	0.9694
TSU	H_0	b_1=36.723 b_3=0.092·*TSU*	2.861	0.798	0.202	0.4120	0.9836
	G	b_1=65.726 b_3=37.844-2.173·*TSU*	2.493	0.226	0.774	1.3327	0.9657
PS	H_0	b_1=47.671 b_3=0.009·*PS*	2.830	0.746	0.254	0.3995	0.9846
	G	b_1=66.688 b_3=-27.881+0.215·*PS*	2.461	0.175	0.825	1.2934	0.9676

where *OM* is the organic matter content of the soil (%), *SAND* is the sand content of the soil (%), *TMW* is mean temperature of the warmest month (°C), *TMAX* is the mean of maximum temperatures of the warmest month (°C), *TSU* is the mean summer temperature (°C) and *PS* is the summer precipitation (mm).

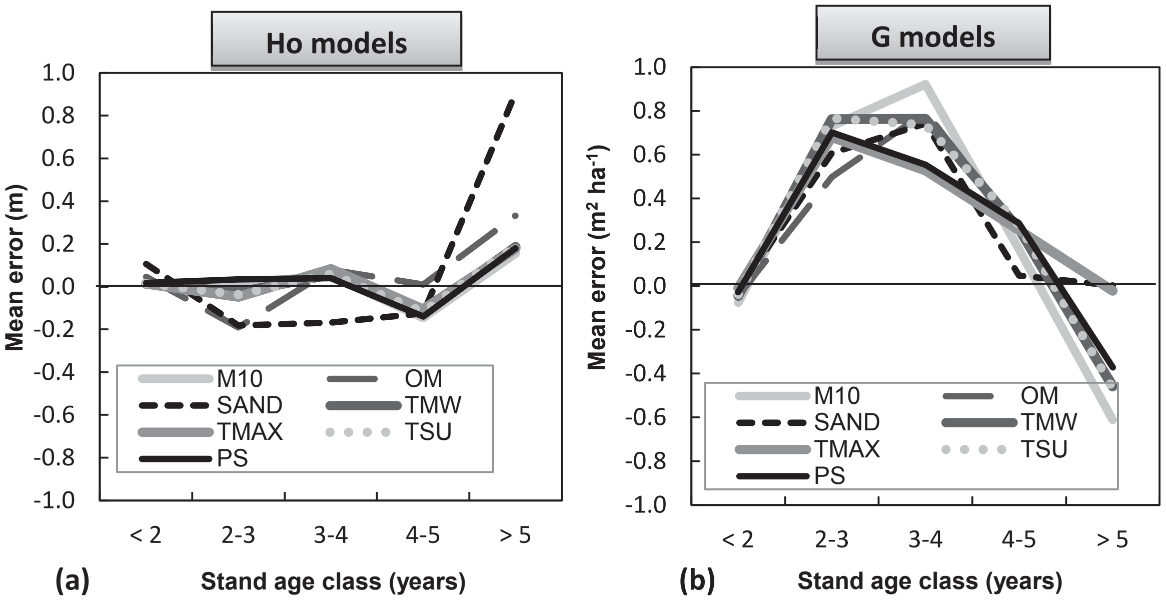

Figure 3.2. Mean errors of dominant height (a) and basal area (b) estimation using the models developed. M10 is the simple model and the others are expanded models which include either organic matter content of the soil (*OM*), sand content of the soil (*SAND*), mean temperature of the warmest month (*TMW*), mean of maximum temperatures of the warmest month (*TMAX*), mean summer temperature (*TSU*) or summer precipitation (*PS*).

As shown in Figure 3.2, despite accuracy being high for all the models ($R^2_{ad}j > 0.95$), in the model which includes sand content of the soil, the accuracy of the dominant height model decreased with respect to the equivalent model without environmental factors (Table 3.4) while, at the same time, the basal area function incorporating sand content was more accurate than that without. Nonetheless, for the models including climate variables, $R^{2}_{adj}{}^{P}$ remained practically the same as in the model without environmental information with respect to dominant height function and rose slightly for the basal area equation. Generally, expanded models which include climate and soil variables are more robust due to them incorporating geographical variability (Nunes et al., 2011), and therefore generate more interesting results when contrasting conditions are available. Thus, although some the models including environmental data developed here have a lower accuracy than the corresponding models without site information, they can still be considered to generate fairly accurate growth curves of dominant height and basal area at the regional level because they can be adapted to incorporate short-term changes in climatic conditions. However, they must be used carefully because they are not suitable for predicting responses to global climate change (Nunes et al., 2011).

Furthermore, it is important to highlight that the interaction between tree growth and environmental factors is a complex one due to the fact that, for example, climate conditions have an impact on the physiological processes of the tree (Pallardy and Kozlowski, 1979). As such, an extension of this study would be to take into account other tools, such as ecophysiological models, which will provide a better understanding of these relationships.

3.3.3. Basal area initialization function

The basal area prediction function was developed after the projection function. To ensure the compatibility of both equations, the Bertalanffy-Richards base model was used as the base equation (Table 3.2). The values of the parameters a_1 and a_3 were replaced by the value of their equivalent parameters, b_1 and $b_{3,}$ in the derivative function (M10) (*Compatible function*). After correction of heterocedasticity, the model explained less than 40 % of observed variability (Table 3.6).

Other stand variables and formulations were also included in the base model to evaluate potential improvements in the equation prediction capacity. Dominant height was the variable which was most correlated to basal area, with a Pearson coefficient of 0.8613, followed by stand age and site index, with coefficients of 0.6639 and 0.3570 respectively. All were significant (p-value < 0.001), hence they were considered in the models tested. In contrast, the relation between the number of trees per hectare and basal area was not significant (p-value > 0.05) and therefore it was not taken into account in the models. Weighted regression (Harvey, 1976) was applied to all the models due to the absence of homoscedasticity. Finally, due to the low accuracy of the base equation, an attempt to improve it was made by introducing slight modifications. Although this resulted in a great improvement in accuracy, compatibility between prediction and projection functions was not ensured when the modified prediction equations were used to calculate basal area. As a result it was decided that the best strategy in this case was to test other models and combinations of explanatory stand variables (age, dominant height and site index). Finally, the most accurate model was adapted from the Clutter model (1963) which includes dominant height and stand age as predictor variables (*Accurate function*). The adapted model explained 73.90 % of observed variability, with an $RMSE^{P}$ of 3.66 m^2 ha^{-1} calculated according to *PRESS* residuals, and showed a normal pattern after heterocedasticity correction. The improvement with respect to the compatible function was greater than 50 % in $R^2_{adj}{}^{P}$.

The basal area prediction functions including environmental factors (*Site functions*) are shown in Table 6. Five functions were selected according to fit statistics and their biological behaviour, in the same way as for the projection functions. Most of the variables tested (see Table 3.1) improved the accuracy of the base model, the most notable being the soil variable, *OM* and the climate variables *TMW*, *TMAX*, *TSU* and *PS*, which improved the $R^2_{adj}{}^{P}$ of the function by more than 13 %, in addition to increasing the flexibility of the model. These results support those obtained in the projection functions section, which emphasizes the importance of these factors for *E. nitens* growth in the region.

Table 3.6. Parameters estimated and their approx. p-values and fit statistics based on *PRESS* residuals $^{(P)}$ for the basal area initialization functions: compatible function, accurate function and the functions derived from the latter which includes site environmental parameters.

Initialization function	Model	a_1	a_2	a_3	$RMSE^P$	$R^2_{adj}{}^P$
$G = a_1\left(1 - exp(-a_2 t)\right)^{a_3}$	Compatible	67.281	0.2585 (<0.0001)	3.616	5.9604	0.3206
		a_1, a_3: fixed parameters M10				
$G = \exp\left(\frac{a_1 + a_2 Ho}{Ho + t}\right)$	Accurate	-17.429 (<0.0001)	5.440 (<0.0001)	-----	3.6710	0.7390
$G = \exp\left(\frac{a_1 + a_2 Ho + a_3 X}{Ho + t}\right)$	Site *X=OM*	-14.022 (<0.0001)	5.508 (<0.0001)	-0.324 (0.0191)	2.8540	0.8459
	X=TMW	68.256 (0.0005)	5.621 (<0.0001)	-5.224 (<0.0001)	2.7627	0.8565
	X=TMAX	22.274 (0.0275)	5.620 (<0.0001)	-1.852 (<0.0001)	2.7238	0.8600
	X=TSU	50.187 (<0.0001)	5.609 (<0.0001)	-4.384 (<0.0001)	2.7404	0.8589
	X=PS	-75.431 (<0.0001)	5.653 (<0.0001)	0.384 (<0.0001)	2.8277	0.8497

where *OM* is the organic matter content of the soil (%), *TMW* is mean temperature of the warmest month (°C), *TMAX* is the mean of maximum temperatures of the warmest month (°C), *TSU* is the mean summer temperature (°C) and *PS* is the summer precipitation (mm).

3.3.4. Growth and yield

The models developed in this research could play an important role in *E. nitens* short rotation woody crops plantations because they can help to optimize forest management strategies (i. e. indicating the optimal rotation of the stands) so that maximum advantage can be taken of plantations in the area. Additionally, the outputs which projection functions provide can be used as the inputs for biomass or volume models for a given age; essential tools for forest managers in this kind of stand.

Growth and biomass production of *E. nitens* woody crops were estimated for the site index classes determined in this study using the allometric above-ground biomass equation developed for such plantations (see González-García et al., 2013) at different stand ages. The results showed that at the stand age of

6 years, accumulated stand biomass varied from 110.72 Mg ha^{-1} for the highest site index (*SI*=14 m) to 15.79 Mg ha^{-1} for the lowest (*SI*=5 m).

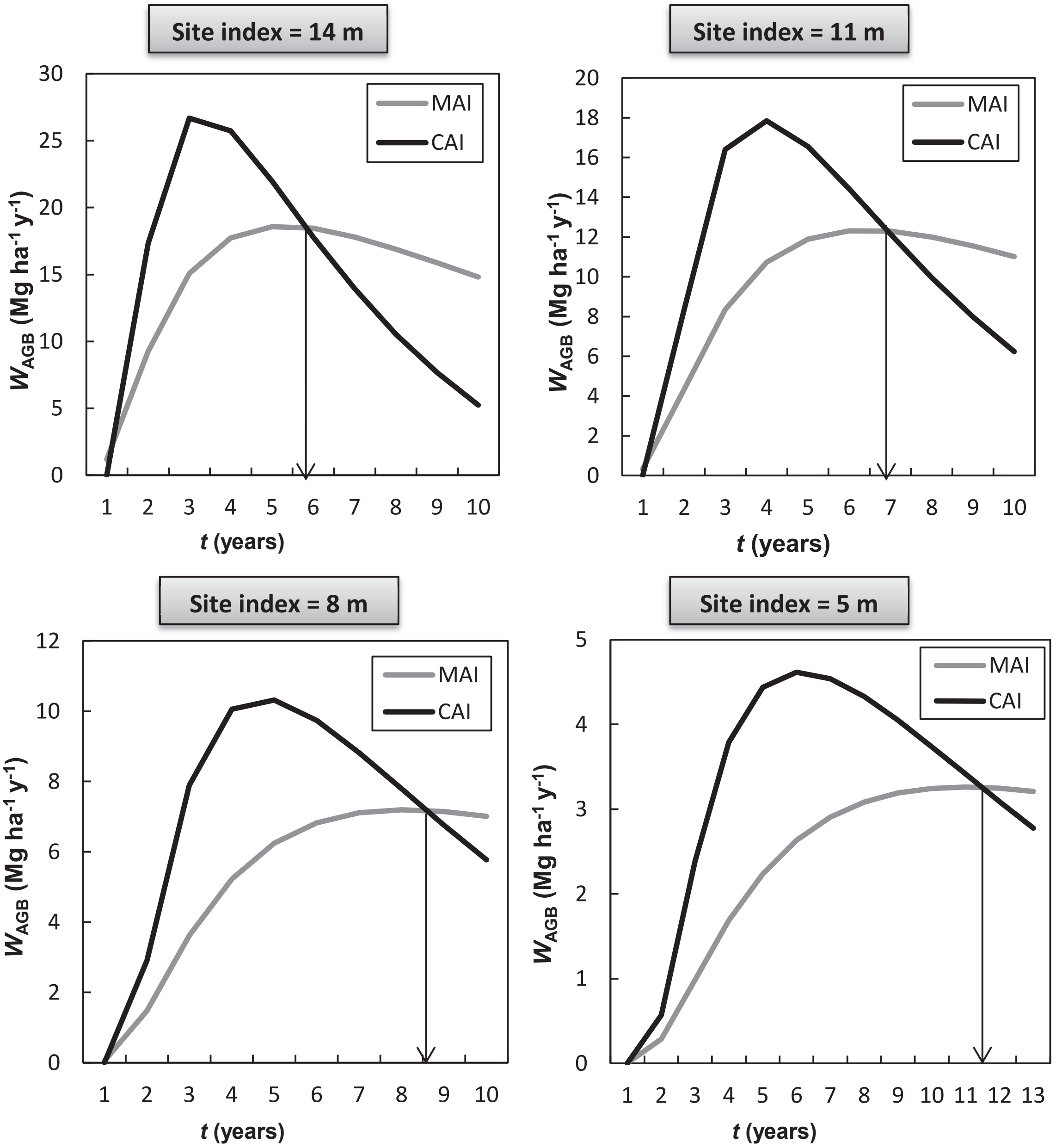

Figure 3.3. Patterns of growth and stand biomass production for *E. nitens* woody crops. *MAI* is the Mean Annual Increment (Mg ha^{-1} y^{-1}) and *CAI* is the Current Annual Increment (Mg ha^{-1} y^{-1}) of above-ground biomass (W_{AGB}). The point where *MAI* and *CAI* curves intersect defines the optimal rotation age of the stand.

Figure 3.3 shows the patterns of increment in stand biomass for the stands of different site quality index using Mean Annual Increment (*MAI*) and Current Annual Increment (*CAI*). Optimal stand age for the harvest was determined using the point where *MAI* and *CAI* curves intersected, and is therefore different for each site index class, and ranged from 6 years for the highest site quality, to 12 for the lowest. These optimal rotation lengths are, of course, extrapolations, as are the fitted curves presented in Figure 3.1, since they concern stand ages not included in the supporting dataset. The average biomass yield, expressed using *MAI*, at the end of the projected rotation was between 3.25 and 18.45 Mg ha^{-1} y^{-1}, according to site quality, these yields being in the same range or above that of the highest quality sites in other short rotation species in Europe (Fischer et al., 2005; Laureysens et al., 2004; Trnka et al., 2008), which have shown good growth responses in the study area. Other results for *E. nitens* short rotation crops in New Zealand (Sims et al., 2001) showed yield range to be from 3 to 7 Mg ha^{-1} y^{-1}, in line with the worst site qualities in the present work. Furthermore, the results obtained in this study are very similar to those found in a study using the dominant height GADA model developed by Pérez-Cruzado et al. (2013) from stem analysis of the same species. While their model, which was fitted for a stand density of between 1100 and 1600 trees ha^{-1}, presents site index curves of 8, 12, 16 and 20 m at a base age of 6 years, if the results are interpolated to the reference age of 4 years used in the present study the results for the two studies in relation to the dominant height model would be practically identical. The above-ground biomass (W_{AGB}) predictions for this growth model ranged from 7 to 36 Mg ha^{-1} y^{-1} depending on site, with an average of 17 Mg ha^{-1} y^{-1} for optimal rotation. Additionally, the productivity of W_{AGB} was 21.5 Mg ha^{-1} y^{-1} for the *E. nitens* static model developed taking into account a planting density of 2400 trees ha^{-1} and a rotation of 11 years (Pérez-Cruzado et al., 2011a).

3.4. Conclusions

The best models obtained in this study for dominant height and basal area projection functions were polymorphic ADA models with single asymptote. The models provided accurate predictions for *Eucalyptus nitens* short rotation woody crops.

The range of average biomass yield in *E. nitens* woody crop stands was from 3.25 to 18.45 Mg ha^{-1} y^{-1} at the end of the rotation, which was projected as between 6 and 12 years, depending on site quality.

This study also shows that stand growth can be predicted by including environmental factors in models, and that this produces good estimations which are useful in terms of suiting the model to small variations in site conditions.

Since *E. nitens* short rotation woody crops in the study zone are currently concentrated in a homogenous area where there is no great variability in climatic data, the future incorporation into the model of information about plantations in neighbouring areas, including the respective environmental data, would be of great value in increasing data variability and facilitating readjustments of the model.

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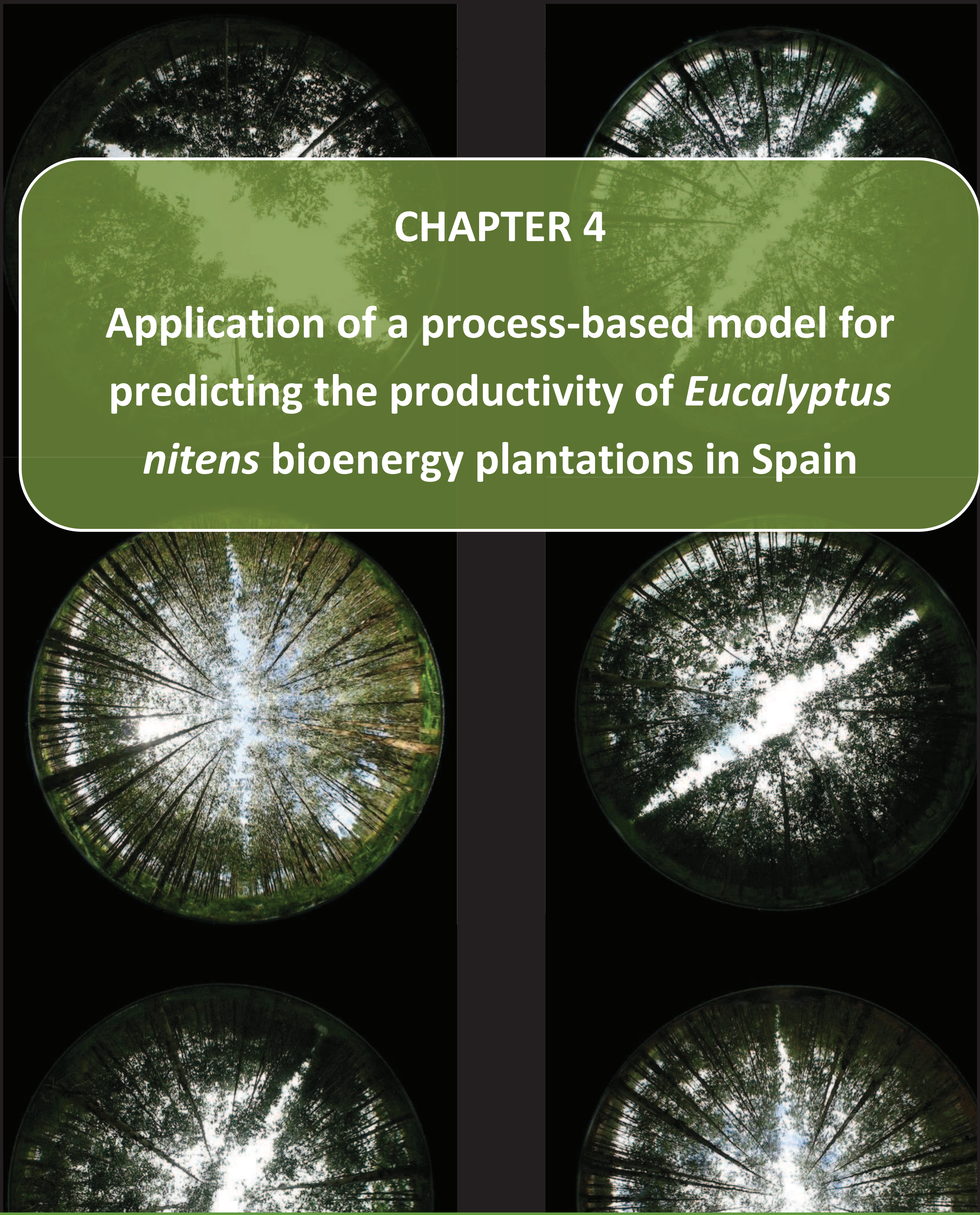

CHAPTER 4

Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain

Article reference

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CHAPTER 4. Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain.

4.0. Abstract

The feasibility of using plantation-grown biomass to fuel bioenergy plants is in part dependent on the ability to predict the capacity of surrounding forests to maintain a sustainable supply. In this study, the potential productivity of *Eucalyptus nitens* (Deane & Maiden) Maiden plantations grown for bioenergy in a region of North-west Spain was quantified using the 3-PG process-based model. The model was calibrated using detailed measurements from five permanent sample plots and validated using data from thirty-five additional permanent sample plots; both sets represented the variability of climate and soils of the region. Plot-scale analysis showed that the model was able to reasonably estimate above-ground biomass and water use when compared with the observed data. Using a representative loam soil characteristic, a spatial analysis was then carried out to predict the potential productivity of *E. nitens* for bioenergy across a potential area for plantation establishment of 2,550 km^2 and to evaluate different management scenarios related to rotation length and stocking. An increase of only 1.9 % in mean annual increment (*MAI*) of above-ground biomass (W_{AGB}) was found between stockings of 3000 and 5000 trees ha^{-1}; for the lower stocking, *MAI* of W_{AGB} increased 4 % for rotation lengths between 6 and 8 years. Production was reduced by low summer rainfall and to a lesser extent by high summer and low winter temperatures, and vapour pressure deficit. Above-ground biomass production was higher by around 12 % when average rather than actual climate data were applied. The information from this study can be used to optimize forest management, determine regional relative potential productivity and contribute to decision making for bioenergy production from *E. nitens* plantations in North-west Spain.

Keywords: *Eucalyptus*, 3-PG model, process-based model, short rotation woody crops, bioenergy, biomass production, spatial analysis, GIS, potential productivity.

4.1. Introduction

Biomass from trees has potential for economic, environmental and social benefits and it has led to a growing interest in planting and managing trees for this purpose (Saxena et al., 2009). Plantations for energy generally have higher stocking at planting and shorter rotation lengths than those managed for pulp or timber. Trees harvested specifically for energy produce better quality feedstock than residual biomass following stem removal for other purposes, because stemwood is the major tree component by the end of the rotation and delivers the highest energy potential (Zhao et al., 2014). However, it is important to tailor feedstock requirements to the capacity of the surrounding landscape to produce a sustainable biomass supply.

The use of models to estimate biomass yield can provide this essential part of the planning process for managing feedstock supply to bioenergy plants. Some models are able to explore the effect of varying climatic conditions and forest management on realised stand productivity. One such model, 3-PG (Physiological Principles Predicting Growth) is a process-based model which embodies the basic processes of forest growth and which has been developed and described in detail by Landsberg and Waring (1997), Sands and Landsberg (2002) and Landsberg and Sands (2010). The model has a simple structure, a lower number of parameters than other more detailed physiological models, and it is freely available. 3-PG has been widely applied to different forest species including several *Eucalyptus* species (Almeida et al., 2004a,b, 2010; Dye et al., 2004; Fontes et al., 2006; Paul et al., 2007; Rodríguez et al., 2009; Rodríguez-Suárez et al., 2010; Sands and Landsberg, 2002; Silva et al., 2012; Stape et al., 2004; Vega-Nieva et al., 2013). In Spain, Pérez-Cruzado et al. (2011) parameterised 3-PG for *Eucalyptus nitens* (Deane & Maiden) Maiden focused on pulp or solid-wood production at stockings from 1000 to 1500 trees ha^{-1}. Process-based models have been applied at a regional scale to predict biomass in short-rotation coppice (*SRC*) plantations of poplars and willows managed for bioenergy (Amichev et al., 2010, 2011; Hart et al., 2014; Headlee et al., 2013; Tallis et al., 2013). However detailed analyses of the effects of climate, soil characteristics and management at plot and regional scales on tree crops grown for biomass remain scarce (Surendran Nair et al., 2012).

Eucalyptus nitens grows naturally in cool temperate climates in Australia. It is also planted as an exotic in similar climates, mainly in Tasmania, Chile, and Spain. *Eucalyptus nitens* was first established for pulpwood in North-west Spain in the 1990's in areas where *Eucalyptus globulus* Labill., the most widespread pulpwood species in Spain (ENCE, 2009), is not able to grow because of low temperatures and frost. With the increasing interest in renewable energy, *E. nitens* is now being planted in this region as an energy crop to produce lignocellulosic biomass for the generation of electrical power or heat energy by combustion.

Spatial analysis is useful for predicting the potential productivity of forests across large areas. 3-PG Spatial (3-PGS) is a modified version of 3-PG which is integrated into a geographic information system (GIS), allowing estimation and analysis at the landscape scale (Almeida et al., 2010; Coops et al., 1998a,b). Thus 3-PGS utilizes data on climate and soils for the different areas in a study region, and can estimate the potential productivity of forest species where they have not been previously planted (Almeida et al., 2010). It is therefore a suitable tool for exploring the potential of new cropping strategies, such as the yields of plantations to be harvested for energy production.

The aim of this study was to predict the productivity of *E. nitens* plantations managed for bioenergy in North-west Spain using the 3-PG model, to examine the key factors that influence and constrain forest growth, and to explore different management strategies related to rotation length and stocking at a regional scale. The results will assist those investing in the establishment of commercial plantations for bioenergy.

4.2. Material and methods

4.2.1. Study area and permanent sample plots

The study area of approximately 5,800 km^2 was located in northern Galicia, in North-west Spain (Figure 4.1). It includes a total of 2,550 km^2 that is suitable for plantation establishment, and is where several *E. nitens* plantations have been established in the last few years to produce biomass for bioenergy. A network of 40 permanent sample plots, each with an area of 400 m^2, was installed across the region to sample the variability of planting densities, ages and site conditions within this plantation estate. The elevation of the plots varied from around 450 to 700 m. Soil preparation in an area dominated by shallow soils included sub-soiling to 1-m depth. Stocking at planting varied from 2300 to 5600 trees ha^{-1}. Fertilizer, 100-150 g 8-24-16 N:P:K per plant, was applied just after planting. Mechanical and chemical weed control was used to minimise competition from weeds.

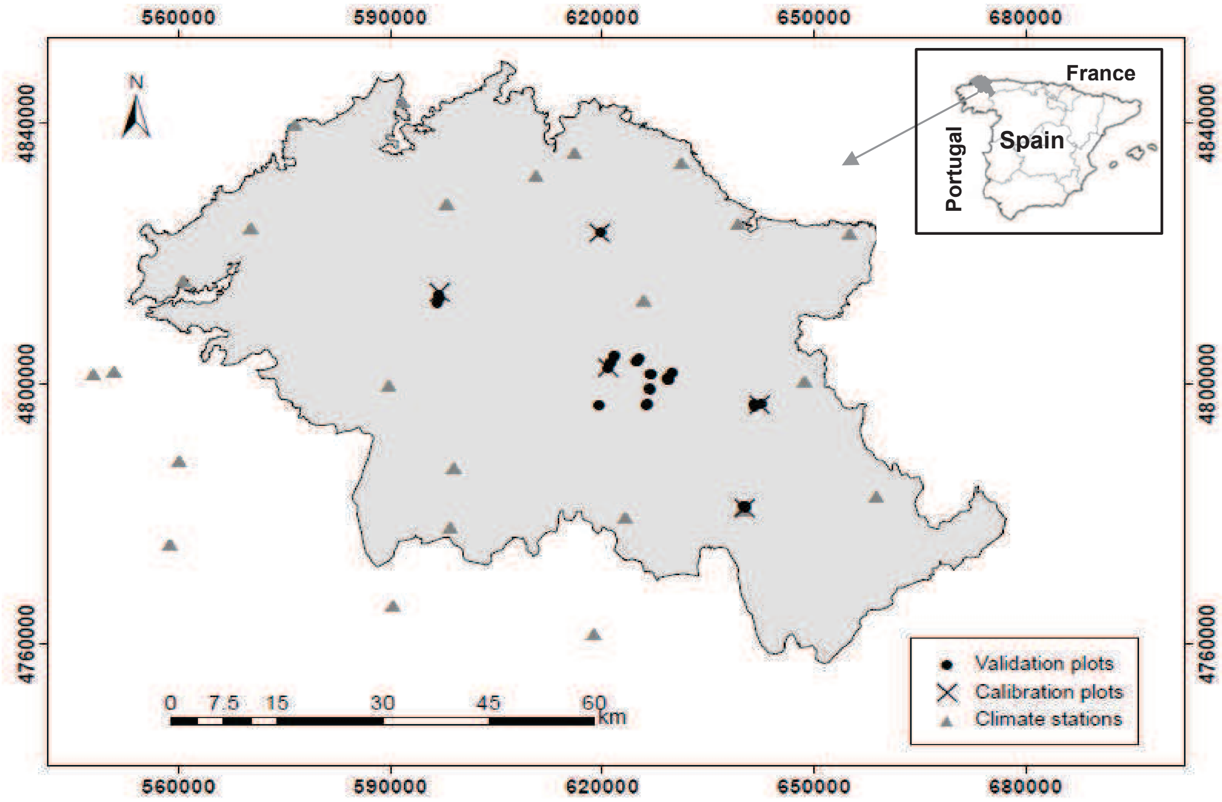


Figure 4.1. Localization of reference plots and climate stations in the study area in North-west Spain. Some plots are not visible since some are very close to each other and overlap.

Nine of the 40 plots (five of them used for model calibration and the other four for validation with the remaining 31 plots) were selected for measurement of the parameters required for modelling, such as stomatal conductance, specific leaf area, litterfall rate and soil texture. These plots represented the range of the existing plantations and respective variability of climate, soil properties, site productivity, stocking and stand age (1.6-5.6 years) (Table 4.1).

Table 4.1. Sites selected for 3-PG model calibration and validation. Site index at reference age of 4 years (*SI*), inventory stand age (*Age*), fertility rating (*FR*), soil class, parent material and average leaf area index at a specified age (*LAI*).

Plot type	Site	*SI* (m)	Age (years)	Stocking (trees ha^{-1})	*FR*	#Soil class	*Parent material	*LAI* (age-years)
Calibration	A-CAN-I	14.2	1.6, 2.6, 3.6	3750	0.9	CL	1	4.2 (3.9)
	POL-RI-I	10.2	3.4, 4.4, 5.4	5250	0.5	TL	2	3.4 (6.1)
	PON-FRA-I	6.5	2.4, 3.4	3475	0.2	T	4	3.7 (4.9)
	PON-PA-II	11.4	1.7, 2.7	2400	0.4	L	5	3.2 (4.2)
	VAL-I-I	9.0	2.7, 3.7	4025	0.4	T	6	4.1 (5.1)
Validation	A-BA-I	6.7	1.8, 2.8	3400	0.4	TL	7	3.4 (4.3)
	A-BA-II	7.1	1.8, 2.8	3525	0.2	L	7	
	A-BEM-I	10.6	1.8, 2.8, 3.8	3725	0.7	L	1	
	A-BEM-II	10.0	1.8, 2.8	4050	0.5	T	1	3.9 (4.3)
	A-CA-I	12.1	1.6, 2.6	4075	0.8	TL	7	
	A-CA-II	13.4	1.6, 2.6	3650	0.9	TL	7	
	A-CAN-II	10.5	1.6, 2.6	3775	0.7	SL	1	
	A-CAR-I	12.2	2.3, 3.3, 4.3	2889	0.9	L	1	
	A-CAR-II	11.2	2.3, 3.3, 4.3	2975	0.8	SL	1	
	A-CAR-III	13.1	2.3, 3.3, 4.3	3025	0.9	SL	1	
	A-CAR-IV	10.1	2.3, 3.3, 4.3	3275	0.8	SL	1	
	A-COR-I	10.2	2.3, 3.3, 4.3	2850	0.5	L	1	
	A-COR-II	11.4	2.3, 3.3, 4.3	2750	0.7	L	1	
	A-PE-I	10.9	1.8, 2.8, 3.8	3200	0.8	SL	3	
	A-PE-II	10.5	1.8, 2.8	3550	0.6	SL	3	
	PAS-MAR-I	11.1	1.6, 2.6	3825	0.7	L	1	
	PAS-MAR-II	9.5	1.6, 2.6	3475	0.4	L	1	
	PAS-RO-I	9.5	1.7, 2.7	3150	0.5	TL	1	
	PAS-RO-II	8.3	1.7, 2.7	3425	0.5	T	1	
	PAS-SAN-I	5.9	3.6, 4.6, 5.6	4975	0.2	L	1	
	PAS-SAN-II	8.0	3.6, 4.6, 5.6	5200	0.5	T	1	3.6 (6.2)
	PAS-SAN-III	8.7	3.6, 4.6, 5.6	5600	0.4	TL	1	
	PAS-SAN-IV	8.0	3.6, 4.6, 5.6	4400	0.4	CL	1	
	POL-RI-II	6.8	3.4, 4.4	5000	0.2	TL	2	
	POL-RI-III	8.2	3.4, 4.4, 5.4	4775	0.3	TL	2	
	POL-RI-IV	7.5	3.4, 4.4, 5.4	5150	0.3	TL	2	
	POL-RI-V	10.1	3.4, 4.4, 5.4	3050	0.3	TL	2	
	POL-RI-VI	11.3	3.4, 4.4, 5.4	3300	0.7	TL	2	
	PON-FRA-II	6.3	2.4, 3.4	2736	0.2	TL	4	
	PON-FRA-III	7.5	2.4, 3.5	3400	0.5	TL	4	4.3 (5.0)
	PON-FRA-	8.4	2.4, 3.6	3475	0.2	TL	4	
	PON-PA-I	10.1	1.7, 2.7	3225	0.3	L	8	
	PON-PA-III	11.0	1.7, 2.7	2550	0.7	L	5	
	PON-PA-IV	7.1	1.7, 2.7	2375	0.3	TL	8	
	VAL-I-II	10.4	2.7, 3.7	4300	0.8	L	6	

#*Soil class*: Loam (L), Clay loam (CL), Silt (T), Silty loam (TL), Sandy loam (SL).

**Parent material*: Slate (1), Slate-Sandstones (2), Slate-Two Micas-Granite (3), Schists-Phyllites (4), Black Slate-Sandstones (5), Two Micas-Granite (6), Pelitic schists-Sandstones (7), Quartzites (8).

4.2.2. Stand growth and yield

Diameter at breast height (1.30 m above ground level) (d, cm) and total stem height (h, m) of all trees in the plots were measured in three inventories carried out in the winter of consecutive years between 2010/2011 and 2012/2013. The first two inventories were done in all 40 sample plots, the third in a sub-set of 18 plots that represented the full range of ages and site qualities. Mean total stem height (H, m), mean diameter at breast height (D, cm), basal area (G, m^2 ha^{-1}) and dominant height (Ho, m), the mean H of the 100 greatest diameter trees per hectare, were calculated for each inventory and plot; site index at the reference age of four years (SI, m) was also calculated (González-García et al., 2015).

Stand above-ground biomass (W_{AGB}, Mg ha^{-1}) and over-bark stem volume (V, m^3 ha^{-1}) were obtained using allometric models for these plantations based on plot measurements and biomass sampling (see González-García et al., 2013a,b for methods of biomass sampling) (Table 4.2). Above-ground biomass in the 3-PG model is the sum of foliar and stem biomass; stem biomass includes branches and bark. The initial biomass per site, which is employed as a model input, was established using two specific equations for estimating foliar and stem mass. For this purpose, ten stands, which were represented by the sample plots, with different stand qualities and characteristics and approximately 1.5 years old, were used. The initial biomass equations were fitted using site index as an explanatory variable, since it presented a strong correlation with the observed biomass data ($R^2_{\mathrm{adj}} > 0.9$).

Table 4.2. Allometric models used to calculate volume and biomass components in *Eucalyptus nitens* bioenergy stands. *W* is biomass for different components (Mg ha^{-1}) where W_{AGB} is above-ground biomass, *V* is over-bark volume (m^3 ha^{-1}), *G* is basal area (m^2 ha^{-1}), H_0 is dominant height (m) and *SI* is site index (m) at the reference age of 4 years (González-García et al., 2013a; 2015).

Variable		Model	R^2_{adj}
Biomass	W_{Foliar}	$W_{\mathrm{Foliar}} = 0.08031 \cdot G^{0.7854}$	0.984
	W_{Stem}	$W_{\mathrm{Branch}} = 0.0506 \cdot G^{1.0241} \cdot Ho^{0.6819}$	0.994
		$W_{\mathrm{Dead\ branch}} = 0.5699 \cdot G^{0.9699} \cdot Ho^{-0.5815}$	0.994
		$W_{\mathrm{Bark}} = 0.1615 \cdot G^{1.1139}$	0.967
		$W_{\mathrm{Wood}} = 0.3306 \cdot G^{1.0333} \cdot Ho^{0.5906}$	0.993
	W_{AGB}	$W_{\mathrm{AGB}} = W_{\mathrm{Foliar}} + W_{\mathrm{Stem}}$	0.993
Volume	V	$V = 1.808 \cdot G^{1.055} \cdot Ho^{0.504}$	0.996
Initial biomass	W_{Foliar}	$W_{\mathrm{Foliar}} = 0.0266 \cdot e^{(0.3887 \cdot SI)}$	0.904
	W_{Stem}	$W_{\mathrm{Stem}} = 0.0433 \cdot e^{(0.2953 \cdot SI)}$	0.903

4.2.3. Climate data

Measurements of monthly air temperature, precipitation, and global solar radiation were collated from a network of 24 automatic weather stations (*AWS*); these data were available online (www.meteogalicia.com). The *AWS* were located within (18) or close (6) to the study region (Figure 4.1).

Climate data from January 2007 to December 2013 were obtained from these *AWS*, the period over which measurements were taken. The monthly variables: maximum and minimum mean temperatures (°C), rainfall (mm), number of rain days and frost days and global solar radiation (MJ m^{-2} day^{-1}) were interpolated for the entire study area surface using an inverse distance weighting method (*IDW*) (Shepard, 1968). The corresponding interpolated values of these variables for the different plots were used as input data in the model at stand (3-PG) and spatial (3-PGS) levels.

4.2.4. Edaphic properties and soil moisture

The soils in the study area are broadly classified as Rankers and Humic Cambisols (FAO, 1991). However, the variability of parent materials among plots was high: slate, slate-sandstones, slate-two micas-granite, schists-phyllites, black slate-sandstones, two micas-granite, pelitic schists-sandstones and quartzites were represented (Table 4.1).

Soil depth was determined for each plot in three randomly selected points with a Dutch auger and ten soil sub-samples between 0 and 20 cm depth were taken. Edaphic analysis of the permanent sample plots (Table 4.3) showed that the soils are acid (pH (H_2O) < 5.3) with high organic matter content (8-22 %).

Table 4.3. Soil properties (0-20 cm) of the sites selected for 3-PG model calibration and validation.

Variable	Min.	Max.	Mean	Std. Dev.
pH (H_2O 1:2.5)	3.90	5.27	4.46	0.29
EC (dS m^{-1})	0.02	0.19	0.06	0.03
OM (%)	7.90	22.27	12.49	3.07
Total N (%)	0.10	0.40	0.22	0.07
C/N ratio	15.79	71.77	35.30	12.66
Available $P^{(a)}$ (mg kg^{-1})	10.20	18.13	14.60	2.10
$Ca_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.04	0.88	0.16	0.15
$Mg_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.06	0.51	0.20	0.09
$Na_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.09	0.45	0.17	0.06
$K_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.12	0.85	0.27	0.13
$Al_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	1.96	14.82	6.64	2.44
SB ($cmol_c$ kg^{-1})	0.45	1.40	0.81	0.25
*CEC*e ($cmol_c$ kg^{-1})	2.84	15.60	7.44	2.43
Sand (%)	13.00	71.72	42.31	14.92
Clay (%)	2.70	39.61	11.87	7.49
Silt (%)	17.17	73.10	45.83	14.04

Methods: **a-** Mehlich, 1953; **b-** Peech, 1947.

Variables: *EC*- Electrical conductivity, *OM*- Organic matter, *SB*- Sum of base cations (Na, K, Ca and Mg), *CEC*e – Effective cation exchange capacity (Sum of base (Na, K, Ca, Mg) and acid cations (Al).

The soil characteristics of each plot were used to establish the growth modifier (0 to 1) for its fertility rating (*FR*). *FR* is in part a subjective parameter because the relationship between tree growth and soil fertility at a particular time is not necessarily represented only by soil chemistry. Moreover, adjustments to this parameter affect biomass production predictions because *FR* is directly related to the estimation of canopy quantum efficiency. The establishment of *FR* values must be independent of plot site index. As well as a specific methodology (Almeida et al., 2010; Vega-Nieva et al., 2013), a degree of expert knowledge may be necessary for its determination (Landsberg et al., 2003). *FR* values were first estimated using equation 4.1 which was based on soil texture (sand content, *sand* (%)) and the effective cation exchange capacity (*CEC*e (cmol$_c$ kg^{-1})) obtained in the edaphic analysis (Table 4.3).

$$FR = 0.2359 + 0.0089 \cdot Sand\ - 0.0117 \cdot CEC\mathrm{e}\,) \qquad (4.1)$$

In some plots, *FR* values were then adjusted ± 0.1 units (Fontes et al., 2006) based on expert opinion; values varied from 0.2 to 0.9 (Table 4.1).

The measured data that describe the soil depth and texture of each plot were used as input in the model. Soil moisture was measured in the nine selected plots. Three access tubes of 1-m depth were installed per plot to determine plot average soil moisture content. A PR2/6 Profile Probe (Delta-T Devices) was used monthly for one year to measure soil moisture in each access tube.

4.2.5. Model parameterisation

4.2.5.1. Biomass partitioning

Allometric equations (4.2, 4.3) for W_{Foliar} (including litterfall rate according to tree age, see equation 4.4) and W_{Stem} fractions were fitted to tree diameter (*d,* cm, Figure 4.2a,b) as the explanatory variable using destructive samples from 120 trees aged from 2.6-4.6 years (see González-García et al., 2013a,b) and eight additional trees aged 2 years (*d* = 2.14 ± 0.8 cm) that were included to increase representation of young trees. The foliage-stem partitioning ratio was 0.3786 for *d* = 2 cm trees (*pFS2*) and 0.0889 for *d* = 20 cm (*pFS20*).

$$W_{\text{Foliar}} = 0.0803 \cdot d^{1.5932} \qquad R^2 = 0.828 \qquad (4.2)$$

$$W_{\text{Stem}} = 0.0983 \cdot d^{2.2222} \qquad R^2 = 0.938 \qquad (4.3)$$

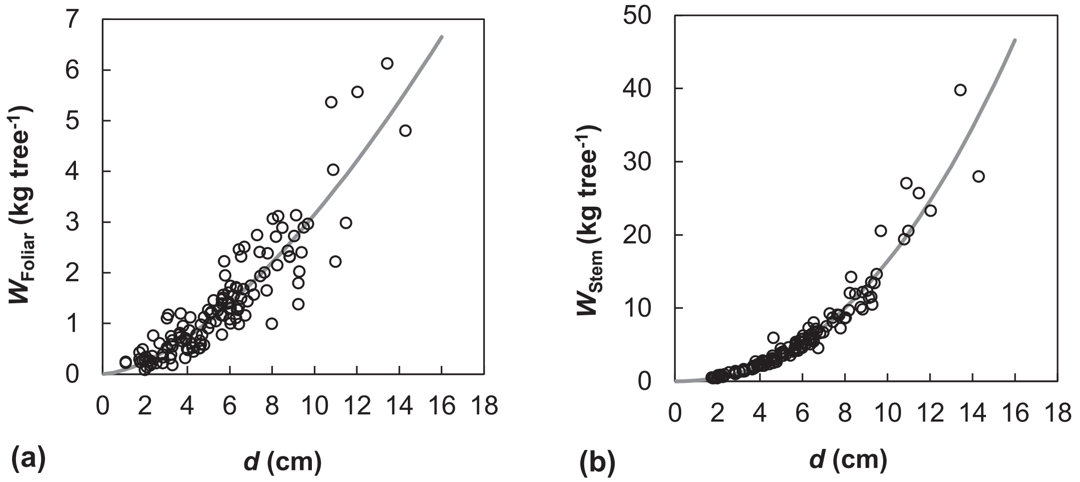


Figure 4.2. The relationships between foliar biomass W_{Foliar} (a) and stem biomass W_{Stem} (b) *vs*. diameter *d* at breast height.

Root data were not available for the model parameterisation so default values of 0.8 and 0.1, respectively, were used for the maximum (*pRx*) and minimum (*pRn*) NPP (Resh et al., 2003; Pérez-Cruzado et al., 2011).

4.2.5.2. Stand litterfall

Litterfall was collected monthly and its dry mass measured for one year in five selected plots (data from three plots were used in the calibration and two in the validation process). Four traps per plot were installed to cover stand variability. The total area of the traps in each plot was 1.8 m^2. A default litterfall rate at $t = 0$ (*gammaF0)* of 0.001 month^{-1} was established (Sands and Landsberg, 2002). From the observed data, the maximum litterfall rate (*gammaF1*) was 0.017 month^{-1} and the age at which litterfall rate has a median value (*tgammaF*) was 12 months (Sands and Landsberg, 2002).

$$gammaF(t) = \frac{1.67 \cdot 10^{-5}}{0.001 + 0.016 \cdot e^{-0.239 \cdot t}} \qquad (4.4)$$

4.2.5.3. Temperature and frost growth modifiers

Temperature affects forest growth and determines the suitability of the species to the site (Landsberg and Sands, 2010). *Eucalyptus nitens* is relatively well-adapted to low and frost temperatures, especially when it is compared with other *Eucalyptus* species (FAO, 1981; Leslie et al., 2012) and it is suited to climates across a wide range of mean annual temperatures (Battaglia, 2006; Booth and Pryor, 1991). However, extreme temperatures affect its photosynthetic performance (Battaglia et al., 1996). In this study the minimum (*Tmin*) and maximum (*Tmax*) growth temperatures were set at 2°C and 32°C (Rodríguez et al., 2009). The finding that *alphaC* was closely related to mean monthly temperature resulted in the optimum temperature (*Topt*) for *E. globulus* being set in 3-PG at 16°C (Sands and Landsberg, 2002). In the absence of a parallel study for *E. nitens*, *Topt* for this study was set at 13°C as the natural distribution of *E. nitens* is found at elevations > 800 m (Pederick, 1979), whereas that of *E. globulus* is typically at < 400 m (Williams and Potts, 1996); this is 2°C less than that nominated by Pérez-Cruzado et al. (2011). The days of production lost due to frost days (*Kf*) was set at 1 for each day of frost when the temperature dropped to ≤ 0°C (Fontes et al., 2006).

4.2.5.4. Canopy characteristics

To obtain specific leaf area (*SLA*), 840 leaves from the nine selected plots were analysed. Young and adult leaves were collected from different parts of the crown of three representative trees per plot in two periods, spring and the end of summer. *SLA* (m^2 kg^{-1}) was calculated as the ratio leaf area:leaf dry weight. To increase the representation of young trees, 15 trees in a *E. nitens* stand of 1.5 years with an average value of *SLA* of 10.7 ± 1.7 m^2 kg^{-1} were similarly sampled. Forty-four leaves from six-month-old nursery plants grouped in three categories according plant size were harvested to estimate *SLA* at age 0 (*SLA0*); the average value of *SLA0* obtained was 11.1 ± 3.8 m^2 kg^{-1}.

A Gaussian function with a non-zero asymptote which describes the temporal change in *SLA* (Sands and Landsberg, 2002) (equation 4.5) was fitted using average observed *SLA* values per site and age obtained in the nine selected plots, the 15 young trees, and average *SLA0* (Figure 4.3a). The results showed that the *SLA* for mature leaves (*SLA1*) was 4.0 m^2 kg^{-1}. The age at which *SLA* has a median value between *SLA0* and *SLA1* (*tSLA*) was 3.5 years.

$$SLA\ (t) = 4.0 + \left(4.0 - 11.1 \cdot e^{-(Ln\ 2) \cdot t/3.5)}\right) \qquad (4.5)$$

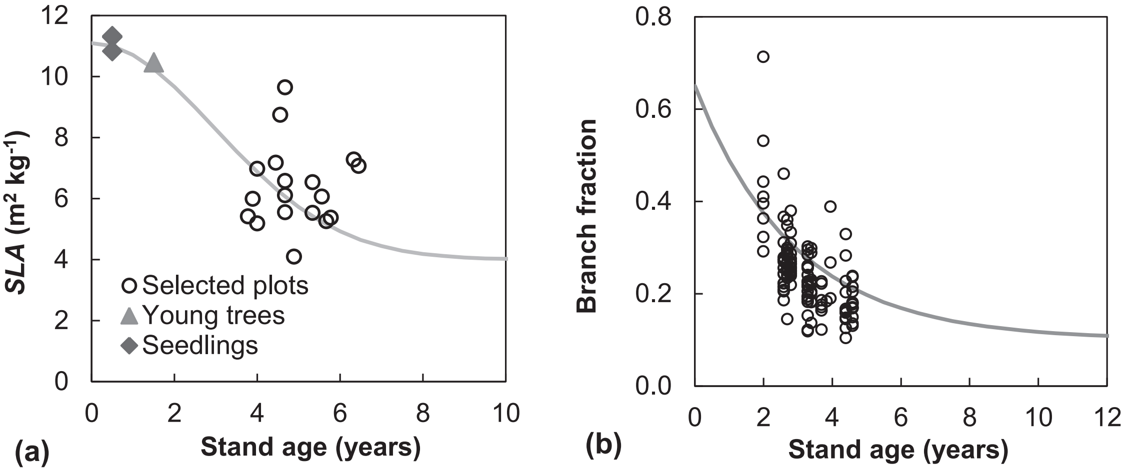


Figure 4.3. (a) The relationship between specific leaf area (*SLA*) and stand age. (b) The relationship between branch fraction and stand age; circles represent observed values in destructive tree samples.

Stand leaf area index (*LAI*) was estimated at the end of the wet and dry seasons in April and September 2013, respectively, using hemispherical photography in the nine selected plots (Table 4.1). The photographs were analysed using WinSCANOPY computer software (Regent Instruments) and the 57° method of Bonhomme et al. (1974). Stand *LAI* values ranged from 2.8 to 4.7 with an average of 3.7 m^2 m^{-2}.

Stomatal conductance and photosynthesis measurements were taken every two hours in two different seasons, spring and the end of summer, using an LI-6400 portable photosynthesis system (Li-Cor Inc., Lincoln, Nebraska, USA). Two selected plots (A-CAN-I and PAS-SAN-II), three trees per plot and five leaves per tree were measured in different crown sections (lower, middle and the upper).

Measurements were made during daylight hours in order to study photosynthetic responses to light and temperature and the data were used in the parameterisation procedure.

4.2.5.5. Mortality rate

No substantial mortality (≤ 7.5 %) was found in the experimental plots in the interval between the first and last inventory. The parameter values (*gammaN0*, *gammaN1*, *tgammaN*) (Table 4.4) were obtained from the mortality function used for *E. nitens* by Pérez-Cruzado et al. (2011).

4.2.5.6. Wood and stand properties

In plantations grown for bioenergy, all above-ground components of the tree are harvested to maximise the quantity of biomass. Branch biomass fraction and stem volume were determined from the destructive harvesting of the 120 sample trees and the eight two-year-old trees referred to above.

For branch biomass fraction, an exponential decay equation to a non-zero asymptote (equation 4.6 and Figure 4.3b) (Sands and Landsberg, 2002) was fitted to obtain the input parameters for 3-PG. The branch fraction was 0.65 for age 0 (*fracB0*) and 0.10 for mature stands (*fracB1*); the age at which branch fraction has a median value (*tB*) was two years.

$$fracB(t) = 0.10 + (0.10 - 0.65 \cdot e^{-((Ln\ 2)\cdot t/2)}) \qquad (4.6)$$

The 3-PG model can predict stem volume in two different ways, either using allometric equations and stem biomass with the fraction of stem biomass in the form of branches and bark, or using basic density of stem wood. The allometric approach has been used here because small errors in basic density can lead to large errors in the estimate of stem volume (Landsberg and Sands, 2010).

An over-bark volume allometric equation was fitted using the volume data (V, m^3 ha^{-1}) obtained from Section 2.2., and mean diameter (D, cm) and stand stocking (N, trees ha^{-1}) (equation 4.7) as explanatory variables. This approach assumes that stem volume is constant for a given diameter because variation in height is not considered.

$$V = 1.7 \cdot 10^{-5} \cdot D^{2.4842} \cdot N^{1.3100} \qquad R^2 = 0.978 \qquad (4.7)$$

4.2.6. Model simulations

The version of 3-PG used in this study was described in Almeida et al. (2007a). It includes a detailed water balance sub-model. Although the model predicts a range of different outputs, this study focused on stocking (N, trees ha^{-1}), mean tree diameter (D, cm), stand volume (V, m^3 ha^{-1}), above-ground biomass (W_{AGB}, Mg ha^{-1}), mean annual increment of W_{AGB} (MAI, Mg ha^{-1} y^{-1}), stand LAI and soil water content (SW, mm). The growth modifiers for soil water (f_{SW}), vapour pressure deficit (f_{VPD}), temperature (f_{TEMP}), frost (f_{FROST}) and fertility (f_{NUT}) which explain the effects of these variables on forest production, were also simulated by the model.

Model efficiency (EF) and the root mean square error ($RMSE$) were calculated to separately verify the predictive ability of the model for the calibration and validation phases. For EF, observed and predicted values of the different variables were assessed using equation 4.8 (Soares et al., 1995); these values can vary from -1 (no fit) to +1 (perfect fit). When positive, the model predicts better than average, and when negative, worse than average. Additionally, $RMSE$ (equation 4.9) provides a measure of the precision of the estimates in the same units as the dependent variable.

$$EF = 1 - \frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \qquad (4.8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}} \qquad (4.9)$$

where Y_i and $\hat{Y}_i$ are the observed and predicted values respectively, $\bar{Y}$ is the mean of the observed values and n represents the total number of observations.

4.2.7. Spatial analysis

The model parameterisation obtained in the calibration phase was applied to simulate the production of *E. nitens* in new plantations managed to supply biomass feedstock. The 3-PGS version was employed to analyse the potential of these plantations to produce bioenergy at the regional scale, and to define potential scenarios for biomass production considering different stocking and rotation length. The primary datasets required to run this model were climate and soil layers, plantation date, rotation length and the specific-species parameters used in the calibration process (Almeida et al., 2010).

Monthly climate maps were built using the actual climate data from the existing *AWS* (Section 2.3), and average maps for each month of the year for the period January 2007 to December 2013. The results of the model obtained by both types of maps were compared to check the difference between predictions with actual and average climate. All the maps were produced in GRID format with a pixel resolution of 200 × 200 m.

Due to the scarcity of soil spatial information, the "loam" soil texture class was selected for modelling because it is likely to be the most representative soil type across all the studied plots. April was selected as the month to start the simulations because spring is the most suitable season for stand establishment due to high water availability. Initial biomass at the age of 1.6 years was set at 1 Mg ha^{-1} for foliage and root biomass fractions and 1.7 Mg ha^{-1} for the stem biomass fraction. A value of 0.7 was assigned as *FR* (i.e. it was constant) for the spatial simulation on the basis that areas with low to medium soil fertility will be adequately fertilised after planting.

3-PGS can be used to compare productivity between different management practices (Almeida et al., 2004b). In this study, differences in W_{AGB} and *MAI* were analysed using the scenarios (1) stocking: 3000, 4000 and 5000 trees ha^{-1}, and (2) rotation length: 6, 7, 8 and 9 years.

To provide a realistic approach to this simulation, the spatial analysis was restricted to lands where the establishment of *Eucalyptus* plantations is permitted by the forest code and which have < 30 % slope that enable mechanization in the management and the harvesting of the plantations. The total surface area considered was 2,550 km^2.

4.3. Results

4.3.1. Stand level predictions

The developed and applied parameters values of 3-PG for *E. nitens* are shown in Table 4.4. Whether the source of each parameter is observed, derived from observed data, obtained from a specific reference or a default value is indicated, as are the units and notation. All the simulations at stand level included in this section were carried out using actual climate data for the period over which growth was measured.

Using these parameters in the calibration process, the model efficiencies, *EF* showed that 3-PG predicted between 65.9 and 81.3 % of the observed values of variables related to forest growth (Figure 4.4). For *N*, *EF* was 0.99, for biomass variables *EF* was > 0.68 (*RMSE* < 10 Mg ha^{-1}); for *V*, *d* and *SW EF* was > 0.51. In the validation phase, *EF* was between 0.34 and 0.99 for all variables. Increases in *EF* in the validation compared to the calibration model were observed for *D*, *V*, W_{Foliar}, W_{Stem}, W_{AGB} and *MAI*.

There was good agreement between observed and predicted values of above-ground biomass, W_{AGB} and *MAI*, which suggests that the model parameterisation was adequate to estimate growth variables. However, the model underestimated the highest values of W_{AGB} and *MAI* and overestimated the lowest, although this was less pronounced with W_{AGB} (Figure 4.4e,f).

Table 4.4. List of parameters used in 3-PG model.

Variable and meaning	Symbol	Units	Sourc	Value
Biomass partitioning and turnover				
Allometric relationships & partitioning				
Foliage:stem partitioning ratio @ d = 2 cm	*pFS2*	-	DO	0.3786
Foliage:stem partitioning ratio @ d = 20 cm	*pFS20*	-	DO	0.0889
Constant in the stem mass v. diam. Relationship	*aWS*	-	DO	0.0983
Power in the stem mass v. diam. Relationship	*nWS*	-	DO	2.2222
Maximum fraction of *NPP* to roots	*pRx*	-	D	0.8
Minimum fraction of *NPP* to roots	*pRn*	-	R[a]	0.1
Volume of soil accessed by 1 kg of root *DM*	*spRootVol*	m^3·kg^{-1} root	D	2
Litterfall & root turnover				
Maximum litterfall rate	*gammaF1*	month^{-1}	O	0.017
Litterfall rate at t = 0	*gammaF0*	month^{-1}	D	0.001
Age at which litterfall rate has median value	*tgammaF*	months	D	12
Average monthly coarse root turnover rate	*gammaR*	month^{-1}	D	0.015
NPP & conductance modifiers				
Temperature modifier				
Minimum temperature for growth	*Tmin*	°C	R[b]	2
Optimum temperature for growth	*Topt*	°C	P	13
Maximum temperature for growth	*Tmax*	°C	R[b]	32
Frost modifier				
Days production lost per frost day	*kF*	days	R[c]	1
Fertitlity effects				
Value of 'm' when *FR* = 0	*m0*	-	D	0
Value of 'f$_{NUT}$' when *FR* = 0	*fN0*	-	D	0.6
Power of (1-*FR*) in *gmNutr*	*fNn*	-	D	1
Atmospheric CO$_2$ effects				
Ratio of alpha at 700 and 350 ppm	*gmCalpha700*	-	D	1.4
Ratio of canopy conductance at 700 and 350 ppm	*gmCg700*	-	D	0.7
Salinity effects				
Salinity below which no effects of salt on growth	*EC0*	dS·m^{-1}	D	999
Salinity above which growth ceases	*EC1*	dS·m^{-1}	D	999
Power of *EC* in *gmSalt*	*ECn*	-	D	1
Age modifier				
Maximum stand age used in age modifier	*MaxAge*	years	DO	40
Power of relative age in function for *fAge*	*nAge*	-	D	4
Relative age at *fAge* = 0.5	*rAge*	-	D	0.95
Stem mortality & self-thinning				
Mortality rate for large t	*gammaN1*	%·year^{-1}	R[b]	0.6
Seedling mortality rate (t = 0)	*gammaN0*	%·year^{-1}	R[b]	0.25
Age at which mortality rate has median value	*tgammaN*	years	R[b]	9
Shape of mortality response	*ngammaN*	-	D	1
Max. stem mass per tree @ 1000 trees/hectare	*wSx1000*	kg·tree^{-1}	R[b]	285
Power in self-thinning rule	*thinPower*	-	D	1.5
Fraction mean single-tree foliage biomass lost per dead tree	*mF*	-	D	0
Fraction mean single-tree root biomass lost per dead tree	*mR*	-	D	0.2
Fraction mean single-tree stem biomass lost per dead tree	*mS*	-	D	0.2

Variable and meaning	Symbol	Units	Source	Value
Canopy structure and processes				
Specific leaf area				
Specific leaf area at age 0	*SLA0*	$m^{2\cdot}$kg-1	O	11.1
Specific leaf area for mature leaves	*SLA1*	$m^{2\cdot}$kg-1	DO	4
Age at which specific leaf area = (*SLA0*+*SLA1*)/2	*tSLA*	years	DO	3.5
Light interception & *VPD* attenuation				
Extinction coefficient for absorption of PAR by canopy	*k*	-	D	0.5
Age at canopy cover	*fullCanAge*	years	O	3
LAI for 50% reduction of *VPD* in canopy	*cVPD0*		D	5
Rainfall interception				
Maximum thickness of water retained on leaves	*tWaterMax*	mm	D	0.25
Maximum proportion of rainfall evaporated from canopy	*MaxIntcptn*	-	R[d]	0.32
LAI for maximum rainfall interception	*LAImaxIntcptn*	-	D	3
Production and respiration				
Canopy quantum efficiency	*alphaCx*	molC·molPAR^{-1}	R[b]	0.07
Edge tree growth % enhancement	*edgeEffect*	-	D	20
Ratio *NPP*/*GPP*	*Y*	-	D	0.47
Conductance				
Maximum stomatal conductance	*gSx*	m·s^{-1}	O	0.011
Radiation for *gS* = *gSx*/2	*IgS*	W·m^{2}	D	100
Maximum canopy conductance	*MinCond*	m·s^{-1}	D	0
Maximum canopy conductance	*MaxCond*	m·s^{-2}	D	0.02
LAI for maximum canopy conductance	*LAIgcx*	-	D	3.33
Defines stomatal response to *VPD*	*CoeffCond*	mBar^{-1}	DO	0.05
Canopy aerodynamic conductance	*gAc*	m·s^{-1}	D	0.2
Soil aerodynamic conductance	*gAs*	m·s^{-2}	D	0.02
Wood and stand properties				
Branch fraction				
Branch fraction at age 0	*fracB0*	-	DO	0.65
Branch fraction for mature stands	*fracB1*	-	DO	0.10
Age at which *fracB* = (*fracB*0+*fracB*1)/2	*tB*	years	DO	2
Stem volume				
Constant in the stem volume relationship	*aV*	-	DO	$1.7\cdot10^{-5}$
Power of *D* in the stem volume relationship	*nVB*	-	DO	2.4842
Power of stocking in the stem volume relationship	*nVN*	-	DO	1.3100
Conversion factors				
Intercept of net v. solar radiation relationship	*Qa*	W·m^{2}	R[e]	-8.85
Slope of net v. solar radiation relationship	*Qb*	-	D	0.8
Molecular weight of dry matter	*gDM_mol*	gDM·mol^{-1}	D	24
Conversion of solar radiation to PAR	*molPAR_MJ*	mol·MJ^{-1}	D	2.3

Source of parameter **O**: observed; **DO**: derived from observed data; **D**: default; **P:** proposed; **R**: reference; **a-**Resh et al., 2003; **b-**Pérez-Cruzado et al., 2011; **c-**Fontes et al., 2006; **d-**Huber and Iroume, 2001; **e-**Almeida and Landsberg, 2003.

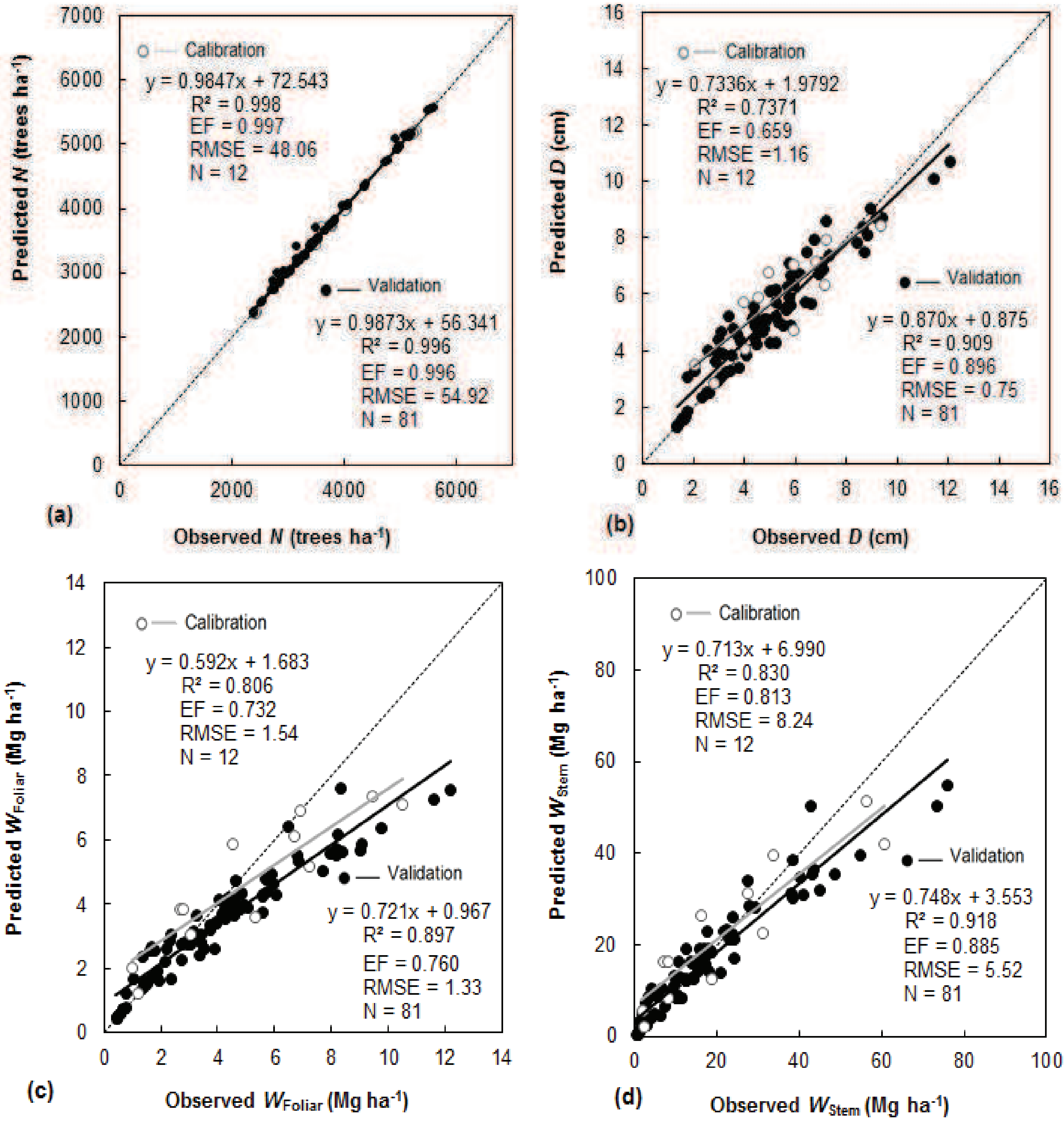


Figure 4.4. Relationship between observed and predicted for the variables: (a) stocking: *N*, (b) mean diameter at breast height: *D*, (c) foliar biomass: W_{Foliar} and (d) stem biomass: $W_{\text{Stem.}}$ The numeric data included in the graphs represent: lineal equations (y), coefficient of determination (R^2), 3-PG model efficiency (*EF)*, root mean square error *(RMSE)* and number of data used (*N*) for the calibration and validation phase. The dashed line represents the 1:1 isoline.

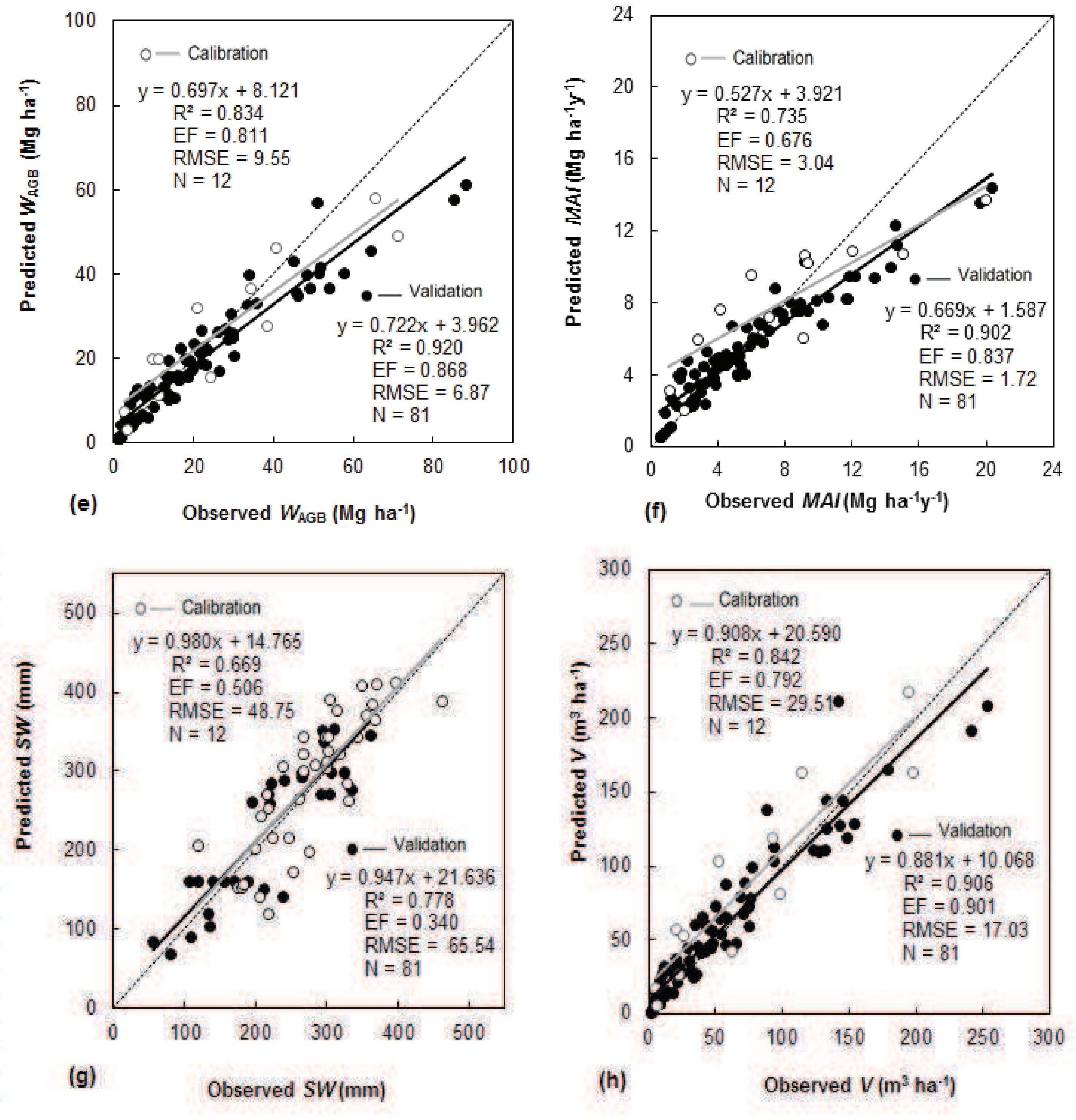


Figure 4.4. Relationship between observed and predicted for the variables: (e) above-ground biomass: W_{AGB}, (f) mean annual increment of above-ground biomass: *MAI*, (g) soil water content: *SW* and (h) stem volume: *V*. The numeric data included in the graphs represent: lineal equations (y), coefficient of determination (R^2), 3-PG model efficiency (*EF*), root mean square error *(RMSE)* and number of data used (*N*) for the calibration and validation phase. The dashed line represents the 1:1 isoline.

There was reasonable agreement between the predicted and observed values for monthly *SW* (Figure 4.5a); the model was able to follow variability in *SW* with time and capture the extremes. *EF* for this variable was 0.51 and 0.34 for the calibration and validation phases, respectively, which is considered acceptable (Almeida et al., 2007b). Reductions in soil moisture during summer resulted in very low values of the soil water modifier, $f_{SW} < 0.05$ (Figure 4.5b). This was associated with low precipitation. Between July and September, it was around 35 mm month^{-1} on average; however in 2010 and 2013 precipitation was < 12 mm per month. Current monthly increment (*CMI*) was directly influenced by *SW* and *CMI* varied from 0 to 5 Mg ha^{-1} month^{-1} (Figure 4.5a). Air temperature also influenced forest growth, but had much less impact than *SW* deficit. High summer temperatures and *VPD*s reinforced the effects of *SW* deficit; the minimum values of f_{TEMP} and f_{VPD} were around 0.8 and 0.7, respectively (Figure 4.5b). Low winter temperatures also affected growth; minimum f_{TEMP} was 0.5, and minimum f_{VPD} was 0.9 (Figure 4.5b). The mean f_{SW}, f_{TEMP} and f_{VPD} for all sites and an entire rotation of nine years were respectively 0.73, 0.87 and 0.83.

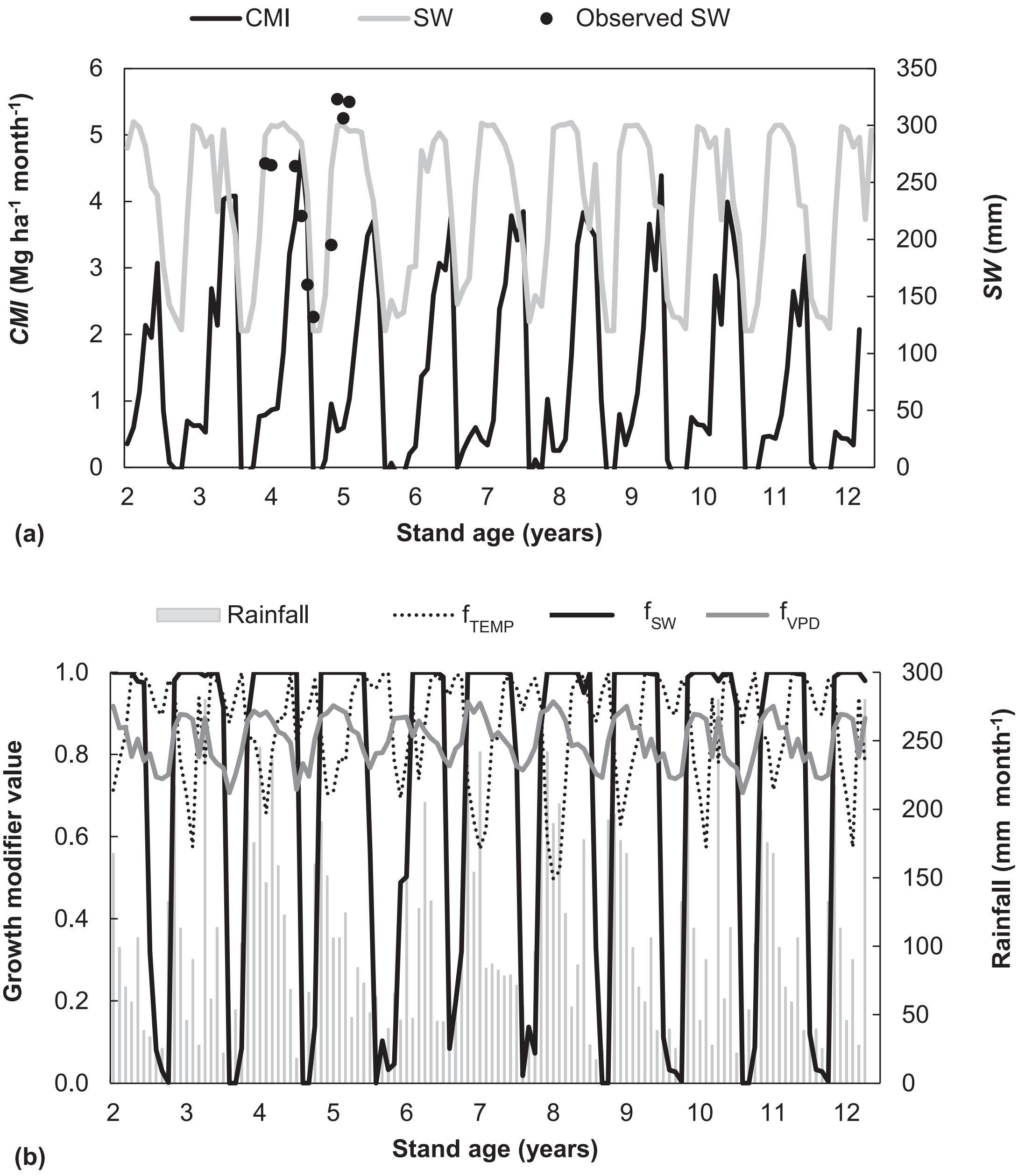


Figure 4.5. (a) Predicted and observed values for soil water (*SW*) and current monthly increment (*CMI*) in a sample plot with silt soil texture. (b) Predicted values for the soil water growth modifier (f_{SW}), temperature growth modifier (f_{TEMP}), vapour pressure growth modifier (f_{VPD}) and rainfall for the same sample plot.

4.3.2. Spatial analysis

Potential productivity was affected by water availability in the summer months, as a consequence of rainfall distribution. The north of the study area had higher biomass production than the south because precipitation was higher and better distributed during summer (Figure 4.6).

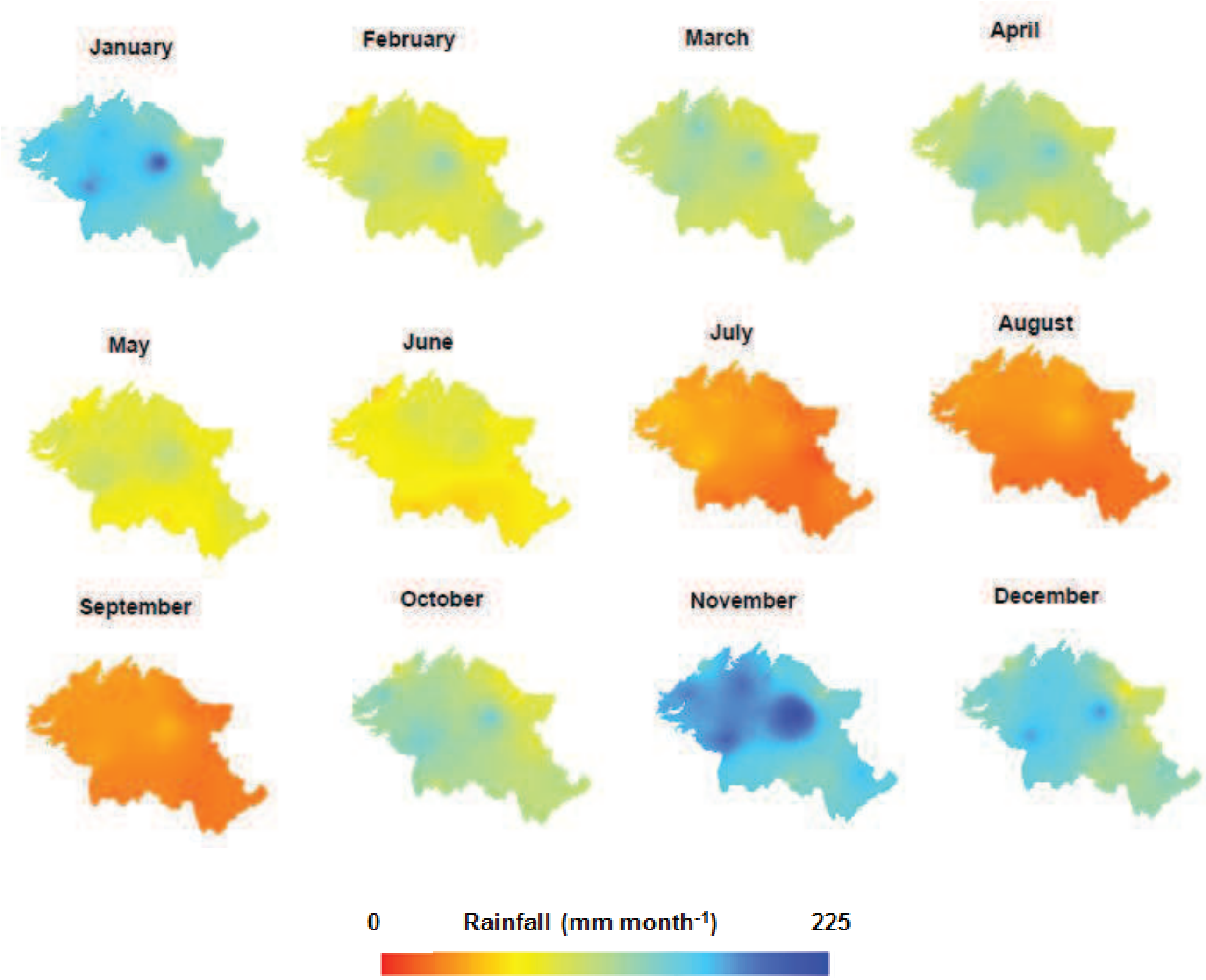
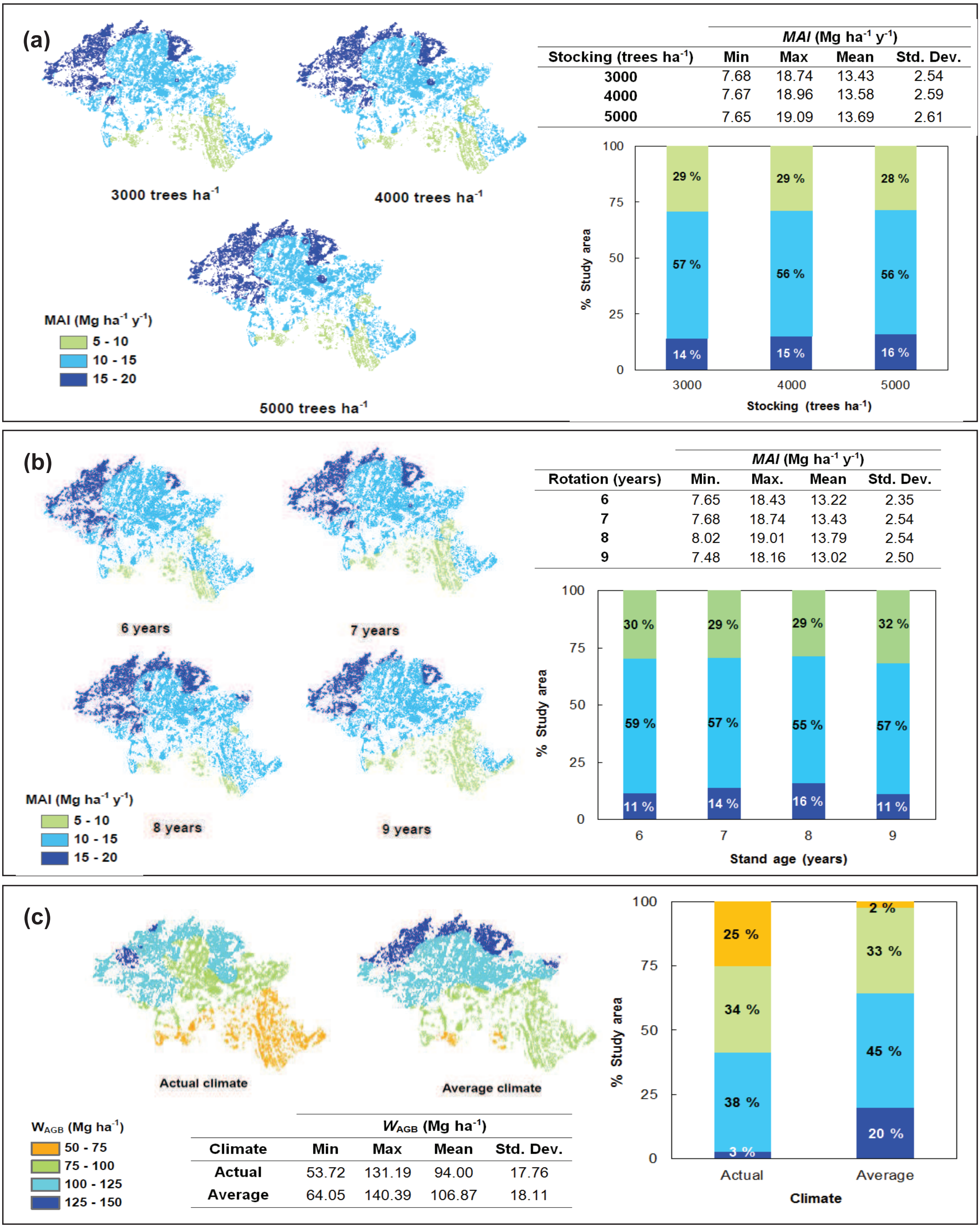


Figure 4.6. Spatial and seasonal variation in precipitation for average climate data (2007-2013).

Using three productivity classes for *MAI* from 5 to 20 Mg ha^{-1} y^{-1} with intervals of 5 Mg ha^{-1} y^{-1} and a rotation length of 7 years, *MAI* increased with stocking (Figure 4.7a). However differences in average *MAI* were only 1.9 % between 3000 (13.4 Mg ha^{-1} y^{-1}) and 5000 trees ha^{-1} (13.7 Mg ha^{-1} y^{-1}). For three rotation lengths between 6 and 8 years and a stocking of 3000 trees ha^{-1}, *MAI* increased gradually with rotation length from 13.2 Mg ha^{-1} y^{-1} at age 6 years to 13.8 Mg ha^{-1} y^{-1} at age 8 years, a productivity increase of 4 %; at age 9 years it decreased to 13.0 Mg ha^{-1} y^{-1} (Figure 4.7b).



	MAI (Mg ha^{-1} y^{-1})			
Stocking (trees ha^{-1})	Min	Max	Mean	Std. Dev.
3000	7.68	18.74	13.43	2.54
4000	7.67	18.96	13.58	2.59
5000	7.65	19.09	13.69	2.61

	MAI (Mg ha^{-1} y^{-1})			
Rotation (years)	Min.	Max.	Mean	Std. Dev.
6	7.65	18.43	13.22	2.35
7	7.68	18.74	13.43	2.54
8	8.02	19.01	13.79	2.54
9	7.48	18.16	13.02	2.50

	W_{AGB} (Mg ha^{-1})			
Climate	Min	Max	Mean	Std. Dev.
Actual	53.72	131.19	94.00	17.76
Average	64.05	140.39	106.87	18.11

Figure 4.7. Spatial variation in *MAI* of above-ground biomass for (a) different stockings: 3000, 4000, 5000 trees ha^{-1} and rotation of 7 years, (b) different rotation length: 6-7-8-9 years using a stocking of 3000 trees ha^{-1} and (c) spatial variation in above-ground biomass for stocking of 3000 trees ha^{-1} and rotation of 7 years using actual or average monthly climate.

The proportion of W_{Stem} in W_{AGB} increased with stand age from 0.72 at age 2 years to 0.95 at age 12 years; it increased from 0.89 to 0.93 between ages 6 and 9 years. The proportion allocated to W_{Stem} was 1.7-1.0 % (6-12 years) greater for a stocking of 3000 trees ha^{-1} compared to 5000 trees ha^{-1} (Figure 4.8a). The mean *D* of trees at 3000 trees ha^{-1} was at least 3 cm (or 20 %) greater than for the higher stockings between ages 6 and 9 years (Figure 4.8b).

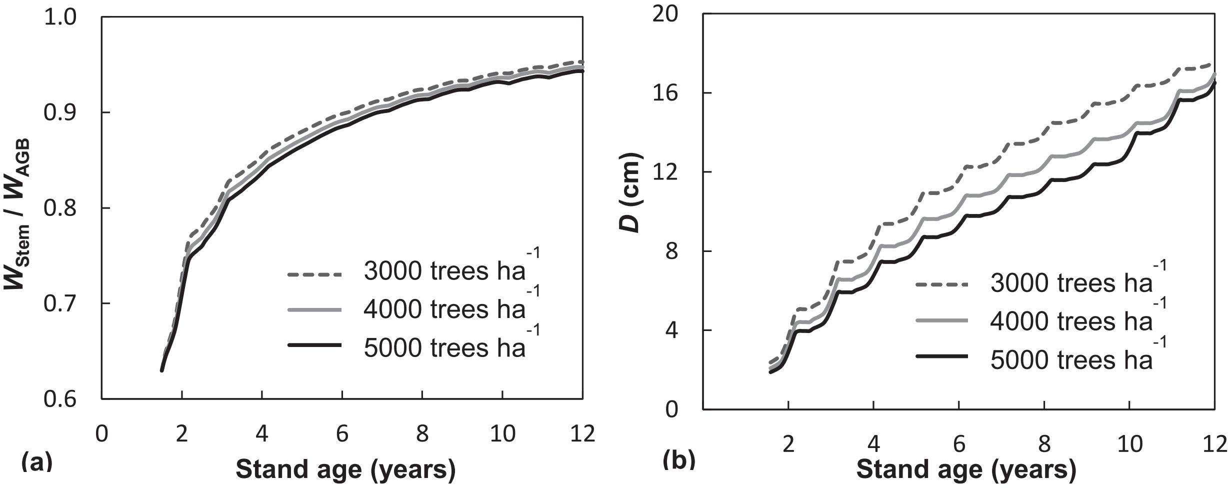


Figure 4.8. Comparison between different stockings: 3000, 4000 and 5000 trees ha^{-1} for (a) the proportion of W_{Stem} in W_{AGB} and (b) mean diameter (*D*).

The effects of average and actual climate on W_{AGB} were compared assuming a stocking of 3000 trees ha^{-1} and a rotation length of 7 years with intervals of 25 Mg ha^{-1}. Average climate produced higher mean W_{AGB} by 12 % when compared with the predictions using the actual climate (Figure 4.7c).

4.4. Discussion

The results show that 3-PG can be used for modelling stand development of *E. nitens* plantations managed for the production of biomass for bioenergy with acceptable accuracy. The model was also able to produce long-term growth estimates, identify and quantify the effects of the environmental factors that determine tree growth in the study region, and examine the effects of stocking and rotation length on yield. Forest managers can therefore use 3-PG to predict plantation productivities and to test different management strategies for building capacity and optimising their investments in bioenergy supplies.

The plot scale simulations showed that the model is able to estimate growth across a wide range of sites. The best predictions were for sites of average productivity. Thus, although the model was calibrated using sample plots that represented the greatest range of variability in soils and climate, the productivity of very low and very high yielding plantations was still predicted with lower than desirable accuracy. This may be related to the limited number of times data was collected, only twice at the least productive site. Another potential reason is uncertainties about soil depth and respective *SW* (Almeida et al., 2007; Landsberg and Sands, 2010). Observed values of soil depth were generally low and if roots are penetrating deeper layers, *SW* and growth will be underestimated as the trees are less vulnerable to water stress than estimated by the model.

Above-ground biomass, W_{AGB}, the most important variable to be able to predict when growing plantations for bioenergy, had the highest model efficiencies, with *EFs* of 0.81 and 0.87 for the calibration and validation sites, respectively. Stand volume *EF* was 0.79 for calibration and 0.90 for validation. Higher *EF* for validation than calibration sites is most probably linked to the much greater number of plots and the larger percentage of average productivity sites used for validation. In a 3-PG calibration model for *E. globulus* in Portugal, *EF* values for *V* and W_{Stem} were also > 0.7; *EF* for W_{Foliar} was ≤ - 0.24, much lower than in the current study, but this was attributed to a poor estimation of litterfall used in model parameterisation (Fontes et al., 2006). By contrast, in the validation process of 3-PG in a parallel study in Spain with *E. nitens* (Pérez-Cruzado et al., 2011), *EF* and *RMSE* for W_{Foliar} at three sites (range 0.87-0.91 and 0.28-1.08, respectively) were greater and less than those in the current study (0.76 and 1.3, respectively). Where 3-PG has been applied to poplar species being managed for bioenergy, R^2 for the relationship between predicted and observed W_{AGB} in the validation stage was 0.89 (Headlee et al., 2013) and similar to this study (0.87), confirming that strong relationships are obtainable for this variable; for mean diameter, R^2 varied from 0.54 to 0.98 in the model validation across a number of sites and stockings (Amichev et al., 2010). The value obtained for *D* in this study of *E. nitens* was within this range (0.90).

The regional monthly rainfall variability had a strong effect on f_{SW} which was < 0.2 for periods of up to four months during the summer. Levels of *SW* became sufficiently low to have a marked effect on stand productivity as has been found previously for *E. nitens* for the same stands (González-García et al., 2015) and for an adjacent region (Pérez et al., 2011). By contrast, a CHAID (Chi-square automatic interaction detection) analysis of the effects of water deficit on growth of *Castanea sativa* (Afif-Khouri et al., 2011) and *Pinus pinaster* (Álvarez-Álvarez et al., 2011), also in North-west Spain, concluded that available water was not a factor limiting their growth, possibly because these species are more tolerant to water stress or local differences between the study areas. Water deficit has previously been shown to be a major factor influencing *E. nitens* productivity in Chile in areas that have a marked seasonal drought (Rodríguez et al., 2009) and in Australia, where it has been shown to be associated with physiological changes in osmotic potential and bulk elastic modulus (Beadle et al., 1995; White et al., 1996). The growth of *E. globulus* grown in North-west Spain at elevations < 500 mm is also affected by the length of the drought period (Merino et al., 2003), though this species is less susceptible to water stress than *E. nitens* (White et al., 1996). Nevertheless, levels of available water in the study region remained, on average, much higher than those experienced in inland Mediterranean climates in Spain where irrigation during the spring and summer is essential for the survival of bioenergy plantations (Pérez-Cruzado et al., 2014). Thus in spite of the regular summer droughts experienced in North-west Spain, survival of rain-fed *E. nitens* plantations remained high and *MAI*s were > 7 to < 19 Mg ha^{-1} y^{-1} at harvest.

Stand productivity was less affected by reduced summer rainfall in the northern than southern region. This rainfall gradient generated fluctuations in forest growth to the extent that production can be severely limited for between 2 and 4 months during this dry summer period. Thus monthly current W_{AGB}

production varied from 0 to 5 Mg ha^{-1} $month^{-1}$, indicating the importance of water as a determinant of plantation productivity in North-west Spain. Water is a factor constraining the growth of *Eucalyptus* plantation estates elsewhere (Almeida et al., 2007b; Mendham et al., 2011; Stape et al., 2010; White et al., 2009).

Although less marked than for rainfall, seasonal changes in temperature also led to some reductions in growth (González-García et al., 2015). In summer, reductions in f_{TEMP} occurred when high temperatures coincided with reduced precipitation. Reduced stem growth in *E. nitens* associated with high summer temperatures has also been observed in irrigated stands in Tasmania (Downes et al., 1999). In winter, maximum reductions in f_{TEMP} were more severe (0.5 *v.* 0.8 in summer). In spite of *E. nitens*' relatively high frost hardiness (FAO, 1981), its capacity for photosynthesis is reduced at very low temperatures (Battaglia et al., 1996). The stomatal conductance of *E. nitens* is highly sensitive to *VPD* (White et al., 1999) and 3-PG showed that *VPD* reduces growth throughout the year.

In short-rotation woody plantation crops, higher stockings are associated with shorter rotations and more rapid and complete site occupancy (Mead, 2005; Powers, 1999). In the current study, stand level W_{AGB} and V increased with stocking but mean tree diameter at the higher stockings was 20 % less than at the lowest stocking (3000 stems ha^{-1}). Higher stockings, also tend to result in a lower proportion of wood, and a higher proportion of branches and bark at harvest (Zhao et al., 2011, 2014), though in this study the proportion of these components could not be estimated separately as they were included in W_{Stem}. Thus growing *E. nitens* at 3000 stems ha^{-1} maximises the main source of energy from the plantation, although leaves which accounted for 7-10 % of the biomass at harvest have a higher calorific value than wood (Pérez et al., 2011; Senelwa and Sims 1999).

MAI increased with increasing stocking from 3000 to 5000 stems ha^{-1} though differences were very small (< 2 %). As lower stocking is associated with reduced costs of establishment, management and harvesting (Darrow, 1984; Mead, 2005), 3000 stems

ha^{-1} can be considered the most suitable for *E. nitens* in this region. This stocking is consistent with that used for *Eucalyptus* bioenergy stands in the southern United States (González et al., 2011); in New Zealand, even lower stockings (2200 stems ha^{-1}) have been used for bioenergy based on *Eucalyptus* species (Sims et al., 1999).

For a stocking of 3000 trees ha^{-1}, *MAI* increased with rotation age, but only by 4 % between ages 6 and 8 years. Thus rotation length can be selected in this interval of stand ages, perhaps in conjunction with preferred stem diameter and desired frequency of harvesting operations. These changes in *MAI* with rotation age are similar to those observed by González-García et al. (2015) for medium and high site quality sites supporting *E. nitens* bioenergy stands and by González et al. (2011) for *Eucalyptus* woody crops in the United States. Productivity differences obtained spatially according to the climatic conditions showed that short rotation lengths could be applied on the best sites of the study area where plantations had a *MAI* class of 16-20 Mg ha^{-1} y^{-1}.

Above-ground biomass production was overestimated by 12 % when historical average rather than actual climate data were applied. Average climate data are often used in spatial modelling (Landsberg et al., 2003). However, in environments that are subject to extreme climatic events, for example drought as in this study, productivity is more likely to be overestimated because the average climate will tend to minimise their effects on productivity. Along the Atlantic coast in Brazil, Almeida et al. (2010) showed that using average climate can overestimate stem growth of eucalypt plantations by up to 25 % when compared with actual climate. As extreme events are likely to become more frequent, the use of actual climates for productivity prediction is likely to become more important as well as for examining potential future climates (Dale et al., 2001).

This study has shown that the 3-PG process-based model can accurately predict above-ground biomass production, W_{AGB} of *E. nitens* plantations managed for bioenergy. Available water, and to a lesser extent maximum and minimum temperatures, and *VPD*, were the main constraints on growth. Very small changes in *MAI* of W_{AGB} with rotation length and stocking led to a recommendation that these can be 3000 trees ha^{-1} and 6 years respectively; these also maximise the relative production of wood and minimise time to harvest. The spatial scale of the study further illustrated that scenarios of anticipated site productivity across large landscapes can be made if combined with spatial information derived from GIS (Almeida et al., 2010; Dye et al., 2004; Rodríguez et al., 2009). A limitation was the lack of information that accurately describes the high variability of soil properties in the region. Better descriptions of soil texture and soil depth will lead to more accurate measures of soil water holding capacity and fertility, and therefore biomass prediction. Nevertheless in its current form, this model can provide the necessary information for regional industries and forest managers to invest in bioenergy from *E. nitens* plantations. The conversion of abandoned forest or marginal lands to bioenergy plantations could contribute considerably to satisfy future energy demand in this region and reduce its dependency on fossil fuels.

4.5. References

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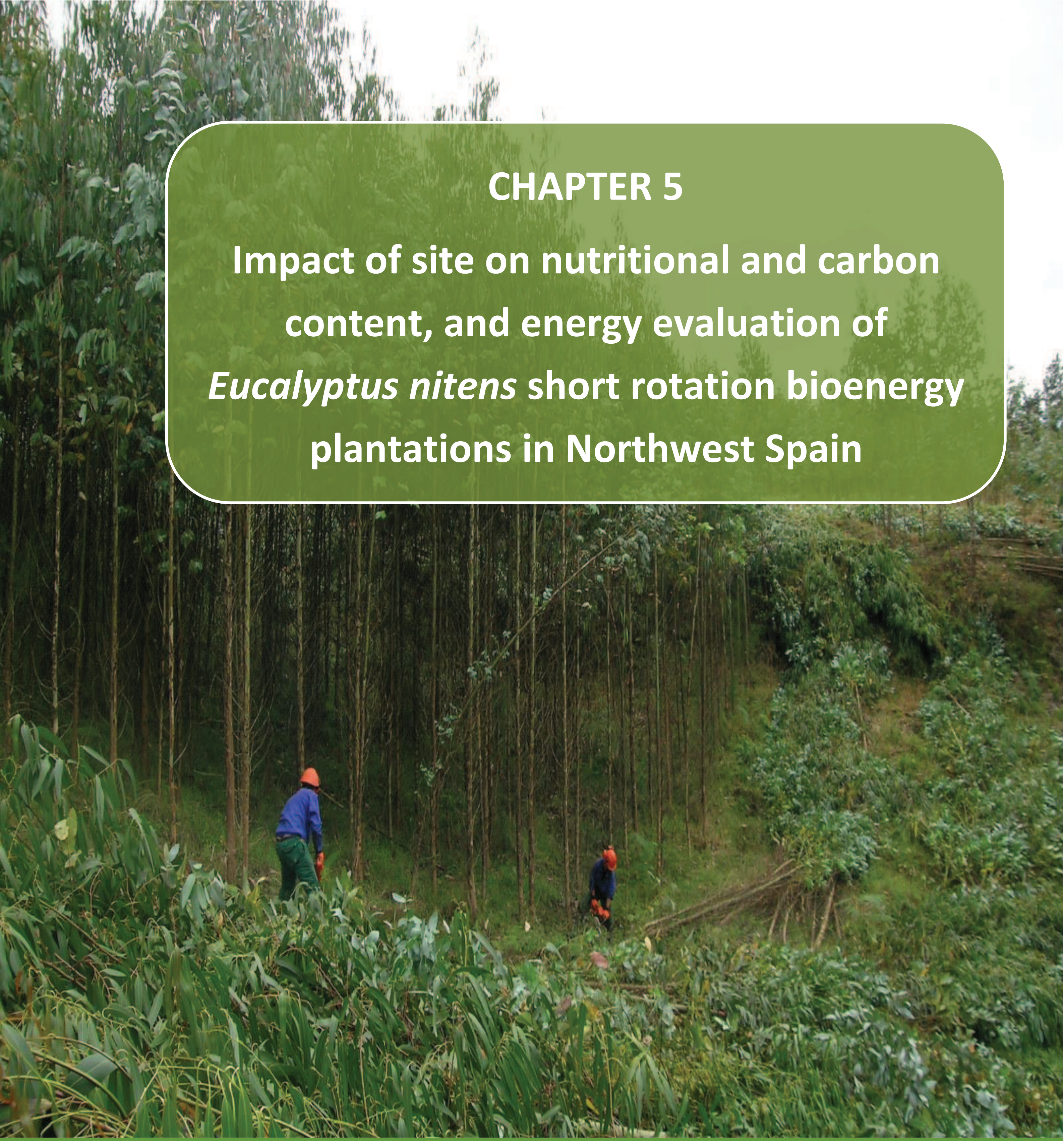

CHAPTER 5

Impact of site on nutritional and carbon content, and energy evaluation of *Eucalyptus nitens* short rotation bioenergy plantations in Northwest Spain

Article reference

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CHAPTER 5. Impact of site on nutritional and carbon content, and energy evaluation of *Eucalyptus nitens* short rotation bioenergy plantations in Northwest Spain

5.0. Abstract

This study provides essential information related to the nutrient and carbon levels and the energy potential of *Eucalytpus nitens* (Deane & Maiden) Maiden bionenergy plantations located in Northwest Spain. Nutritional analysis showed that leaves and bark had the highest concentrations of N, P, K and Mg. Carbon concentration was constant for all above-ground tree components. Nutrients and carbon were analysed at stand level according to plantation productivity. Stemwood, the main tree component at the end of the rotation, had the highest nutrient content, except for N and Ca which were highest in leaves and bark respectively. Based on this study, the nutrient content of above-ground biomass was 243-706 kg N, 44-122 kg P, 131-375 kg K, 121-329 kg Ca and 25-67 kg Mg per ha at the end of the bioenergy rotation (6-12 years, depending on site quality) and 19-56 Mg C ha^{-1}. Energy analysis showed a fairly constant Net Calorific Value for wood, 18.32±0.19 MJ kg^{-1}. The results obtained provide essential information for implementing the most appropriate forest management system in these bioenergy plantations, and therefore promote the sustainable use of woody crops.

Keywords: *Eucalyptus,* woody crops, site quality, bioenergy, nutrient, carbon, energy potential, calorific value.

5.1. Introduction

Short rotation woody crops can produce high biomass yields in a short period of time and play a key ecological and economic role as an alternative to abandoned agricultural lands and as a renewable power source (Pellegrino et al., 2011).

Woody crops are particularly suitable as a bioenergy source because their cycles are relatively short compared with traditional forestry. However, since in bioenergy plantations the whole tree is harvested to maximize yields, tree components such as branches, leaves and bark which contain a significant accumulation of nutrients (Merino et al., 2005; Rodríguez-Soalleiro et al., 2004; Zhao et al., 2014), are extracted. In addition, the shorter the rotation, the higher the ratio of crown components in the above-ground biomass, which compounds this problem as these, especially the foliage, are the components with the highest nutrient concentrations (Bosco et al., 2004; Laclau et al., 2000). Increased use of forest fuels thus results in an intense export of plant nutrients from the forest (Raulund-Rasmussen et al., 2008) and hence, harvesting of such crops and the concomitant nutrient export from the site should be major considerations in sustainable production (Guo et al., 2002). Nutrient removal resulting from biomass harvesting can easily exceed nutrient contributions through natural means, such as the alteration of mineral or atmospheric inputs and therefore woody crops can produce greater soil damage than longer rotation plantations (Raulund-Rasmussen et al., 2008).

There is a great degree of uncertainty with regard to the concentrations of nutrients acquired by species and their distribution through the various tree components (Paré et al., 2013) which needs to be addressed in order to provide the tools necessary for forest managers to make decisions which ensure the sustainability of land use. In the northwest of Spain nutritional information is available for *Eucalyptus globulus* Labill. (Balboa, 2005; Brañas et al., 2000; Rodríguez-Soalleiro et al., 2004) although currently information for *Eucalyptus nitens*, a species with great bioenergy potential in this area (Pérez-Cruzado et al., 2011) is limited, a notable exception being a study of nutritional information for this species in relation to wood or pulp production at stand ages of 9-13 years and stockings from 400 to 1400 trees ha^{-1} (Rodríguez da Costa, 2010).

Furthermore, interest in the use of *Eucalyptus* plantations for thermal or electric power in the northwest of Spain highlights the importance of establishing information regarding the energy content of a stand (Pérez et al., 2006, 2011). The most suitable energy crop species should combine high production with high quality biomass (Kumar et al., 2010) and *Eucalyptus* have higher energy potential than other fast growing energy species such as *Populus* and *Pawlonia* (Villanueva et al., 2011). Within the genus the energy potential of residual biomass (tree fractions obtained from wood harvesting that are not used for wood or pulp production) has been found to be higher for *E. nitens* than for *E. globulus* in the north of Spain (Pérez et al., 2006). A better understanding of biofuel properties facilitates the increase in the use of forest energy, which helps mitigate climate change on a global scale, among other advantages (Laurila, 2013).

The importance of *Eucalyptus* species in the forestry sector of Northwest Spain, as well as the increasing interest in bioenergy systems and the lack of knowledge pertaining to the influence of forestry management and site quality on nutrient and carbon content within the system, have led to the following objectives being defined for this work: (1) to assess the nutritional status of *E. nitens* bioenergy plantations and (2) to study the concentration and distribution of nutrients in above-ground biomass; (3) to estimate the level of nutrients removed at the end of the rotation (depending on productivity). At the same time, (4) the carbon content and the (5) energy potential of these crops were evaluated to provide essential information for the use and management of these bioenergy plantations.

5.2. Material and methods

5.2.1. Stand characteristics

The study was carried out in Northwest Spain in the distribution area of the bioenergy plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden (McAlister provenance) (Figure 5.1). The dataset used in this study came from 40 experimental plots, each of 400 m^2, installed in *E. nitens* stands which had been previously established using seedlings. These plots were subjectively chosen to represent the range of site conditions, ages and stocking densities (2300 to 5600 trees ha^{-1}) for this type of plantation in the study area. The climate of the area is defined as European Atlantic with an average annual precipitation of approximately 1200 mm and an average annual temperature of 11°C.

In this region *Eucalyptus* are generally planted in existing forestry land in soils which are limited in terms of forest productivity, although in recent decades there has been an increase in the use of abandoned agricultural land, which is highly productive (Merino et al., 2003).

The study stands had been fertilized using 100-150 g per plant of 8/24/16 NPK immediately after plantation, equal to 230-840 kg of fertilizer ha^{-1} (18-67 kg N ha^{-1}, 55-202 kg P ha^{-1} and 37-134 kg K ha^{-1}) according to plant stocking. Chemical and mechanical weed control had been carried out when necessary to avoid competition, especially during the first stages of the plantations (Bennett et al., 1996).

5.2.2. Sample collection

The destructive sample used in this study was composed of 120 trees (three per plot) aged between 2 and 5 years, which represented the height-diameter distribution in stands obtained in a previous inventory (for further information see González-García et al. (2013a,b)). These trees were cut down and separated into five tree components: leaves, branches, dead branches, stemwood and bark, to estimate above-ground tree biomass, as described in

(González-García et al., 2013a). The subsample consisted of 25 % by weight of the crown components (leaves and branches) and stem disks (for wood and bark) which were taken to the laboratory and oven dried to a constant weight at 65°C to avoid nutrient volatilisation.

Furthermore, from each trunk several other wood disks were cut at various heights from the ground and transported to the laboratory and stored prior to energy evaluation. A total of 17 wood samples from 14 sites, all corresponding to disks cut at a height of 0.5 m from the ground, were selected for energy evaluation according to several criteria, such as plot location, site quality, stand age and tree diameter.

Figure 5.1 shows the locations of the sample collection points and Table 5.1 lists the descriptive statistics of the sample trees and the disks selected for this study.

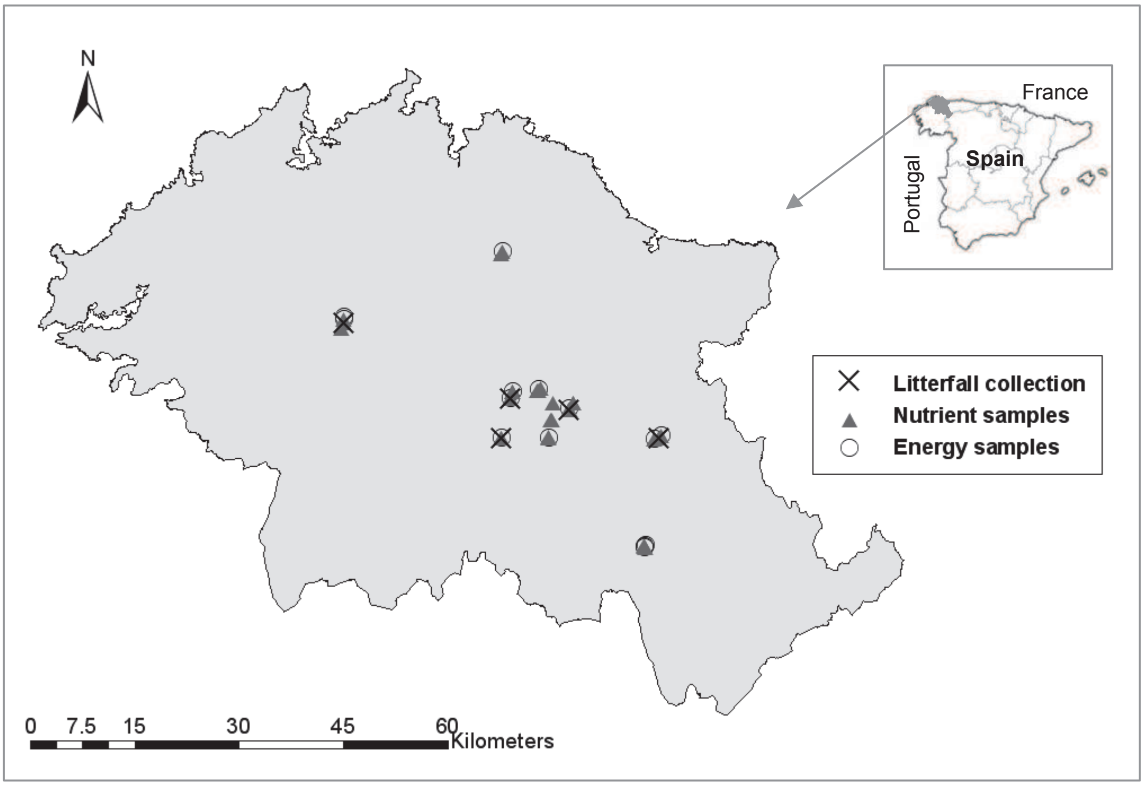


Figure 5.1. Study area and location of sample collection.

Table 5.1. Descriptive statistics for the main variables measured in the sample of biomass trees (120 trees) and stemwood disks (17 trees).

Variables	Min.	Max.	Mean	Std. Dev.
Total height – h (m)	2.61	15.48	6.43	2.33
Diameter at breast height – d (cm)	1.75	14.30	5.77	2.58
Above-ground biomass - W_{AGB}(kg)	0.58	45.87	7.60	7.44
Stemwood volume – V (dm^3)	1.26	137.71	19.76	21.95
Disk diameter at 0.5 m height – $d_{0.5}$(cm)	2.70	15.75	7.22	3.22

Litterfall was collected monthly during 1 year in five sites (Figure 5.1) which covered plantation variability according to stand age (3-7 years by the time the samples were collected), stocking (2300-5600 trees ha^{-1}), site quality and location. Stand age was higher in this case than in the tree biomass sampling (Table 5.1) because litter was collected some considerable time after biomass destructive sampling. Four foliar traps, each with a total area of 1.8 m^2, were distributed within each of the selected stands and the litterfall mass collected then taken to the laboratory and dried to constant weight.

5.2.3. Nutritional evaluation

For the nutrient analysis, the dried biomass samples of the three trees felled per plot were milled and all samples of the same component were mixed to produce a representative sample of the site and the component. Fifty such samples 10 per tree component were analysed, corresponding to different sites qualities, tree ages and stockings to cover the variability existing in the stands.

The percentage of total C and N was determined by high temperature combustion using an automatic analyser, Leco-TruSpec CHN. Although Na is not considered a nutrient, it is an important element in bioenergy because it produces corrosion in boilers and thus Na concentration was considered in this study. Ca, Mg, K and Na were extracted by acid digestion in a microwave using HNO_3 and HCl and determined by atomic absorption (EPA, 1996). The pH of the extract was then adjusted and P was analysed by colorimetry (Olsen and

Sommers, 1982) while Ca, Mg, Na and K were measured by atomic absorption.

Variations in the concentration of the different elements between the tree components analysed (leaves, branches, dead branches, stemwood and bark) were analysed individually for each element using the non-parametric Kruskal-Wallis Test (Breslow, 1970).

The concentrations of nutrients in the foliage are the most frequently sampled and analysed component, and hence those that are more easily comparable between studies (Judd et al., 1996). Typical ranges of foliar nutrients in live leaves obtained from *Eucalyptus* species (Judd et al., 1996) together with reference values for *E. nitens* (Will, 1986) obtained by different laboratories around the world (IUFRO *Inter-laboratory Comparisons*), and reference values for *E. nitens* in the region (Rodríguez da Costa, 2010) were used to evaluate the nutritional status of the plantations (Table 5.2) as well as the soil information from the stands, which is presented in Table 5.3.

Table 5.2. Typical values of nutrients in live leaves for *Eucalyptus* species (Judd et al., 1996), reference values for *E. nitens* obtained by different laboratories around the world (Will, 1986) and in the region (Rodríguez da Costa, 2010).

	Foliar nutrient concentration (g kg^{-1} biomass)				
Range	**N**	**P**	**K**	**Ca**	**Mg**
Typical *Eucalyptus* spp.	10.0-23.0	0.5-1.5	4.0-14.0	5.0-10.0	2.0-4.0
Reference *E. nitens* (world)	15.9-25.4	1.2-1.7	6.3-10.5	4.2-7.0	0.8-1.4
Reference *E. nitens* (region)	15.76±1.53	1.0±0.2	4.2±0.8	4.2±0.8	1.6±0.3

Table 5.3. Soil properties of the stands studied (40 sites).

Variable	**Min.**	**Max.**	**Mean**	**Std. Dev.**
pH (H_2O 1:2.5)	3.90	5.27	4.46	0.29
Electrical conductivity (dS m^{-1})	0.02	0.19	0.06	0.03
Organic matter (%)	7.90	22.27	12.49	3.07
Total N (%)	0.10	0.40	0.22	0.07
C/N ratio	15.79	71.77	35.30	12.66
Available $P^{(a)}$ (mg kg^{-1})	10.20	18.13	14.60	2.10
$Ca_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.04	0.88	0.16	0.15
$Mg_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.06	0.51	0.20	0.09
$Na_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.09	0.45	0.17	0.06
$K_{CEC}^{(b)}$ ($cmol_c$ kg^{-1})	0.12	0.85	0.27	0.13
$Alc_{EC}^{(b)}$ ($cmol_c$ kg^{-1})	1.96	14.82	6.64	2.44
Sum of base cations ($cmol_c$ kg^{-1})	0.45	1.40	0.81	0.25
Effective cation exchange capacity ($cmol_c$ kg^{-1})	2.84	15.60	7.44	2.43
Sand (%)	13.00	71.72	42.31	14.92
Clay (%)	2.70	39.61	11.87	7.49
Silt (%)	17.17	73.10	45.83	14.04

Methods: (a) Method described in Mehlich (1953), (b) Method described in Peech (1947).

Mean nutrient content was estimated for each tree component according to site index (*SI*), which is an indicator of forest site quality, defined as the dominant height (H_0) of the stand at a specific base age. In total, four quality classes have been defined for *E. nitens* woody crop stands in Northwest Spain: 5, 8, 11 and 14 m (class midpoint) at a reference age of 4 years (González-García et al., 2015). The projections of dominant height and basal area in the present study, which were necessary for the biomass estimation at the end of the rotation, were obtained from the dynamic growth model and initialization function fitted in (González-García et al., 2015).

The biomass of each tree component at stand level was estimated using the allometric models previously developed for *E. nitens* woody crops (González-García et al., 2013a) using dominant height and projected basal values. Once the biomass of the different tree components was estimated, these values were multiplied by the mean nutrient concentration (N, P, K, Mg, Ca) of the corresponding tree component to quantify nutritional content of each site quality class at the end of the rotation. Rotation length was obtained from the intersection of Mean Annual Increment (*MAI*) and Current Annual Increment (*CAI*) data and ranged from 6 to 12 years for the highest and the lowest site quality respectively (González-García et al., 2015).

Finally, carbon content at stand level was calculated for all the above-ground biomass components using the same methodology as explained earlier for nutrient content estimation.

5.2.4. Energy evaluation

In this study, only the wood component was analysed in relation to energy potential although information for the other biomass components was also taken into account, using results derived from studies of *E. nitens* forest residues in the north of Spain (Pérez et al., 2006, 2008, 2011).

For energy evaluation the collected and stored stemwood disks (from the height of 0.5 m) were ground separately in a cutting mill with a bottom sieve of 1 mm. Subsequent analyses were carried out using a LECO TGA-701 to determine moisture content and the ash and volatile matter content of the samples. In addition, final analyses to obtain C, H and N levels, were made using a LECO CHN-2000 and with a LECO-S632 to determine sulphur content, while oxygen content was calculated as the difference. All analyses were made in duplicate.

Calorific values were determined using an IKA C4000 calorimeter which provides a direct evaluation of Gross Calorific Value (*GCV*). Net Calorific Value (*NCV*) was calculated from *GCV* values by applying the H content of each sample.

5.3. Results and discussion

5.3.1. Nutritional evaluation

The results of the nutrient analysis for *E. nitens* woody crops are shown in Table 5.4. Leaves showed the highest mean value of N, 14.58 g kg^{-1}, which is significantly higher (p-value < 0.05) than in the other components, while the wood and dead branches components had the lowest, 2.06 and 2.58 g kg^{-1}, respectively. Similar trends were found in the P and K analyses, where mean values were 2.38 g kg^{-1} and 4.95 g kg^{-1} in leaves, for both elements respectively. Theses nutrient concentrations showed significant differences with respect to other tree components. On the contrary, P and K concentrations in dead branches were significantly lower than in the other fractions. Thus, in general terms, the magnitude of concentration of the elements N, P and K was as follows: leaves > bark > branches > wood > dead branches, although the order of the latter two components occasionally changed. In terms of Mg, bark, followed by leaves, showed the highest mean values, the difference between them being significant, and wood the lowest. The concentrations for this element ranged from 0.27 to 1.67 g kg^{-1}. In contrast, Ca values were highest in bark and dead branches.

Similar patterns of nutrient distribution in biomass components have been found in various *Eucalyptus* studies (Balboa, 2005; Brañas et al., 2000; Guo et al., 2002; Judd et al., 1996; Laclau et al., 2000; Misra et al., 1998; Rodríguez da Costa, 2010; Rodríguez-Soalleiro et al., 2004), although the dead branch component was not considered in most cases.

Na concentration ranged from 0.56 to 0.84 g kg^{-1} and did not show significant differences between tree components (Table 5.4). These Na values were higher than those obtained by Rodríguez da Costa (2010) for the same species in the region, except in bark in which concentration was higher in the previous study.

Table 5.4. Content and distribution of elements in the different above-ground tree biomass components (10 samples per component) for tree age from 2 to 5 years. In the mean column, the same letter indicates that there are no significant differences (p-value < 0.05) in the concentration of the element analysed between tree components.

Element	Tree component	Min.	Max.	Mean	Std. error
N ($g\ kg^{-1}$ biomass)	Leaves	5.78	18.37	14.58a	0.11
	Branches	2.86	6.29	4.61c	0.03
	Dead branches	1.81	3.57	2.58d	0.02
	Wood	1.36	3.40	2.06d	0.02
	Bark	3.16	7.62	5.62b	0.04
P ($g\ kg^{-1}$ biomass)	Leaves	0.79	2.87	2.38a	0.19
	Branches	0.58	1.72	1.13b	0.11
	Dead branches	0.12	0.42	0.28d	0.03
	Wood	0.25	1.40	0.76c	0.12
	Bark	0.42	1.62	1.33b	0.12
K ($g\ kg^{-1}$ biomass)	Leaves	3.83	5.74	4.95a	0.17
	Branches	2.00	4.70	3.43c	0.31
	Dead branches	0.51	1.70	0.86d	0.14
	Wood	1.28	4.25	2.72c	0.37
	Bark	2.59	7.06	4.44b	0.36
Ca ($g\ kg^{-1}$ biomass)	Leaves	3.08	7.86	5.28b	0.46
	Branches	2.54	10.38	5.51b	0.72
	Dead branches	7.14	13.64	9.86a	0.60
	Wood	0.20	1.26	0.62c	0.10
	Bark	5.52	16.14	10.92a	1.12
Mg ($g\ kg^{-1}$ biomass)	Leaves	0.98	1.68	1.35b	0.07
	Branches	0.32	1.04	0.69c	0.06
	Dead branches	0.50	1.02	0.74c	0.06
	Wood	0.12	0.60	0.27d	0.05
	Bark	1.08	2.18	1.67a	0.11
Na ($g\ kg^{-1}$ biomass)	Leaves	0.35	1.19	0.68a	0.07
	Branches	0.35	1.43	0.84a	0.10
	Dead branches	0.30	0.80	0.56a	0.05
	Wood	0.36	1.69	0.71a	0.13
	Bark	0.28	1.57	0.66a	0.13

Mean foliar nutrient concentrations were within the typical range for the species in respect of N, K and Ca, albeit that they were below the typical range in some stands. However, a high P concentration was found in leaves, higher than the typical range, and is evidence of the fact that this nutrient was found to be available in the soil in concentrations of 10-20 mg kg^{-1}, where 5 mg P kg^{-1} is considered to be the limiting threshold in agricultural crops. This is likely to be the result of a positive response to fertilization in these stands given that unfertilized soils in the region generally have low levels of P, on the limit or lower than the threshold cited, as well as the added problem of the tendency for P to form complexes with metals in the soil, thereby making it inaccessible to plants (Calvo de Anta, 1992). In contrast, for Mg, none of the stands analysed reached the typical minimum foliar concentration (< 2 g kg^{-1}) which is probably linked to the low availability of this element in the soil. In general the soils analysed in this study had low values of exchangeable Mg and Ca. This is in line with the typical values found for the acidic forest soil of the region (Balboa-Murias et al., 2006; Brañas et al., 2000; Calvo de Anta, 1992), which are lower than the thresholds considered as limiting for agricultural crops, i.e. 0.4 and 1.5 cmol$_c$ kg^{-1} for Mg and Ca respectively (Buol et al., 1975; Calvo de Anta et al., 1992). For K, although the soil concentration had been modified by fertilization following planting, 30 % of the stands had values lower than 0.2 cmol$_c$ kg^{-1}, the threshold below which deficiencies are characterized in crops.

Comparing the findings of the current study with other studies for *E. nitens* in the region (Rodríguez da Costa, 2010), K and Mg concentrations were found to be similar, N was slightly lower, while Ca was slightly higher but all were in a similar range in the two studies. On the contrary, P concentrations were much higher in the current study than in the *E. nitens* stands evaluated by (Rodríguez da Costa, 2010). The stands in the latter were considerably older (9-13 years) and had much lower stocking densities (400-1400 trees ha^{-1}) than the plantations studied here (2 to 5 years at stockings of 2300-5600 trees ha^{-1}). It may well be that the young age of the stands, as well as the high rate of fertilization applied as a result of the high stocking (55 to 202 kg P ha^{-1}) may have had an effect on the results obtained in this study.

Finally, according to the reference values for *E. nitens* from several laboratories around the world, foliar levels of N and K were below the normal range, while Ca and Mg were both within it, and P was above the reference values (Will, 1986).

Nutrient removal estimations are represented in Figure 5.2. Estimations of nutrient content for the stemwood fraction at stand level were: 20-60 kg P ha^{-1}, 70-215 kg K ha^{-1} and 7-21 kg Mg ha^{-1}, depending on site quality. Furthermore, leaves had the highest N (90-193 kg ha^{-1}) while Mg levels were similar in wood (7-21 kg ha^{-1}) and in leaves (8-18 kg ha^{-1}). Finally, the bark component presented the highest value for Ca, 32-94 kg ha^{-1}, followed by branches, 27-85 kg ha^{-1}. Table 5.5 presents the total nutrient content, both for the plantation cycle and annually (depending on rotation length) for the lowest and the highest site quality.

Table 5.5. Nutrient extraction in above-ground biomass at stand level (from low to high site quality) for complete rotation and annually.

	N (kg ha^{-1})	**P (kg ha^{-1})**	**K (kg ha^{-1})**	**Ca (kg ha^{-1})**	**Mg (kg ha^{-1})**
Rotation	243-706	44-122	131-375	121-329	25-67
Annual	21-118	4-20	11-62	11-55	2-11

These estimations show that nutrient content varies greatly according to site quality and the specific nutrient involved. However, an approximately 3-fold differences between nutrient content in low and high quality stands was found across all nutrients when the rotation was considered, compared to a 5-fold difference when considering nutrient content on an annual basis.

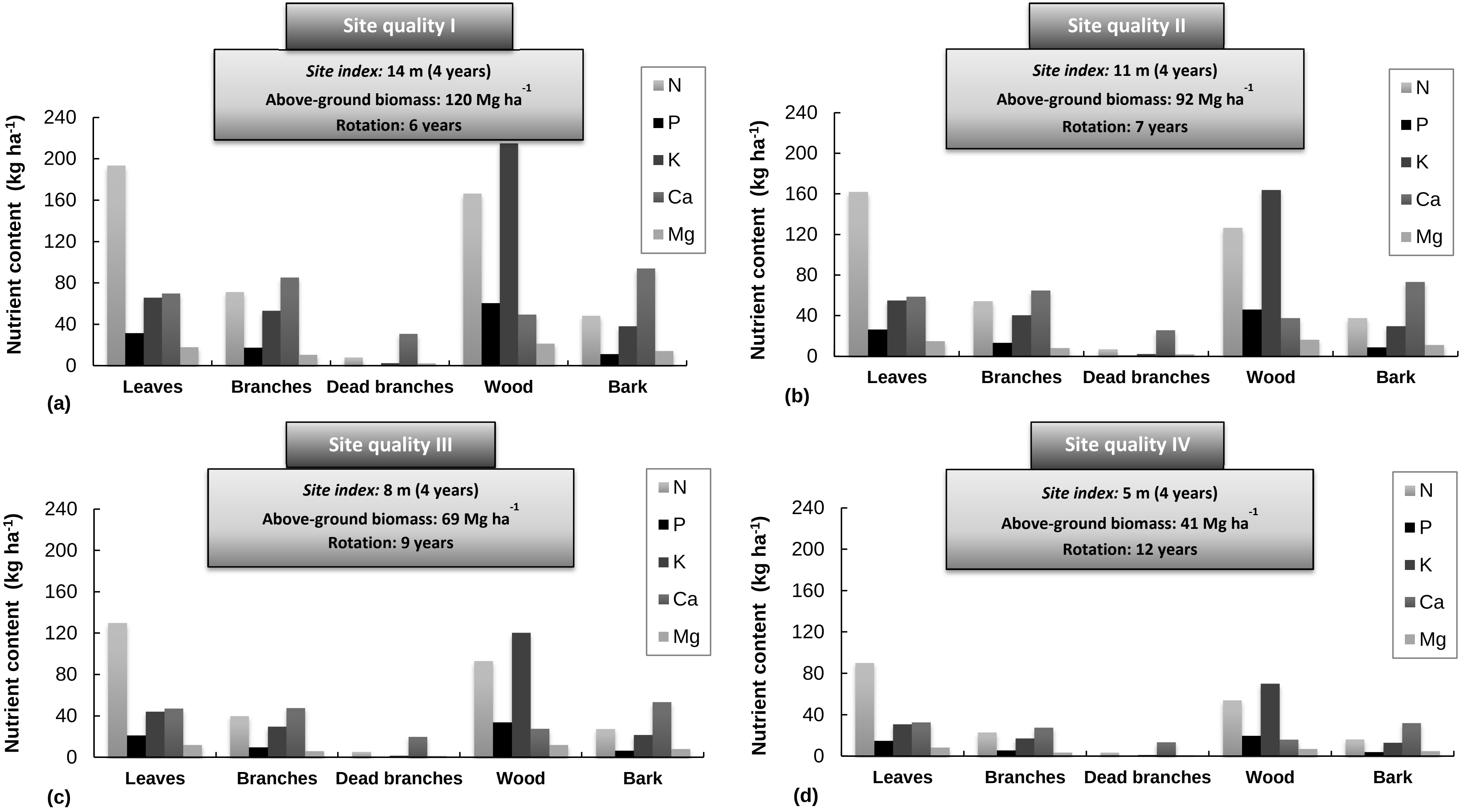
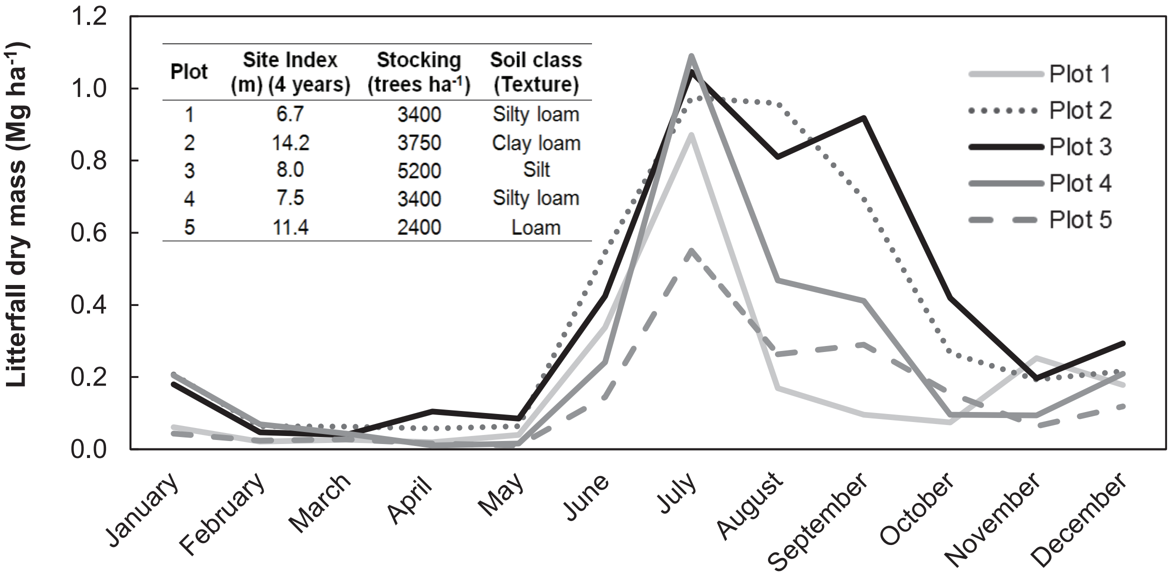


Figure 5.2. Nutrients quantification in above-ground biomass tree components according to site quality (site index (a) 14 m, (b) 11 m, (c) 8 m and (d) 5 m at base age of 4 years) at the end of the rotation projected using the growth models and biomass equations developed for *E. nitens* woody crops (González-García et al. 2013a; 2015).

Despite the results provided here being reference values obtained from stands of differing site quality, forest managers should use concentrations of different nutrient elements to estimate specific nutrient extraction by multiplying them by the actual biomass production of the plantation in question and using this as the input with which to calculate the nutrient cycle, together with other system inputs (atmospheric deposition, bedrock degradation, atmospheric fixation, above and belowground litter turnover etc.) and outputs (volatilization, lixiviation, etc) in order to determine the re-fertilization needs of the stand.

Litterfall rates showed in Figure 5.3 exhibited the same trend in annual variation. They peaked in the dry season and at the onset of the rainy season, as has been found in other studies (Cizungu et al., 2014). Monthly litterfall was highly variable, ranging from 0.01 to 1.09 Mg ha^{-1}, and the annual mean was between 1.71 and 4.56 Mg ha^{-1} (depending on stand), lower than in other studies of 3- to 7-year-old *E. nitens* plantations in Chile (4-9 Mg ha^{-1} y^{-1}) (Aparicio, 2001; Bonomelli and Suárez, 1999; Geldres et al., 2006).

Figure 5.3. Monthly litterfall variation in the different stands.



Plot	Site Index (m) (4 years)	Stocking (trees ha^{-1})	Soil class (Texture)
1	6.7	3400	Silty loam
2	14.2	3750	Clay loam
3	8.0	5200	Silt
4	7.5	3400	Silty loam
5	11.4	2400	Loam

Options other than chemical fertilizers can be applied to avoid compromising soil fertility, and consequently productivity, in bioenergy plantations. Fertilization with ash, the solid residue produced after biomass combustion, which is rich in inorganic elements previously taken up from the soil during tree growth is one possible way to close the nutrient cycle. Another alternative is sewage sludge, which provides essential nutrients for plant growth, and organic matter which improves soil structure and water storage (Brown et al., 2011). However, the use of ashes or sewage needs to be calculated according to the specific characteristics of a plantation to obtain efficient nutrient consumption and to avoid problems focused on soil or groundwater contamination, especially when these products contain compounds such as heavy metals (Guo et al., 2002).

5.3.2. Carbon estimation

The results of the carbon (C) analysis showed, as expected, a fairly constant content in the above-ground components, the average being 47.09 %. Leaves had the highest values at 50.20 % while bark had the lowest, 44.70 %, both exhibiting significant differences with respect to the other components, and the major tree component, wood, contained 46.67 % (Table 5.6). These values thus provide a more accurate carbon transformation value for *E. nitens* woody crops, of great use since carbon content is easily overestimated if the typical transformation value, 50 %, is used by default, as is the case in some studies of other species (Lamlom and Savidge, 2003; Zhang et al., 2009; Zhao et al., 2014).

Other studies for *E. nitens* in Northwest Spain have obtained higher mean values of C, for example Rodríguez da Costa (2010) found levels of 57.23 % for all tree components, 50.12 % for wood, and Pérez et al. (2006) obtained results of 53.12 % for wood and 50.99 % for the other components. For *E. globulus* in the same region (Brañas et al., 2000) a higher value for leaves (53.1 %) but similar values for wood (46.5 %), bark (43.1 %) and branches (46.5 %) have been found.

Table 5.6. Distribution and content of carbon in the different above-ground tree biomass components (10 samples per component). In the mean column, the same letter indicates that there are no significant differences (p-value < 0.05) in the concentration of the element analysed between tree components.

	Carbon content (%)			
Component	**Min.**	**Max.**	**Mean**	**Std. error**
Leaves	49.18	50.83	50.20a	0.20
Branches	45.72	47.94	46.61b	0.22
Dead branches	46.12	49.04	47.22b	0.32
Wood	45.61	48.08	46.69b	0.28
Bark	43.48	46.55	44.70c	0.28

Carbon sequestration in biomass was estimated at stand level according to site quality (Figure 5.4). The wood component had the highest carbon content (12-37 Mg ha^{-1}), due to it comprising the largest portion of the biomass, followed by leaves and branches. Total carbon capture was 19-56 Mg ha^{-1} at the end of the rotation and 2-9 Mg ha^{-1} y^{-1} when rotation length was taken into account. Other studies (Pérez-Cruzado et al., 2011; Pérez et al., 2006) obtained estimations of 12.7 and 17.0 Mg C ha^{-1} y^{-1} for *E. nitens* stands with stockings of 1300 and 2400 stems ha^{-1} respectively, taking into account litter and above-ground biomass in longer rotations.

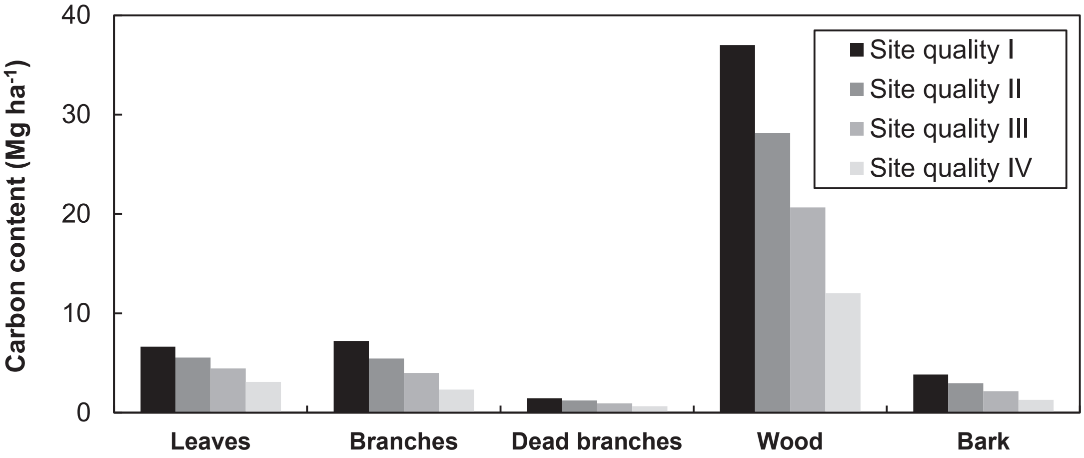


Figure 5.4. Carbon content in bioenergy stand by site quality at the end of the rotation.

5.3.3. Energy evaluation

Table 5.7 shows the results of the energy evaluation for the wood component and the reference rates for the other biomass tree components according to (Pérez et al., 2006, 2008, 2011). Stemwood showed constant results for calorific values, with an average of 19.54 and 18.32 MJ kg^{-1} for *GCV* and *NCV* respectively. This low variability in the heating value of wood is due to the great uniformity in its composition, although this is not the case for other components, such as bark and leaves, which are more heterogeneous (Senelwa and Sims, 1999). The heating values found in the current work are similar to those obtained in other *Eucalyptus* studies for wood (18.8-19.5 MJ kg^{-1}) (Dalianis et al., 1996; Frederick et al., 1985) and higher than for poplar and willow short rotation woody crops, where *GCV* has been found to be 17.3 and 18.7 MJ kg^{-1} respectively (McKendry, 2002).

In a study analysing the residual biomass of several species, in addition to being the most easily available, *Eucalyptus* had the highest values (*GCV*: 18.4 MJ kg^{-1}; *NCV*: 17.1 MJ kg^{-1}) with leaves and bark showing the highest and the lowest *GCV* respectively (Pérez et al., 2008). Leaves of *E. nitens* were also found to have the highest heating value, an average *GCV* of 22.6 MJ kg^{-1}, in another study (Senelwa and Sims, 1999).

The results of element analysis (Table 5.7) showed there to be little variation in composition between samples, thereby corroborating the low variability in heating value (Kumar et al., 2010). The fact that the percentage of N (< 0.5 %) and S (< 0.04 %) found in the species is low in comparison with fossil fuels (McKendry, 2002) is obviously of environmental importance.

Table 5.7. Results of elemental and proximate analyses, and determination of calorific value (17 samples).

Component	Variable	Min.	Max.	Mean	Std. Dev.
Wood	C (%)	48.57	49.75	49.15	0.38
	H (%)	5.70	6.13	5.93	0.09
	N (%)	0.35	0.50	0.44	0.04
	S (%)	0.01	0.04	0.02	0.01
	O (%)	43.28	44.88	44.20	0.44
	Ash (%)	0.48	1.13	0.76	0.19
	VM (%)	79.14	80.80	80.07	0.51
	*FC** (%)	18.51	19.79	19.18	0.42
	GCV (MJ kg^{-1})	19.22	19.86	19.54	0.18
	NCV (MJ kg^{-1})	18.00	18.68	18.32	0.19
Leaves[(a)]	*GCV* (MJ kg^{-1})	10.48	22.55	----	----
Branches[(a)]	*GCV* (MJ kg^{-1})	8.92	18.64	----	----
Bark[(a)]	*GCV* (MJ kg^{-1})	7.00	19.94	----	----

(*VM*: Volatile Matter, *FC*: Fixed Carbon, *GCV*: Gross Calorific Value, *NCV*: Net Calorific Value).
[(a)] Average data derived from (Pérez et al., 2006, 2008, 2011) with 0-50 % moisture content, including adults and young trees.
* Determined by difference.

In the combustion process, first Volatile Matter (*VM*) is burnt off as gas leaving behind the Fixed Carbon (*FC*) as char, which later burns in the solid state. The low value of fixed carbon content found in this work is attributable to the high *VM*, and illustrates that the bulk of the woodfuel material was consumed in the gaseous state during combustion (Senelwa and Sims, 1999). *VM* and *FC* values were 79.14-80.80 % and 18.51-19.79 % respectively, lower than those obtained for this species in 3 year rotations, where the values were 91.9 % and 6.9 % for *VM* and *FC* respectively (Senelwa and Sims, 1999).

Ash content in this study ranged from 0.5 to 1.1 % for the stem wood component (average 0.76 %), values in line with the those established for woody species (Kumar et al., 2010; Senelwa and Sims, 1999; Villanueva et al., 2011), which are considerably lower than for herbaceous species (Jenkins et al., 1998; McKendry, 2002). The average percentage of ash is lower in *E. nitens* than in other *Eucalyptus* species such as *E. globulus* (Pérez et al., 2006, 2011; Senelwa and Sims, 1999) resulting in two advantages: a lower quantity of nutrients needs to be provided to the soil, and less maintenance is required in boilers.

5.4. Conclusions

This study presents a nutritional, carbon and energy analysis of *E. nitens* bioenergy plantations in order to promote sustainable forest management.

Leaves and bark were the components with the highest nutrient concentration, except in the case of Ca, where bark and dead branches were the principal components. The nutritional state of the stands showed high levels of P, which can be associated with soil fertilization, and a clear Mg deficiency. Stemwood was the main tree component at the end of the rotation and the fraction with the highest content of P, K, Mg and Na, while N and Ca were stored mainly in leaves and bark respectively.

All the tree components were fairly consistent with respect to C content. Leaves had the highest C concentration although wood, as in the nutrient analysis, had the largest quantity. Mean C content in above-ground biomass was 2-9 Mg C ha^{-1} y^{-1}, depending on forest productivity. Stemwood showed consistent *NCV* (18.32 MJ kg^{-1}) with low ash content.

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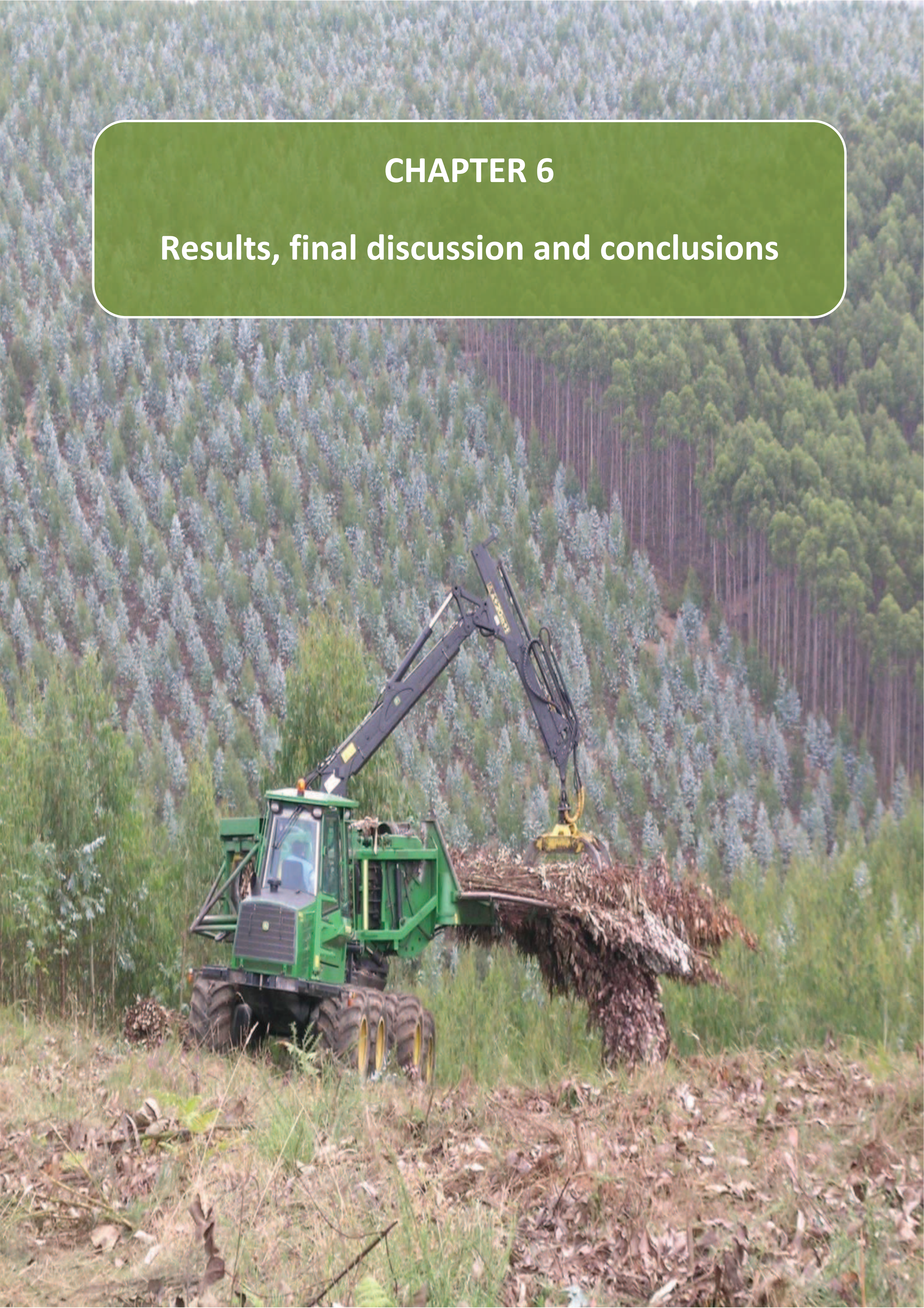
CHAPTER 6

Results, final discussion and conclusions



CHAPTER 6. Results, final discussion and conclusions

6.1. Results and general discussion

Woody biomass is one of the largest potential sources of renewable energy in the EU and can contribute to achieving political and environmental objectives in total energy consumption in addition to producing other economic and social advantages. With this type of biomass, *SRWC,* and specifically the species *E. nitens,* which has great potential in the Northwest of Spain (Pérez-Cruzado et al., 2011; Pérez-Cruzado and Rodríguez-Soalleiro, 2011), can be used to promote the benefits of this type of energy in this area.

The development of support tools, as well as further information in relation to decision making in *E. nitens* energy crop production is therefore essential for the sustainable and viable management of stands.

The results of **Chapter 2**, which focused on production estimation tools, showed that the biomass equation is the most accurate method for estimating the stem fraction, although any of the methodologies studied can be applied with good predictions. For the crown component, the *BEF* model and the biomass equation provided the best predictions, while the biomass equation was the best prediction tool for above-ground biomass. In both cases constant *BEF* underestimated production, as has been shown in other young stands (Brown and Schroeder, 1999; Fang et al., 1998) and hence it is not recommended when other methods can be used because serious errors may arise (Guo et al., 2010; Tobin and Nieuwenhuis, 2007).

The best predictor variables for the biomass equations at tree level were diameter followed by live crown height, for the crown, and diameter followed by total height, for stem component as has also been determined in other studies (Sochacki et al., 2007; Zewdie et al., 2009). At stand level, basal area and dominant height provided the greatest accuracy. For the *BEF* evaluation, total height was the variable most closely associated with tree *BEF* for both crown and whole tree, as found in previous studies (Sanquetta et al., 2011), followed by diameter and age. In contrast, stem *BEF* was quite constant and equivalent to the basic density of wood. At stand level dominant height, mean quadratic diameter, basal area and age had the strongest relationship with *BEF*, whose value tends to stabilize with stand growth (Sanquetta et al., 2011; Soares and Tomé, 2012).

Selection of the estimation tool for predicting tree or stand production (simplified or accurate biomass equations, constant *BEF*, *BEF* model or volume) in *E. nitens* woody crop plantations can be made depending on the variables available and the accuracy level required.

For the dynamic growth model (**Chapter 3**), polymorphic ADA models with a constant single asymptote were those which provided the best predictions for the dominant height and basal area projection functions. This model has also been used to fit growth models for other forest species in Spain such as poplars (Barrio-Anta et al., 2008). In this Thesis, the site index was defined for dominant heights of 5, 8, 11 and 14 m at the reference age of 4 years based on site quality and the projected optimal rotation length found to be between 6 and 12 years, depending on site quality. The estimations of above-ground biomass mean increment were from 3 Mg ha^{-1} y^{-1} to 18 Mg ha^{-1} y^{-1} at the end of this rotation using the biomass models developed in **Chapter 2**. These ranges of production are very similar to those obtained by Pérez-Cruzado et al. (2013) for a dominant height GADA model with lower stockings (< 1500 trees ha^{-1}) for the same species in the area.

In recent years, environmental factors have become a key factor in forest growth models (Bravo-Oviedo et al., 2011; Nunes et al., 2011). The dynamic growth model fitted here (**Chapter 3**) evaluated the inclusion of environmental factors as expanded models, which demonstrated a similar level of accuracy in prediction as for the simple model. Indeed, it has been shown that their inclusion produces more robust and flexible functions which take into account small variations in environmental conditions (Nunes et al., 2011). The environmental variables selected for the growth model here were the edaphic variables, organic matter content and sand content, and the climate variables related to temperature and summer precipitation. In contrast to in other studies with high environmental variability (Pérez-Cruzado et al., 2014), a linear structure for the expanding model parameters was selected to incorporate variables in the model.

Dominant height and stand age were the predictive variables selected for the basal area initialization function (**Chapter 3**). This function explained 50 % more of the data variability than did the base equation of the growth model selected for the basal area projection function. The accuracy and robustness of the basal area initialization function increased when site variables were included. The environmental variables selected almost perfectly match those cited for the growth model.

In **Chapter 4**, the high level of agreement between the observed and the 3-PG model predicted values of production variables suggests that the parameterisation of the model is appropriate. Although the model is able to estimate growth across a wide range of sites, the best predictions were for sites of average productivity, and this may be attributable to the limited number of times data was collected and uncertainties about soil depth and soil water content (Landsberg and Sands, 2010).

Plantations with stocking of 3000 trees ha^{-1} produced similar mean increment in biomass to those with higher stocking (**Chapter 4**), achieved through a 20 % increase in mean stemwood diameter, in addition to lower associated production costs. These results therefore suggest that lower planting densities, which are in the same range as for other *Eucalyptus* studies (González et al., 2011; Sims et al., 1999) are more appropriate in these plantations. Additionally, the ideal rotation for the characteristics defined for a typical site is between 6 and 8 years because, although the maximum mean increment is achieved around age 8 years, production is in fact practically the same as at 6 years and therefore the lower rotation is recommended as it minimises time to harvesting (**Chapter 4**). These rotation lengths, which can be related to medium-high site qualities are in accordance with the results for the dynamic growth model (**Chapter 3**), where optimal rotations were 6, 7 and 9 years for site qualities I, II and III respectively.

Potential productivity was affected by water availability in the summer months, mainly related to rainfall and, to a lesser extent, maximum and minimum temperature and *VPD*, although this reduction in water availability is not comparable with the periods of drought which occur in Mediterranean areas, where stand survival may be affected. This effect was also found in the empirical growth model when climatic variables were included (**Chapter 3**), and emphasizes the importance of water deficit for stand development as shown previously for this species in other countries such as Chile or Australia (Rodríguez et al., 2009; White et al., 1996). At the same time, the results obtained in **Chapter 4** showed that above-ground biomass production is overestimated by around 12 % when average rather than actual climate data are used. This fact, which has also been demonstrated in other studies of the 3-PG model (Almeida et al., 2010), highlights the importance of using actual climate data, when available, to avoid errors in predictions.

The growth models developed in this Thesis (**Chapters 3** and **4**) obtained suitable ranges of accuracy and both are appropriate for decision making. Despite the fact that the process model can be considered a more realistic tool because it takes into account physiological processes of trees growth, it requires a large amount of specific data for its use. Therefore the decision whether to use this model (**Chapter 4**) or the dynamic growth model (**Chapter 3**) depends on the information available for the plantation, the output required and the accuracy desired.

Energy crops have an environmental impact in terms of soil nutrition since biomass extraction may affect land use potential for the future. The nutritional evaluation obtained in **Chapter 5** showed that leaves and bark are the components with the highest nutrient concentration (N, P, K, Mg), except in the case of Ca, where bark and branches are the principal components. These distribution patterns are in accord with other *Eucalyptu*s studies in the region (Balboa, 2005; Brañas et al., 2000; Rodríguez da Costa, 2010; Rodríguez-Soalleiro et al., 2004). The plantations studied were in the typical range for the species of N, K and Ca, although some stands were below this range. P concentrations were higher than the typical rate and other studies for the same species in this area (Rodríguez da Costa, 2010) which can be explained by the soil fertilization of the plantations at the time of planting. A clear Mg deficiency and low values of exchangeable Ca, associated with the low availability of these elements in the soils of the region (Balboa, 2005; Calvo de Anta, 1992) are evident.

Stemwood, the main tree component at the end of the rotation is the main tree for P, K, Mg and Na, while N and Ca were stored mainly in leaves and bark respectively (**Chapter 5**). The nutrients extracted in above-ground biomass harvesting were estimated, according to site production (**Chapter 3**), as 243-706 kg N, 44-122 kg P, 131-375 kg K, 121-329 kg Ca, 25-67 kg Mg and 29-86 kg Na per ha (**Chapter 5**). The nutrients extracted should be specifically estimated according to current biomass production and the nutrient cycle to be replaced taken into account in order to maintain soil productivity for subsequent rotations.

The estimation of the carbon stock in biomass and soil in plantations is important from the point of view of global climate change (Ruiz-Peinado et al., 2012). The results of carbon analysis specified in **Chapter 5** show a constant concentration in all above-ground tree components. Although leaves had the highest C concentration, wood was the largest content. Mean C content in above-ground biomass was 2-9 Mg C $ha^{-1}y^{-1}$ depending on forest productivity. These results were lower than those obtained for older stands of the species in the region (Pérez et al., 2006; Rodríguez da Costa, 2010).

The study of energy properties is very important in the use of woody crops as biofuels in order to estimate the energy potential that can be generated. *E. nitens* energy stands had a constant calorific value for stemwood with a mean *NCV* of 18.32 MJ kg^{-1} (**Chapter 5**), higher than other *SRWC* species such as poplar or willows (McKendry, 2002) and with a mean ash content < 1 %, which is lower than in herbaceous crops and other species such as *E. globulus* (Jenkins et al., 1998; Pérez et al., 2011, Senelwa and Sims, 1999).

The results obtained in this Thesis provide valuable information for regional industries and forest managers and will therefore contribute to promoting investment in the bioenergy sector. This could in turn contribute considerably to satisfying future energy demand in the region, reduce dependency on fossil fuels, create employment and provide an alternative use for abandoned or marginal land in the area.

6.2. Conclusions

- ✓ The **methods for the estimation of biomass and volume** for *E. nitens* bioenergy plantations developed in this Thesis allow the simple prediction of production at any time in the rotation using tree or stand variables. Biomass equations are the most accurate method for the stem fraction, although any of the studied methodologies can be applied with good predictions. However, the use of constant *BEFs* for the crown and above-ground components is not recommended because they underestimate production, and hence other methodologies such as *BEF* models or biomass equations should be applied.
- ✓ The **dynamic stand growth model** presented here is a useful tool for management and planning of *E. nitens* plantations. This model is formed of two types of functions: transition functions for projections of basal area and

dominant height (essential for site quality evaluation using site index) and output functions for volume and above-ground biomass estimation.

- ✓ The inclusion of **environmental variables** in the dynamic growth model results in similar accuracy to using the model without them, in addition to it producing more robust and flexible functions which are able to take into account small variations in environmental conditions within the range studied.
- ✓ The **process-based model** fitted in this Thesis proves the importance of climate factors in plantation growth, especially precipitation during summer. Additionally this model applied at spatial level using GIS methodologies shows differences in forest production according to climate variability in the distribution area of *E. nitens* bioenergy plantations. The use of average rather than actual climate is not recommended because, if not, production is overestimated.
- ✓ The **nutritional evaluation** and the quantification of biomass components show the nutritional impact that is produced by above-ground biomass extraction at the end of the rotation according to site quality. In addition to the nutritional evaluation, the carbon content and the calorific value together with other energy variables provided in this Thesis are essential information for the sustainable and profitable management of the bioenergy plantations.

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ANNEXES

ANNEX I. Publications

Impact Factor report of the publications included in the Thesis (JCR 2013)

Article 1 (Chapter 2)

Title: Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain

Authors: Marta González-García, Andrea Hevia, Juan Majada, Marcos Barrio-Anta

Reference: (2013) Biomass and Bioenergy 54, 147-157

DOI: 10.1016/j.biombioe.2013.03.019

Category	Impact Factor	Rank	Quartile
AGRICULTURAL ENGINEERING	3.411	2/12	Q1
BIOTECHNOLOGY & APPLIED		41/165	Q1
ENERGY & FUELS		20/83	Q1

Article 2 (Chapter 3)

Title: Dynamic growth and yield model including environmental factors for *Eucalyptus nitens* (Deane & Maiden) Maiden Short rotation woody crops in Northwest Spain

Authors: Marta González-García, Andrea Hevia, Juan Majada, Rosa Calvo de Anta, Marcos Barrio-Anta

Reference: (2015) New Forest **DOI:** 10.1007/s11056-015-9467-7

Category	Impact Factor	Rank	Quartile
FORESTRY	1.783	15/64	Q1

Article 3 (Chapter 4)

Title: Application of a process-based model for predicting the productivity of *Eucalyptus nitens* bioenergy plantations in Spain

Authors: Marta González-García, Auro Almeida, Andrea Hevia, Juan Majada, Chris Beadle

Reference: (2015) Global Change Biology Bioenergy **Status:** Accepted

Category	Impact Factor	Rank	Quartile
AGRONOMY	4.284	2/79	Q1
ENERGY & FUELS		12/83	Q1

Article 4 (Chapter 5)

Title: Impact of site on nutritional and carbon content, and energy evaluation of *Eucalyptus nitens* short rotation bioenergy plantations in Northwest Spain

Authors: Marta González-García, Andrea Hevia, Juan Majada, Fernando Rubiera, Marcos Barrio

Reference: iForest – Biogeosience and Forestry – **Status:** Under review

Category	Impact Factor	Rank	Quartile
FORESTRY	1.150	29/64	Q2

BIOMASS AND BIOENERGY 54 (2013) 147–157

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Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain

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ABSTRACT

Above-ground allometric biomass and BEF equations were developed in *Eucalyptus nitens* crops, in age sequence from 2 to 5 years and tree density between 2300 and 5600 ha^{-1}. All models were fitted for crown, stem and total above-ground biomass at tree and stand level and explained a high percentage of data variability ($R^2_{adj} > 0.90$). Biomass Expansion Factors (BEFs) were calculated for all categories and showed great variation, mainly for crown and total biomass. BEFs and stand-tree variable behaviour was analysed to develop BEF models to improve the predictions of constant BEF calculated here. Although all studied variables had significant relationships with BEF, dominant height showed the closest correlation with the crown and total biomass, the equations explaining 99% of biomass variability. Quadratic mean diameter, basal area and age were selected for the stem model. They explained more than 87% of the stem biomass variability. The comparison of the three approaches, biomass and BEF equations and constant BEFs, showed that biomass equations provided the most accurate predictions for stem and total components, followed by BEF equations. Constant BEFs proved the least accurate method for estimating biomass and only provided satisfactory results in relation to stem biomass. In contrast, for the crown component, BEF equations provided slightly more accuracy predictions than biomass equations. The best methodology for biomass production estimation depends on available resources and the level of required accuracy; however, our results suggest that constant BEF should be avoided whenever possible, at least for crown and total aerial biomass.

1. Introduction

Short Rotation Forestry (SRF) refers to fast growing tree species with special characteristics which enable high biomass yields to be produced in a short period of time. Generally this biomass is used to obtain heat and electricity in combustion or second generation biofuels like bioethanol [1].

SRF may go some way to meeting energy demands currently met by fossil fuels in addition to contributing to the mitigation of climate change due to the great potential of

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young or middle-aged stands to sequester carbon and avoid fossil fuel emissions through bioenergy use, especially if they can be intensively managed [2].

Eucalyptus species are commonly used nowadays as woody crops because of their fast growth and high productivity. Furthermore, they adapt well to various sites and their management is simple compared with other common forest species. Consequently, *Eucalyptus* spp. is one of the most important commercial species in Spain and its principal use is in pulpwood production. In Galicia, the region of the country with the highest surface area covered by these species, *Eucalyptus* stands comprise 18% of the total forests cover [3].

Eucalyptus nitens (Deane & Maiden) Maiden began to be used in reforestation in Spain in the nineties, expanding into northern inland areas where the most widespread *Eucalyptus* species (*Eucalyptus globulus* Labill) was not able to survive due to the low temperatures [4]. In addition to frost resistance [5,6], *E. nitens* has great potential as an energy crop due to its fast development, high yields and resistance to pests and diseases. A regional study in the north of Spain showed a greater energy potential in the various tree components of *E. nitens* compared to *E. globulus* when forest waste was used for biomass production [7]. This is very interesting due to *E. nitens* wood value is lower than *E. globulus* due to the higher specific consumption for pulp production so it is a promising species for energy use and market price stability. Hence the establishment of this species in Northwest Spain as short rotation plantations for energy production.

Biomass estimation methods are very important for quantifying the energy potential or carbon stock in forests in order to meet the Kyoto Protocol objectives as well as for other environmental and nutritional stability studies. The most important tools for this are biomass equations and biomass expansion factors (BEFs). Biomass equations are mathematical relations which transform tree or stand variables (e.g. diameter at breast height, total height, basal area, dominant height etc.) into biomass estimates. BEFs on the other hand, are multipliers that enable the expansion of the growing stock (i.e., the stem volume of living trees) to be calculated, for total or component biomass, at tree or stand level [8–10].

Most of the available BEFs are constant and only volume data is required for biomass calculation. However, these constant BEF values for each species are average values which, it is widely acknowledged, are sometimes inaccurate because they depend on the age and density of the stand and site quality [8,11–14], something which is even more marked in young stands because they change so rapidly over time [13,15]. To reduce the inaccuracy of constant BEF values, BEF equations have been developed recently in specific studies, including stand variables as predictors [16–19]. In Spain, Ref. [20] developed different biomass and BEF equations for the major commercial species in the Northwest of the country. With regard to *E. nitens*, a recent study to quantify biomass using equations was carried out by [21] in traditional pulp production plantations with densities between 500 and 1600 trees ha^{-1}. However for short rotation (2–5 years) and high density (2300–5600 trees ha^{-1}) plantations there are no estimation tools available at the moment. Such methods would be of great value for forest management decisions in addition to quantifying biomass and carbon stock. Therefore, the objective of this work is to develop biomass prediction tools at tree and stand level (equations and constant BEFs) for *E. nitens* short rotation plantations in Northwest Spain and to carry out a comparison of the accuracy of each approach.

2. Material and methods

2.1. Material

2.1.1. Study area

The study was carried out in Galicia, in the northwest of Spain. The area has a temperate Atlantic climate with mean temperatures of the warmest and the coldest month of 19 and −5 °C respectively, and an annual precipitation of 1000–1500 mm, distributed throughout the year with the lowest monthly rainfall during summer. The inland areas generally have periods of frost (up to 50 days per year in total) from December to February. According to authors in Ref. [22] the soils in this region are Rankers and Humic Cambisols. The coordinates of the plots were 43° 10′ 27″–43° 32′ 56″N and 7° 48′ 39″–7° 14′ 10″W.

2.1.2. Characteristics of the stands and data collection

Forty square experimental plots of 400 m^2 size were identified and selected in the study area. They were subjectively chosen to represent the existing range of ages, stand densities and site conditions. The tree stocking density ranged from 2300–5500 ha^{-1} in either single or double row and plantation age from 2 to 5 years. Due to the young stage of the plantations, less than 5 years, and the importance of planting time for the initial growth of the tree in the first year, the exact stands age was calculated. For this purpose, the difference between the plantation and the measurement date in addition to the length of vegetative growth period were taken into account. The altitude ranged between 450 and 700 m above sea level. Soils were acid (pH (H_2O) < 5) with a high content of organic matter and an effective average depth of 0.43 m. The average slope of the plots was 13%. Most of the stands were flat, an important characteristic which facilitates mechanization activities in this type of plantation [23]. The following silvicultural treatments were carried out in the stands; fertilization in the first stage and chemical and mechanical weed control when needed to avoid competition problems.

Two inventories were carried out in all the plots in the winter of two consecutive years, the second being just prior to the destructive biomass sampling. Table 1 presents the descriptive statistics of the main tree and stand variables of the plots used in this study.

Diameter at breast height, dbh (d), total height (h) and height of the live crown (h_v) were measured in all trees within the plots using callipers and digital hypsometer, respectively. The information about diameter and height distribution was used to select the tree sample for developing biomass and volume models. At the end of the study, a total of 120 trees covering, as far as possible, the variation in tree height for a given diameter, were selected for destructive sampling. All selected trees were taken from the middle of the plantations to avoid the edge effect on the tree variables [24]. Fig. 1 shows the relationship between height and diameter of the selected trees.

Table 1 – Summary statistics of the main plots variables of the two inventories.

Variable	Inventory	Minimum	Maximum	Mean	Std. Dev.
Age (years)	1	1.56	3.56	2.35	0.74
	2	2.56	4.56	3.35	0.74
N° of trees per hectare	1	2375.00	5600.00	3664.38	833.52
	2	2375.00	5550.00	3641.19	826.17
Basal area (m^2 ha^{-1})	1	0.46	14.28	4.18	3.56
	2	1.97	19.30	9.38	4.67
Dominant height (m)	1	2.39	9.75	5.07	1.87
	2	4.28	13.35	7.71	2.07
Total height (m)	1	0.46	10.40	3.78	1.79
	2	1.00	14.16	6.00	2.03
Diameter at breast height (cm)	1	0.15	10.27	3.42	1.86
	2	0.30	13.30	5.35	2.12

The classic destructive sampling methodologies used for conventional forestry (i.e. for timber purposes) is not appropriate for short woody crops [24,25] due to the small tree sizes because young age of the trees and the high density planting used to produce biomass as quickly as possible. In addition, *Eucalyptus* bioenergy plantations employ a whole tree harvester and all tree biomass is used to produce energy hence the calculation of the biomass of individual tree components (i.e. leaves, thick branches, thin branches, dead branches, bark, wood, etc.) is not a priority for the user. Therefore, in this study, as well as total tree biomass, only crown and stem components were considered to estimate above-ground biomass, which is more appropriate and useful.

After each tree was felled, diameters at breast height, total height, and height of the live crown were measured using callipers and measuring tape, to the nearest 0.1 cm and 1 cm respectively. Above-ground tree biomass was separated into crown biomass and stem (barked logs with a thin-end diameter of 2 cm). The fresh weight of the crown was measured to the nearest 50 g and representative subsamples were selected and weighed in the field. The crown subsamples were an estimation of the proportion of sample fresh weight, approximately 25%, over the total fraction fresh weigh. The stem was divided into logs of 0.5 m long and subsequently weighed to the nearest 100 g. Three wood disks were cut from each stem at regular intervals. These disks together with the crown subsamples were weighed fresh in the field and taken to the laboratory to oven-dry at 65 °C to a constant weight. Based on the ratio of dry biomass to fresh biomass, the biomass of each component was calculated and then summed to obtain the aboveground biomass of each tree. Table 2 lists the descriptive statistics of the sampled trees.

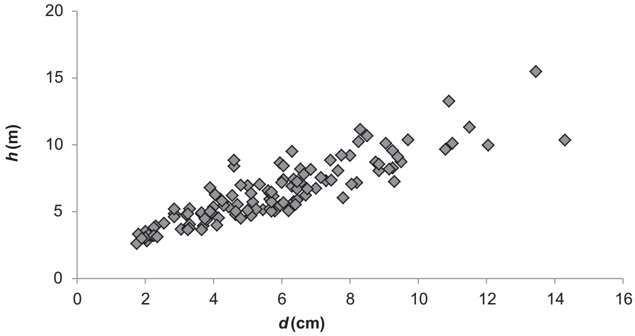

Fig. 1 – Scatter plot of the total tree height (*h*) against diameter at breast height (*d*) for the sample of trees destructively sampled.

2.2. *Methods*

2.2.1. *Above-ground biomass models and fit.*

Allometric equations are widely used for forest biomass assessment [22,26–28] and relate the growth of one part of an organism to another part or to the tree as a whole [29]. Hence, the total above-ground biomass and its components were regressed on tree or stand variable using the following power function:

$$W_i = \beta_0 \cdot X^{\beta_1} + e_i \qquad (1)$$

Where W_i represents the biomass of each tree component (i = stem, crown or total) at tree level (kg) or at stand level (Mg ha^{-1}), X denotes the dependent tree or stand variable, β_0, and β_1 are parameters and e_i is the model error.

The equations were fitted individually and the heterocedasticity, inherent to biomass or volume equations, was corrected by weighted regression. Weighting factors were obtained using the method proposed by authors in Ref. [30]. The homocedasticity of the residues was checked by authors in Ref. [31]. Collinearity among variables may produce errors in parameters or in regression coefficients [32,33]. Its presence was evaluated with the condition number (IC). According to Refs. [34,35] an IC in the range of 30–100, is indicative of problems associated with collinearity, and if IC is above 1000 it suggests the problems are serious.

Table 2 – Descriptive statistics of sampled trees for fitting of the biomass and volume equations.

Component	Minimum	Maximum	Mean	Std. dev.
h (m)	2.61	15.48	6.43	2.33
hv (m)	0.40	7.40	2.69	1.38
d (cm)	1.75	14.30	5.77	2.58
Crown (kg)	0.19	12.17	2.72	2.30
Stem (kg)	0.30	34.79	4.90	5.27
Total (kg)	0.58	45.87	7.60	7.44
Volume (dm^3)	1.26	137.71	19.76	21.95

Finally a nonlinear simultaneous equation system at each level (tree and stand) was fitted, considering the total biomass equation as a sum of the stem wood and crown biomass equations in order to ensure additivity for biomass estimation [36]. Parameter estimation of the models was accomplished by Seemingly Unrelated Regression (SUR), using SAS/ETS Model Procedure [37].

The complete process was implemented for two systems of equations depending on the included variables at tree and stand level. At tree level, one of the equation systems was fitted using exclusively diameter as predictor variable to simplify the model while in the other system all the tree variables were taken into account to find out the most accurate system. The independent variables were total height (h), live crown height (h_v) and diameter at breast height (d) (Table 2). On the other hand, using the same strategy that at tree level, two families of equations were obtained for the stands, one of them using only basal area and the other including the best explanatory variables. At this level, the studied variables were age of the stand (t), number of trees per hectare (N), basal area (G), dominant height (H_o) and quadratic mean diameter (d_g) (Table 1).

2.2.2. *Biomass expansion factor (BEF) models and fit*

Volume data are necessary to obtain BEFs. For this purpose, total tree volume over bark was calculated as the sum of the individual log volumes estimated with the Smalian formula considering the top section of the tree as a cone. BEFs at tree level were calculated with sample trees volume and biomass in order to study the allometry of the species and to provide a constant value for each component of the tree.

Since volume equations are not available for short rotation plantations of *E. nitens* so they were developed in this work. Thereafter, allometric equations were fitted at tree and stand level using weighted regression to account for heterocedasticity in a similar way to in the biomass models. In addition, depending on the explanatory variables included in the equations two types of models were developed with the same objectives and characteristics than in the biomass functions. A correlation analysis was carried out to select the best variables of the listed in the previous section to be used as independent variables for the most accurate volume model at tree and stand level. Finally BEFs were computed for all the plots using stand biomass and volume. BEF was calculated with the following equation:

$$\mathrm{BEF_i} = \frac{\mathrm{W_i}}{\mathrm{V_i}} \tag{2}$$

Where $\mathrm{BEF_i}$ represents the biomass expansion factor (tree: kg m^{-3}; stand: Mg m^{-3}), W_i is dry weight of above-ground biomass (tree: kg; stand: Mg ha^{-1}) and V_i is the total volume over bark (tree: dm^3; stand: m^3 ha^{-1}).

Although this work focuses on predicting BEF equations, a constant value of BEF at stand level was calculated as the average value of all plot BEFs so that it could be compared with the values obtained from the equations.

Several stand variables were computed for each plot: age of the stand (t), number of trees per hectare (N), basal area (G), dominant height (H_o) and quadratic mean diameter (d_g).

A correlation analysis was carried out to study the possible relationship between BEF and the main variables at tree and at stand level. For this purpose a lineal model was considered and the Proc Corr Procedure of SAS/ETS [37] was used.

Positive correlation means that one variable increases, when the other tends to increase and negative correlation implies the opposite trend. Complementarily coefficients close to ±1 show a strong correlation and a t-test is utilized to determine if the correlation coefficient is significant ($p < 0.05$) or not.

Finally, the selection of the best stand variables for use in the BEF equations was decided by correlation analysis results and graphs.

2.2.3. *Model evaluation and comparison*

The performance of the biomass, volume and BEF equations was assessed through graphical analysis and goodness of fit statistics. The comparison statistics used were the adjusted coefficient of determination ($\mathrm{R^2}_{\mathrm{adj}}$) and the root mean square error (RMSE). The adjusted coefficient of determination measures the amount of observed variability explained by the model and the RMSE provides a measure of the precision of the estimates in the same units as the dependent variable. Calculations were made following the formulae:

$$\mathrm{R^2_{adj}} = \left(1 - \frac{\sum_{i=1}^{n}\left(\mathrm{Y_i} - \widehat{\mathrm{Y}}\right)^2}{\sum_{i=1}^{n}\left(\mathrm{Y_i} - \overline{\mathrm{Y}}_i\right)^2}\right) \cdot \left(\frac{n-1}{n-p}\right) \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{Y_i} - \widehat{\mathrm{Y}}_i\right)^2}{n-p}} \tag{4}$$

Where $\mathrm{R^2}_{\mathrm{adj}}$ is the adjusted coefficient of determination, RMSE denotes the root mean square error, $\mathrm{Y_i}$ is the real value, $\widehat{\mathrm{Y}}_i$ is the value predicted by the model, $\overline{\mathrm{Y}}_i$ is the average value, all of which refer to the dependent variable under study, n is the total number of datasets and p represents the number of parameters included in the model.

The use of a new independent dataset is the only method that can be regarded as a truly appropriate validation for a new model [38]. Alternative approaches can be employed for this purpose, like splitting the dataset into two portions or double cross-validation, although, they do not provide any additional information about the predictive ability of the models [39,40]. Unfortunately, in this work no validation dataset was available and therefore it was decided that the best strategy was to use all the datasets to fit the best and strongest model.

Finally, a comparison of the three approaches of above-ground stand biomass estimation (biomass and BEFs equations and constant BEF) was carried out. In this comparison, the errors for the different methods were calculated as the difference between the stand biomass obtained with the aggregation of the biomass of all trees in the plot (by applying the tree biomass equations) and the biomass estimated at stand level using the three analysed approaches.

A schematic representation of the complete process with all the specific phases at tree and stand level is shown in Fig. 2.

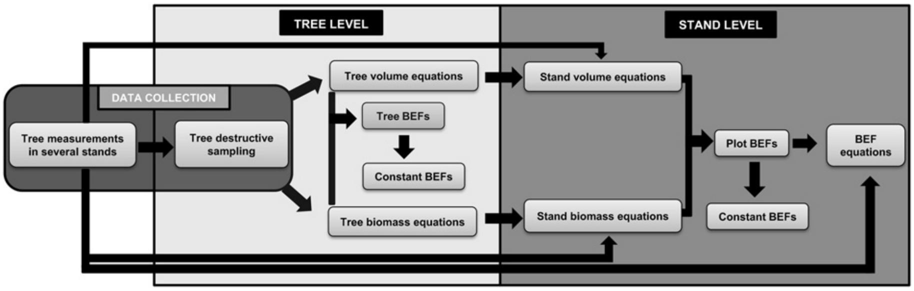

Fig. 2 – **Scheme of the process followed in the three approaches of aboveground biomass estimation used in this work.**

3. Results and discussion

3.1. Above-ground biomass equations

Information about tree and stand biomass equations is given in Table 3. Diameter was the main predictor tree variable because it shows a high correlation with all tree biomass components [13,41–43]. In addition, measuring diameters is easier and cheaper than other tree variables. Hence, a biomass equation system using only diameter as explanatory variable is provided in this work. However the combination of diameter with other tree variables, e.g. total height, generally improve the accuracy of the biomass equations [41,43,44]. Hence, all possible combinations of the variables were tested and the most accurate equation system was developed to obtain the best fit. Finally, for this system, together with diameter, live crown height for the crown component and total height for the stem were selected to introduce in the models. These models explain between 92 and 98% of tree sample variability compared with the simplified models whose results range from 90 to 94%.

The best predictor variable at stand level for crown and stem components was basal area. The simplified equation system reached accurate results with R^2_{adj} approximately between 96 and 99%. However the inclusion of dominant height in the equations considerably improved R^2_{adj} and RMSE decreased. Hence, both variables were selected to be used in the most accurate biomass stand system. All the estimate parameters for the two levels, tree and stand, were highly significant at $p < 0.0001$. As expected, the best coefficients of determination were obtained for equations at stand level with values close to 1. However all the values were above 0.9, indicating a high degree of accuracy for the aboveground biomass estimation. White's Test and predicted residue graphs showed that heterocedasticity was corrected by weighted regression for all the functions. The values of the condition numbers (IC) were in all the systems fewer than 40, indicating there were no serious collinearity problems.

Taken together, the results suggest that the equations developed are suitable for application to stands with similar characteristics to those analysed here.

Table 3 – **Estimated parameters and statistical values for dry weight biomass equations and for over bark total volume functions at tree and at stand level.**

Level	Equation	Type	Component	Equation	RMSE	R^2_{adj}	W.T.
Tree	Biomass	Simplified	Crown	$W_C = 0.113 \cdot d^{1.742}$	0.6875	0.9116	0.2601
			Stem	$W_S = 0.081 \cdot d^{2.201}$	1.6229	0.9059	0.7642
			Total	$W_T = \sum(W_c + W_S)$	1.8577	0.9382	0.6109
		Accurate	Crown	$W_C = 0.090 \cdot d^{2.012} \cdot h_v^{-0.276}$	0.6369	0.9242	0.2470
			Stem	$W_S = 0.040 \cdot d^{1.580} \cdot h^{0.945}$	0.8040	0.9769	0.9690
			Total	$W_T = \sum(W_c + W_S)$	1.2356	0.9727	0.5741
	Volume	Simplified	Stem	$V = 2.990 \cdot 10^{-4} \cdot d^{2.240}$	0.0053	0.9432	0.0642
		Accurate	Stem	$V = 1.571 \cdot 10^{-4} \cdot d^{1.775} \cdot h^{0.772}$	0.0022	0.9903	0.8091
Stand	Biomass	Simplified	Crown	$W_C = 1.446 \cdot G^{0.810}$	0.8120	0.9592	0.6074
			Stem	$W_S = 0.887 \cdot G^{1.211}$	1.3651	0.9737	0.3748
			Total	$W_T = \sum(W_c + W_s)$	1.1069	0.9919	0.6831
		Accurate	Crown	$W_C = 2.525 \cdot G^{0.982} \cdot H_o^{-0.465}$	0.6378	0.9748	0.5934
			Stem	$W_S = 0.429 \cdot G^{0.998} \cdot H_o^{0.589}$	0.7036	0.9930	0.2739
			Total	$W_T = \sum(W_c + W_s)$	0.8485	0.9952	0.9229
	Volume	Simplified	Stem	$V = 3.292 \cdot G^{1.248}$	4.477	0.9825	0.0505
		Accurate	Stem	$V = 1.808 \cdot G^{1.055} \cdot H_o^{0.504}$	2.1872	0.9958	0.2102

Where W is individual tree (kg) or stand (Mg ha^{-1}) biomass and V is individual tree volume (m^3) or stand volume (m^3 ha^{-1})depending on the level of the equation, d represents diameter at breast height (cm), h is total height (m), h_v denotes height of the live crown (m), G is the basal area (m^2 ha^{-1}), H_o represents dominant height (m), RMSE is the root mean square error for the tree (kg) or the stand equation (Mg ha^{-1}), R^2_{adj} is the adjusted coefficient of determination of the model and W.T. is the result of heterocedasticity White's Test ($\alpha < 0.05$).

3.2. *Biomass expansion factors*

The first step to calculate BEFs is to develop tree volume equations. These equations were fitted firstly at tree level to estimate, then at stand level. The goodness of fit statistics (Table 3) and the graphical analysis showed the models to be good.

Biomass components demonstrate various natural changes depending on site index and the tree development phase [45]. The wood proportion increases with age while that of leaves and branches decrease [14,46–48]. Therefore constant values of biomass expansion factors are highly variable and generally inaccurate [8,10,16,18,49]. This leads to biomass underestimations in young or poor quality stands and, on the contrary, overestimations in mature or highly productive stands [50–52].

Constant BEFs (average values) of 0.43 and 0.50 were obtained at tree and stand level respectively from the total biomass data. Table 4 shows BEF values for both studied levels and in general for crown and total BEFs. The values ranged widely because they are dependent on age and other tree or stand characteristics. In contrast, stem BEFs were very constant which could be due to the fact that the variables used to calculate stem BEF, volume and biomass, whose relation is the basic density of wood, are obviously proportional.

Apart from the stem component, it seems that use of constant BEF values may induce serious errors in biomass or carbon estimation such that the development of BEF equations is the recommended approach when the data are available [16,17,53–56]. BEFs are age dependent because tree allometry and biomass partitioning varies as a function of age [8,12,13]. It is important to highlight that in this study, it is considered that tree age is the same variable as stand age because it is forest plantations that are under consideration.

All coefficients of correlation for crown and total BEF were significant ($p < 0.0001$) and negative, decreasing with tree size and increasing age. The correlation analysis indicates that total height is the tree variable most closely associated with these BEFs, followed by diameter and age. Total height has also been found to be the most accurate explanatory variable to estimate tree BEF in other studies [55,57]. On the other hand, stem BEF had no significant relationships with the main tree variables in this study for the reasons previously explained. Fig. 3 shows the graphs which relate BEF values and tree variables. The graph lines represent the constant BEF for each studied category (stem, crown or whole tree) and p is the value of the significance test of the correlation analysis.

The changes in the main tree components during stand development are shown in Fig. 4. When plantations are very young, less than two years of age, crown biomass constitutes the main component of the tree. This is due to the fact that in the first stand stage, maximum foliage development is likely to be crucial for survival under competition conditions [14]. However, this changes when crown closure is achieved and stem growth is accentuated to ensure tree stability [13,14,58]. As a result, in young stands BEF is highly variable because trees are in a vigorous growth phase which produces great changes in biomass partitioning [11,13]. However, this behaviour changes in older stands, where BEF presents an asymptotic behaviour due to the stabilization of growth rate [55] and therefore, most of the tree biomass is allocated to the stem [11,13,14].

The analysis of the relationships between crown, stem and total BEFs and stand variables showed highly significant correlations (<0.001) for the variables age, basal area, dominant height and quadratic mean diameter and, additionally, the correlation with density was significant at the 0.05% level (Fig. 5). The analysed variables show a decreasing pattern over time, presenting a strong initial tendency which becomes almost negligible beyond a certain point [8]. This trend is clearest with dominant height, quadratic mean diameter and basal area [18,20,49], and it tends to stabilize with the growth of the stand [55]. In addition, these results highlight the fact that when a constant BEF is used, estimations may have serious errors [16,17,53–56]. However some studies have determined a limit for the use of constant BEF from a certain value of the predictor variable since when BEF is stabilized, the biomass estimation errors are minimized [18,52]. This could be a good way to simplify the calculations in mature stands where volume information is highly accessible. Nevertheless, it is not possible to apply this criterion in very young stands such as those studied here since there is not a clear constant value of BEF, although the tendency to stabilization does exist. Moreover, other error associated with volume estimation in small trees must be considered, since ratio between independent variables error mensuration and the average value of independent variables is very high on these small trees.

BEF stand models were developed at three components (crown, stem and whole tree). Dominant height was the selected variable for crown and total BEF models (Table 5) since it is the best variable to explain BEF conduct in other apically dominant species [16,18,20]. The dominant height function fitted in this study is the Schumacher's equation [59], which was developed to modelling volume yield of even-aged timber stands. It has been used previously by authors in Ref. [19] in a BEF study with different conifers and broadleaved species. In this equation a new parameter was incorporated to improve the accuracy of the model, which reach an R^2_{adj} of 0.99 in both levels.

The selected model for stem BEF, however, was an allometric Eq. (1) combining the best explanatory variables, quadratic mean diameter, basal area and age.

Table 4 – Constant (average value) and extremes values of BEF calculated at tree (kg dm^{-3}) and stand level (Mg m^{-3}).

Level	Component	BEF			
		Constant	Minimum	Maximum	Std. Dev.
Tree	Crown	0.17	0.06	0.38	0.06
	Stem	0.25	0.20	0.34	0.03
	Total	0.43	0.26	0.82	0.09
Stand	Crown	0.25	0.09	0.62	0.12
	Stem	0.25	0.24	0.27	0.01
	Total	0.50	0.35	0.89	0.13

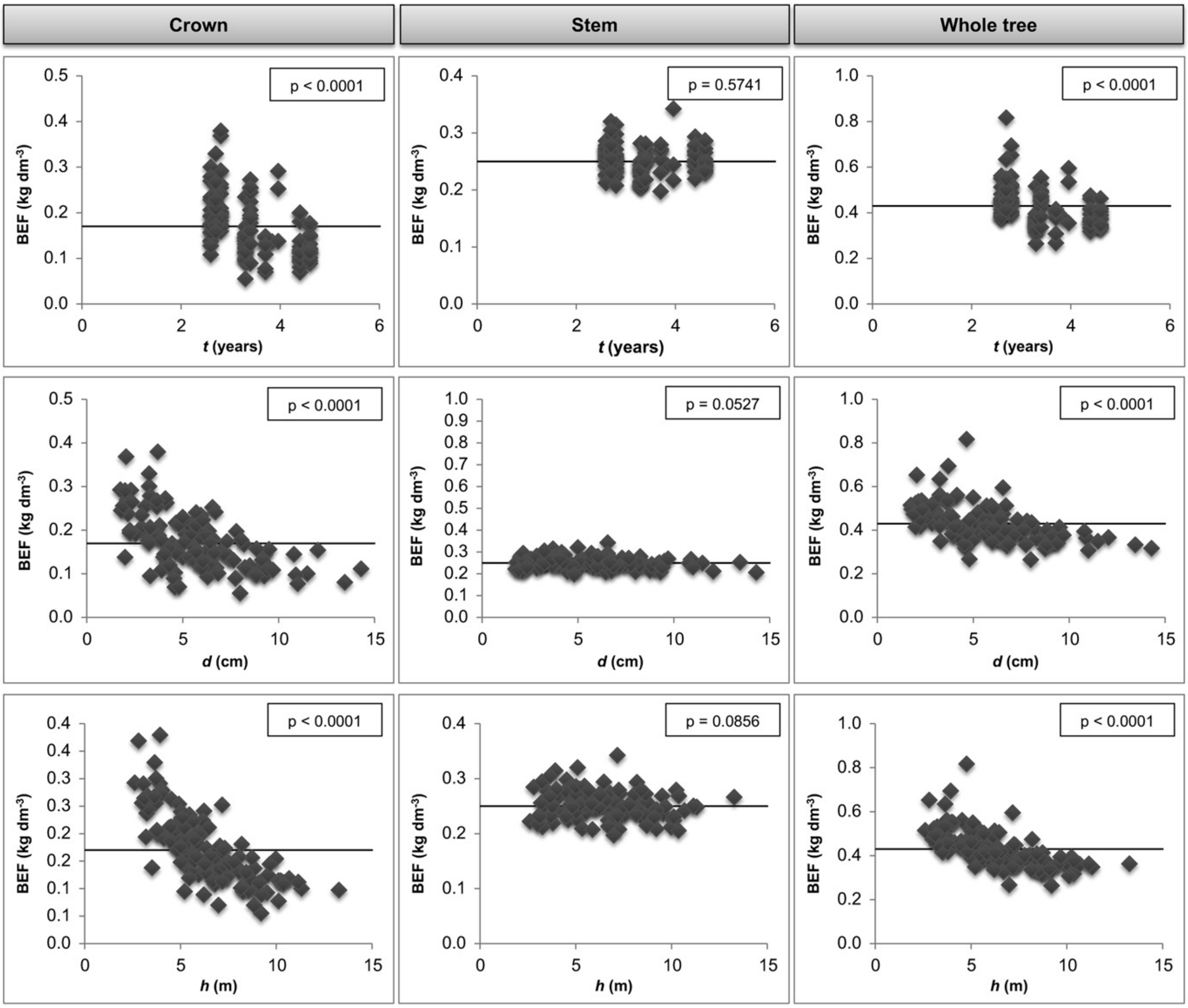

Fig. 3 – Relation between tree BEFs and tree variables: age (*t*), diameter at breast height (*d*) and total tree height (*h*) for crown, stem and whole tree. The graph lines represent the constant BEF (average) for each category. *p* Value is the results of the test of significance in the correlation analysis.

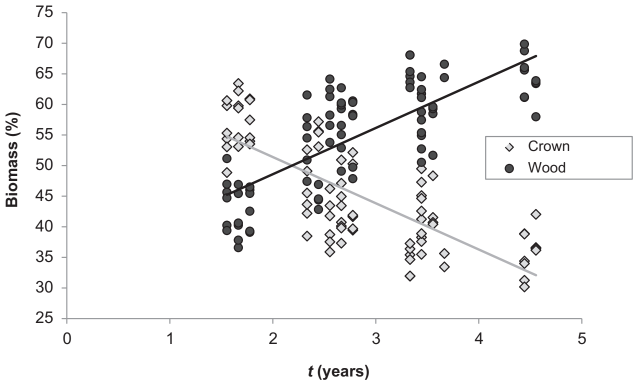

Fig. 4 – Relationship between crown and stem biomass as trees age in *E. nitens* short rotation plantations. Lines are non-parametric average lines of each tree component.

3.3. *Comparison of biomass estimation*

In general, biomass prediction with allometric equations are considered to be the most realistic reference values for calculating biomass. For the stem component in this study, this is true, because the biomass equation ($R^2_{adj} = 0.9930$) with fewer dependent variables is more accurate than the BEF equation ($R^2_{adj} = 0.8718$) and volume equation ($R^2_{adj} = 0.9903$). Furthermore, constant BEF behaves well for this tree component due to the low variation in the value range of the plots. For the total biomass, in contrast, the percentage of variability explained by the biomass equation ($R^2_{adj} = 0.9952$) was almost the same as that explained by the BEF equation including dominant height as stand variable ($R^2_{adj} = 0.9921$). In addition, the crown component R^2_{adj} increased from 0.9748 to 0.9974 when comparing biomass and BEF equations respectively, but showed a poor predictive capacity when constant BEF was tested.

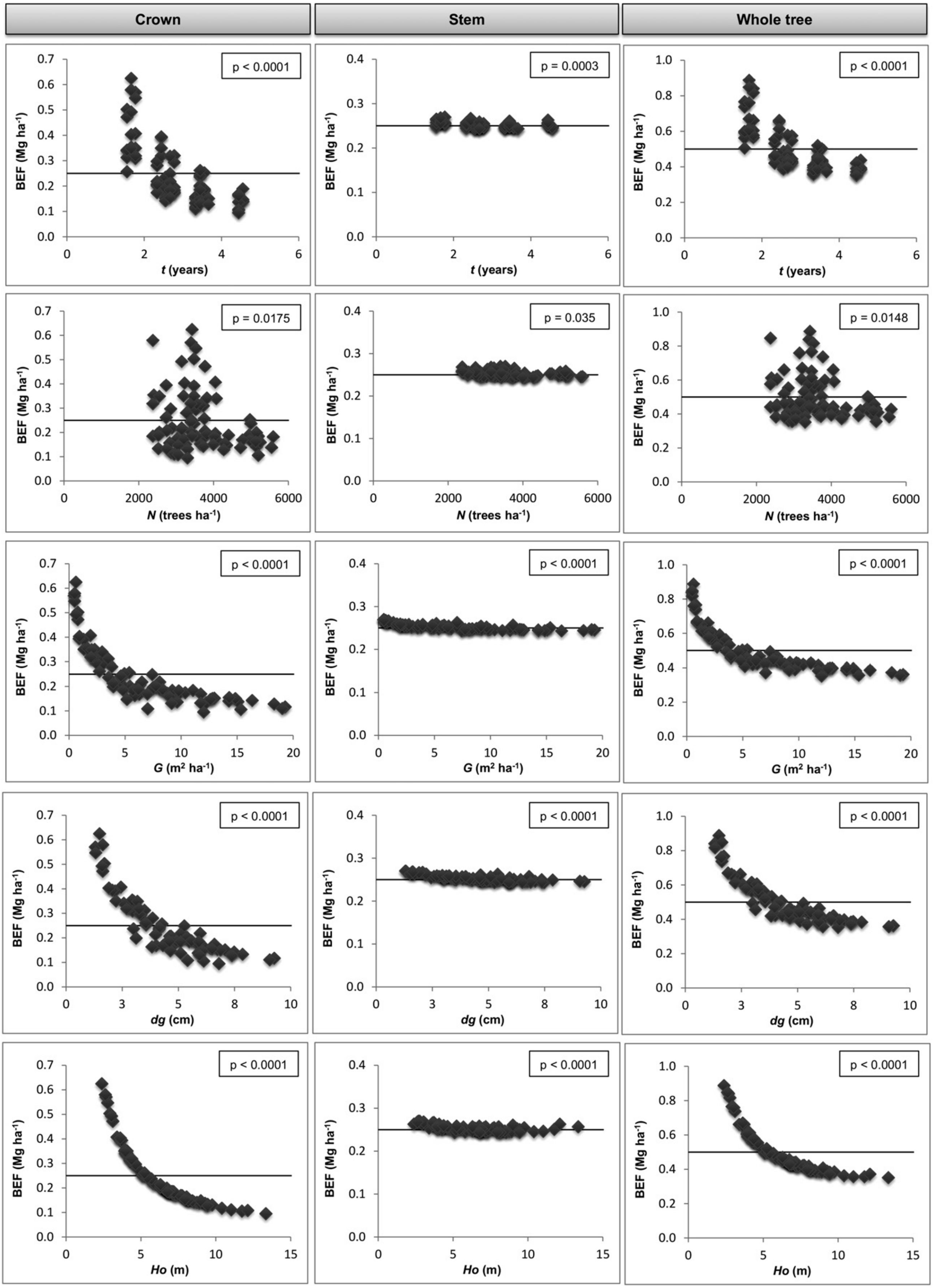
Crown
Stem
Whole tree
p < 0.0001
p = 0.0003
p < 0.0001
p = 0.0175
p = 0.035
p = 0.0148
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
p < 0.0001
BEF (Mg ha-1)
t (years)
N (trees ha-1)
G (m2 ha-1)
dg (cm)
Ho (m)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1.0
0
2
4
6
2000
4000
6000
3
5
8
10
15
20

Table 5 – Estimated parameters and statistical values for BEF stand equations.

Component	Variable	Equation	RMSE	R^2_{adj}
Crown	H_o	$BEF_C = e^{-18.165+\frac{18.812}{H_o^{0.069}}}$	0.0062	0.9974
Stem	d_g, G, t	$BEF_S = 0.250 \cdot d_g^{0.040} \cdot G^{-0.052} \cdot t^{0.0375}$	0.0025	0.8718
Total	H_o	$BEF_T = e^{-1.622+\frac{2.647}{H_o^{0.6223}}}$	0.0113	0.9921

Where BEF is stand biomass expansion factor (Mg m^{-3}), H_o is the dominant height (m), G denotes the basal area (m^2 ha^{-1}), d_g is the quadratic mean diameter (cm), t is the stand age (years), RMSE is the root mean square error of the model (Mg m^{-3}) and R^2_{adj} is the adjusted coefficient of determination of the model.

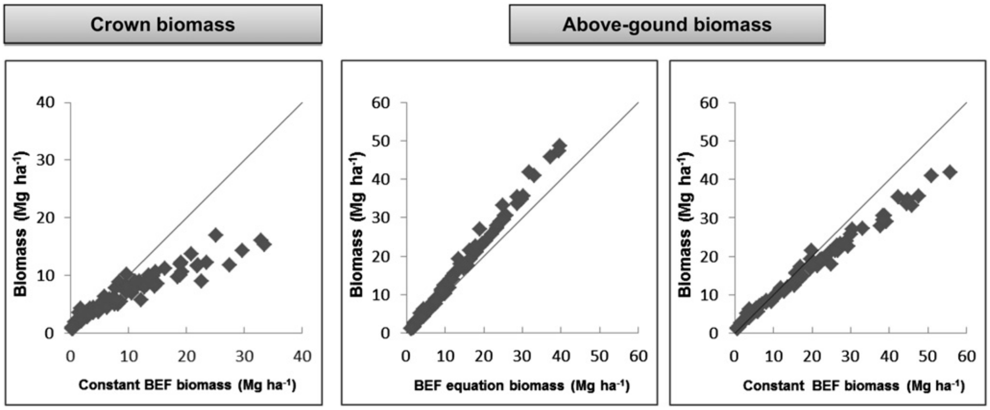

Fig. 6 – Observed biomass vs biomass predicted by constant BEF for crown and by constant BEF and BEF equations for whole tree. The graph lines represent a line with slope of 1:1.

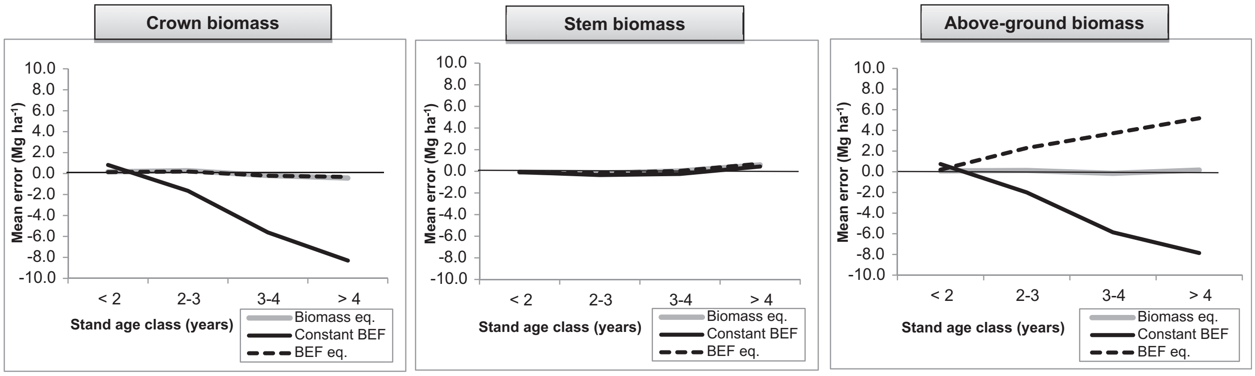

Fig. 7 – Mean errors of biomass estimations using allometric equations, constant BEFs and BEF equations by stand age class for crown, stem and above-ground biomass.

The graphical comparison between the observed and the predicted biomass by the studied methods showed a good trend in the most of the situations. Nevertheless, bias was detected for the crown and the total biomass when constant BEF was used, and the same tendency was also obtained using BEF equations with total biomass (Fig. 6).

Applying biomass equations the general mean error was 0.04 Mg ha^{-1} for the crown and the total biomass and 0.01 Mg ha^{-1} for the stem. It was found to be the most accurate methodology to calculate biomass for stem and total tree. However, for the crown biomass, the best results were obtained using the BEF equation (0.01 Mg ha^{-1}), although they are very similar to those of biomass equation, which could be the best method if volume errors had been considered. The constant BEF value approach was the least accurate method for all three levels, generally resulting in underestimation. Fig. 7 shows the mean errors obtained with the different methods by stand age class. It particularly highlights the

Fig. 5 – Relation between stand BEFs and stand variables: age (t), number of tress per hectare (N), basal area (G), quadratic mean diameter (d_g) and dominant height (H_o); for crown, stem and whole tree. The lines represent the constant BEF (average) for each category. p Value is the results of the test of significance in the correlation analysis.

ranges of age for which the models provide especially poor or good predictions. As expected, constant BEF showed the greatest error in most variables and categories compared to biomass and BEF equations. However, this error is not very important in stem component where, although the other methods are more accurate in stands younger than 4 years, the mean error of constant BEF by age class did not reach 0.5 Mg ha^{-1}. For estimating crown component, as indicated above, either biomass or BEF equations could be used as their degree of accuracy is very similar in all stand classes, but constant BEF should be avoided because it produce an increasing level of bias as stand age increases. Finally, for total aboveground estimations, biomass equation is seen to be the best methodology since with the stand growth model BEF tends to produce overestimations, and constant BEF underestimations, with a maximum mean error of 5.18 and 7.86 Mg ha^{-1} respectively.

4. Conclusions

In general BEFs had a good correlation with stand variables because they are age and site dependent. Dominant height, mean quadratic diameter, basal area and age had the strongest relationship with BEF.

The BEF model, followed by biomass equation, provided the best predictions for the crown component even though the error in the intermediate step of volume estimation must be considered. On the other hand, although the best results for the stem fraction were obtained with biomass equations, biomass can be calculated with any of the studied methodologies because all of them provided good predictions. The biomass equation is the most accurate method for total biomass followed by BEF function. Constant BEF value used as default underestimated biomass production and its use is not recommended when other methods are available except in stem component where it does not produce a high degree of errors.

The inclusion of variation in stand size and quality means that the biomass estimation methods which have been developed in this work can be used in other *E. nitens* woody crop plantations with similar characteristics. The user's selection of one of these methods over the other will depend on the available data and the accuracy required in the study.

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Dynamic growth and yield model including environmental factors for *Eucalyptus nitens* (Deane & Maiden) Maiden short rotation woody crops in Northwest Spain

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Abstract A dynamic model consisting of two projection functions, dominant height and basal area, was developed for the prediction of stand growth in *Eucalyptus nitens* bioenergy plantations aged 2–6 years and with stockings of 2,300 and 5,600 trees ha^{-1}. The data came from 40 permanent sample plots, representing site quality variability across the distribution area of *E. nitens* crops. Three inventories were carried out to collect tree data and determine stand variables. Additionally, edaphic, physiographic and climatic information were obtained and included in the model. For both functions, an ADA growth model was selected, which achieved high accuracy. The corresponding growth curves developed in this study had values of 5, 8, 11 and 14 m for dominant height and 4, 14, 24 and 34 m^2 ha^{-1} for basal area at the base age of 4 years. The inclusion of environmental factors (i.e. soil and climatic variables) as parameters in the model resulted in good estimations and increased the model's flexibility to adapt to small variations in site conditions. The model developed here is thus shown to be useful for simulating the growth of *E. nitens* crops when environmental information is available. A prediction function was fitted for use in stands without diameter inventories or not previously occupied by *E. nitens*, and including environmental variables improved its accuracy. Biomass mean annual increment varied from 3.25 to 18.45 Mg ha^{-1} year^{-1} at the end of the rotation, projected as between 6 and 12 years depending on site quality.

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Keywords *Eucalyptus* · Site quality · Bioenergy · Algebraic difference equations · Climate · Soil

Introduction

In recent years, society's concerns about climate change and rises in the price of fossil fuels have increased interest in bioenergy production, particularly short rotation plantations. These produce high biomass yields in a short period of time using fast-growing species such as poplar, willow or eucalyptus, which are used extensively in several countries around the world with a wide range of climates and soils (Wright 2006).

The first *Eucalyptus nitens* (Deane & Maiden) Maiden plantations in the northwest of Spain were established in the early 20th century, principally for pulp production. Even though early studies on the potential use of residual biomass from forest activities, i.e. thinnings and clear cuttings, suggested that it would be insufficient to cover future demand for bioenergy (Pérez et al. 2006), the huge increase in the land area planted with this species in the northwest of Spain in the last decade suggests that this situation has most likely changed. This success of the species is due to the a number of advantages it presents, such as its high energy potential (Pérez et al. 2006), its good resistance to fungus and insects such as *Gonipterus scutellatus* Gyll., and its tolerance of low temperatures (FAO 1981).

Prediction tools are essential in forestry to forecast development and so decide the best management strategies. In relation to energy crops, comprehensive planning is crucial in order to supply biomass when it is required and, furthermore, it is necessary to know the evolution and availability of the stock in a given plantation at a given time. At the same time, it is important that the models used are able to adapt to changing environmental conditions (Fontes et al. 2010).

Dynamic growth models are mathematical equations developed to predict past or future stand states from a given known past or present state (Cieszewski 2003). As such, they can be developed using appropriate data, such as information from inventoried taken at any time, from permanent sample plots or stem analyses. Whole stand models are especially suitable for bioenergy plantations because they are homogeneous, even-aged pure stands where the trees have broadly similar characteristics (García 1988; Vanclay 1994). Such stand models are generally simple due to the fact that they predict forest state using aggregate and stand variables such as basal area, stems per hectare or dominant height.

Dynamic growth models provide a better description of the development of the stand over the time than static models (García 1988) although it is necessary to have more than one measurement over time (longitudinal data) to develop them. The general mathematical expression of these models is $Y = f(t, t_0, Y_0)$, where Y is the value of the function at age t, and Y_0 is the reference variable defined as the value of the function at age t_0.

The use of algebraic difference equations, obtained through the derivation of dynamic equations, has given rise to the "algebraic difference approach" (ADA) when one parameter is site-specific (Bailey and Clutter 1974) or the "generalized algebraic difference approach" (GADA) when more than one parameter depends on the site (Cieszewski and Bailey 2000). The models derived by ADA and GADA are base age and path invariant and they are widely used to develop dominant height and basal area models in even-aged stands (e.g. Cieszewski 2001; Bravo et al. 2011).

GADA requires an explicit definition of how the site-specific parameters change across different sites by replacing them with explicit functions of X (one unobservable independent variable that describes site productivity as a summary of management regimes and ecological factors) and new parameters, while ADA is based on a solution using a single base model parameter (Bailey and Clutter 1974; Cieszewski and Bailey 2000). In this way, the initial selected two-dimensional base equation $(Y = f(t))$ is expanded into an explicit three dimensional site equation $(Y = f(t, X))$ describing both cross sectional and longitudinal changes with two independent variables, t and X. Since X cannot be reliably measured or even functionally defined, the final step involves the substitution of X by equivalent initial conditions t_0 and Y_0 $(Y = f(t, t_0, Y_0))$ so that the model can be implicitly defined and practically useful (Cieszewski and Bailey 2000; Cieszewski 2002).

In Spain, there are several dynamic growth models developed for different forest species and these have recently been collected together (Bravo et al. 2011). For *E. nitens* short rotation woody crops, two management tools, a static model and a process based model, have been developed recently (Pérez-Cruzado et al. 2011a, b). However, they are not dynamic equations and their stand density rates do not go as high as 2,300 trees ha^{-1} (the lowest stocking used in this study). For these reasons, and given the advantages described above for these types of models, dynamic growth models based on algebraic difference equations were developed in this study.

Stand dynamics depend on the productive capacity of the site, which is usually related to climate and soil characteristics, as has been shown in several studies (Bravo-Oviedo et al. 2008, 2011; Nunes et al. 2011). Hence it follows that if this relationship between growth and site parameters is analysed, and the corresponding site variability explained by this analysis is included in growth models, it could help to make the models more flexible with respect to environmental variations and thus improve their accuracy (Bravo-Oviedo et al. 2008; Nunes et al. 2011). This is clearly very important in terms of responding to climate change.

The objective of this study was to develop a dynamic whole-stand model for predicting biomass growth and yield for bioenergy plantations of *E. nitens* across its distribution area in Spain. This model comprised two projection functions, dominant height (allowing site quality classification) and basal area. Soil, climatic and physiographic variables were subsequently included in the model to explore the possibility of improving predictions under a climate change scenario. In addition, a stand basal area prediction function was fitted to provide an initial value of basal area at a given age, when this information is not available.

Materials and methods

Material

The data used to develop the stand model were obtained from 40 permanent sample plots of *E. nitens,* McAlister provenance, located in Galicia, in Northwest Spain (coordinates, 43°10′27″–43°32′56″N and 7°48′39″–7°14′10″W). The plots were subjectively chosen from a number of homogenous energy stands in order to represent the range of ages and site conditions existing in the area, and can therefore be considered appropriate for developing growth models.

The stands were planted between 2007 and 2009, and 400 m^2 experimental plots were established in the middle of the stands to avoid edge effects at the end of 2010. The tree stocking density ranged from 2,300 to 5,600 trees ha^{-1} and trees were planted in either single or double lines, depending on the sample plot. The physiography of the plots was characterized by slopes of between 0 and 38 % (mean 13 %) and an elevation ranging from 400 to 700 m above sea level.

In this region, soils are Rankers and Humic Cambisols, according to FAO (1991). Soil depth to bed rock was determined for each plot in three randomly selected points using a Dutch auger, and ten soil sub-samples from depths of between 0 and 20 cm were taken to determine edaphic characteristics.

The pH was measured using both KCl (1:2.5) and H_2O (1:2.5,) and the latter (diluted 1:5) was also used to analyse electrical conductivity. Organic matter content was determined by the dichromate oxidation method. Total N was determined by Kjeldahl digestion and available P was measured by colorimetry using Mehlich reagent (Mehlich 1953). Exchangeable cations (K, Mg, Na and Ca) were extracted with 1 M NH_4Cl (Peech 1947), and exchangeable Al was extracted with 1 M KCl and analysed by atomic absorption. The sum of cation exchange and effective cation exchange capacity (sum of exchangeable cations and exchangeable Al) were calculated. Finally, particle size distribution, to determine soil texture, was analysed by the pipette method using sodium hexametaphosphate and Na_2CO_3 as dispersant (Gee and Bauder 1996).

Plot climatic variables were interpolated using the model proposed by Sánchez-Palomares et al. (1999) which employs the data of the hydrographical basin and the elevation and coordinates of the plots. The estimated variables were mean annual and seasonal precipitation, mean annual temperature, mean temperature in the warmest and coldest months, maximum and minimum mean temperature in the warmest and coldest months, mean summer and winter temperature, annual potential evapotranspiration, annual moisture surplus and deficit and annual water reserve index.

An inventory was carried out in the winters of three consecutive years between 2010/2011 and 2012/2013. In short rotation plantations used for bioenergy it is important to reduce the intervals between measurements as much as possible as there is faster growth and shorter rotations than for other common forest species. Therefore, in this case three annual measurements were considered enough to develop the growth model. The first and the second inventories were carried out in all the plots, while the final inventory only comprised a sub-set of the 40 plots which, however, fully represented the variability of ages and site qualities for the species in the area.

For the inventories, two measurements of diameter at breast height (1.3 m above-ground level) were made, at right angles to each other and to the nearest 0.1 cm, using callipers, and the arithmetic mean of the two measurements was calculated. Total height was also measured for all trees; to the nearest 0.1 m using a digital hypsometer, or to the nearest 0.01 m using a telescopic measuring pole in the smaller stands. Finally, descriptive variables for each tree were also collected (e.g. if they were alive or dead).

Due to the early stage of the plantations (age <6 years) and the importance of time of planting for the initial growth of trees in the first year, the exact stand age was estimated for each plot. For this purpose, the difference between the planting and the measurement date, in addition to the length of the vegetative growth period in each plot, were taken into account.

Following the taking of the inventory, number of trees per hectare, quadratic mean diameter (*dg*), basal area (*G*) and dominant height (*Ho*)—taken as the mean height of the 100 thickest trees per hectare—were calculated for each plot and inventory.

Table 1 presents summary statistics of the stands: the physiographic, edaphic and climatic variables used for model development, including the mean, minimum, maximum and standard deviation.

Table 1 Main variable statistics of the stands studied

Variable	Min.	Max.	Mean	SD
Stand				
Age (years)	1.56	5.56	3.22	1.16
No of trees per hectare	2,375	5,600	3,697	851
Mortality rate (%)	0.00	7.44	1.65	1.97
Basal area (m^2 ha^{-1})	0.46	31.88	9.02	7.06
Quadratic mean diameter (cm)	1.31	12.21	5.16	2.30
Dominant height (m)	2.39	15.68	7.40	3.13
Above-ground biomass (Mg ha^{-1})	1.20	84.85	22.51	18.91
Stem over-bark volume (m^3 ha^{-1})	1.51	253.15	57.48	55.28
Physiographic				
Slope (%)	0.00	37.90	13.40	9.74
Elevation (m)	447.00	697.00	608.53	64.71
Edaphic				
pH (H_2O 1:2.5)	3.90	5.27	4.46	0.29
pH (KCl 1:2.5)	3.19	4.43	3.85	0.29
Electrical conductivity (dS m^{-1})	0.02	0.19	0.06	0.03
Organic matter (%)	7.90	22.27	12.49	3.07
Total N (%)	0.10	0.40	0.22	0.07
C/N ratio	15.79	71.77	35.30	12.66
Available P^a (mg kg^{-1})	10.20	18.13	14.60	2.10
Ca^b_{CEC} ($cmol_c$ kg^{-1})	0.04	0.88	0.16	0.15
Mg^b_{CEC} ($cmol_c$ kg^{-1})	0.06	0.51	0.20	0.09
Na^b_{CEC} ($cmol_c$ kg^{-1})	0.09	0.45	0.17	0.06
K^b_{CEC} ($cmol_c$ kg^{-1})	0.12	0.85	0.27	0.13
Al^b_{CEC} ($cmol_c$ kg^{-1})	1.96	14.82	6.64	2.44
Sum of base cations ($cmol_c$ kg^{-1})	0.45	1.40	0.81	0.25
Effective cation exchange capacity ($cmol_c$ kg^{-1})	2.84	15.60	7.44	2.43
Sand (%)	13.00	71.72	42.31	14.92
Clay (%)	2.70	39.61	11.87	7.49
Silt (%)	17.17	73.10	45.83	14.04
Soil depth (m)	0.20	0.94	0.43	0.15
Climatic				
Annual total precipitation (mm)	1,171.00	1,345.00	1,244.15	39.02
Spring precipitation (mm)	292.00	338.00	311.85	10.35
Summer precipitation (mm)	140.00	156.00	146.83	4.17
Autumn precipitation (mm)	320.00	369.00	340.05	11.32
Winter precipitation (mm)	418.00	481.00	445.30	13.94
Mean annual temperature (°C)	10.30	11.50	10.71	0.30
Mean temperature of the warmest month (°C)	16.10	17.40	16.69	0.33
Mean temperature of the coldest month (°C)	5.00	6.60	5.52	0.44
Mean summer temperature (°C)	15.10	16.50	15.74	0.36
Mean winter temperature (°C)	5.60	7.10	6.05	0.42
Maximum mean temperature of the warmest month (°C)	20.70	23.60	22.14	0.81

Table 1 continued

Variable	Min.	Max.	Mean	SD
Minimum mean temperature of the coldest month (°C)	1.20	3.40	1.98	0.54
Evapotranspiration (mm)	633.00	664.00	643.83	7.42
Annual moisture surplus (mm)	665.00	827.00	736.45	37.58
Annual moisture deficit (mm)	117.00	153.00	136.05	9.50
Annual water reserve index	88.20	119.20	101.78	7.44

[a] Method described in Mehlich (1953)

[b] Method described in Peech (1947)

Methods

Model structure

The model uses stand variables to characterize the system at an initial stage, and projection or transition functions to project stand growth in the future. Any model selected must satisfy the desirable attributes of growth functions (Bailey and Clutter 1974; Parresol and Vissage 1998; Cieszewski 2003): (1) polymorphism, (2) sigmoid growth pattern with an inflexion point, (3) horizontal asymptote at old ages, (4) logical behaviour (height should be zero at age zero and equal to site index at the base age), (5) parsimony and absence of trends in residuals, (6) base-age invariance, and (7) path invariance.

For unthinned stands, a dimensional vector which includes dominant height and basal area as explanatory variables can be enough to describe the state of the stand at a given time (Pienaar and Turnbull 1973). However, although the plantations studied here had not been thinned, tree density may well have decreased over time due to competition. For permanent sample plots, a suitable combination of short and long intervals between measurements is considered necessary in order to study and calculate tree mortality (Tewari et al. 2014). However, this study only considered a short period of time and the mortality rate detected over the 3 years was very low (<7.5 %, Table 1) and thus changes in plantation density were not considered to be of any great significance for the study. The status of the stands was therefore characterized using only dominant height and stand basal area as state variables.

Dominant height and basal area growth functions are two of the most important components of whole-stand models since they are directly related to productive variables such as biomass or volume. In addition, dominant height is the most widely used method for evaluating site quality in pure even-aged stands (Bravo et al. 2011).

In this study two projection functions, dominant height and basal area, were therefore developed.

Models considered

The following base growth models were used to describe dominant height and basal area projection functions: Korf-Lundqvist, Hossfeld and Bertalanffy-Richards. The integral form of each growth function was converted into algebraic difference equations; that is, ADA models when one parameter of the equation was free, or GADA models in the case of two free parameters, resulting in a total of twelve models being fitted. Table 2 shows the basic and the algebraic difference equation (ADA or GADA) forms for the functions considered, as well as references for the various models. Following general notational

Table 2 Models considered for dominant height and basal area projection functions

Base function	Site parameters	Solution for X with initial values (t$_0$, Y$_0$)	Dynamic equation	References	Model
Lundqvist-Korf (1957): $Y = a_1 \cdot \exp(-a_2 \cdot t^{-a_3})$	$a_1 = X$	$X_0 = \frac{Y_0}{exp\left(-b_2 \cdot t_0^{-b_3}\right)}$	$Y = Y_0 \cdot \frac{exp\left(-b_2 \cdot t^{-b_3}\right)}{exp\left(-b_2 \cdot t_0^{-b_3}\right)}$	Bailey and Clutter (1974)	M1
	$a_2 = X$	$X_0 = -Ln\left(\frac{Y_0}{b_1}\right) \cdot t_0^{b_3}$	$Y = b_1\left(\frac{Y_0}{b_1}\right)^{\left(\frac{t_0}{t_1}\right)^{b_3}}$	Bailey and Clutter (1974)	M2
	$a_3 = X$	$X_0 = \frac{-Ln\left(\frac{Y_0}{b_1}\right)/-b_2}{Lnt_0}$	$Y = b_1 \cdot \exp(-b_2 \cdot t^{X_0})$	Ni and Liu (2008)	M3
	$a_1 = \exp(X)$ $a_2 = b_1 + b_2/X$	$X_0 = \frac{1}{2}\left(b_1 \cdot t_0^{-b_3} + Ln\left(Y_0\right) + \sqrt{4 \cdot b_2 \cdot t_0^{-b_3} + \left(b_1 \cdot t_0^{-b_3} + Ln\left(Y_0\right)\right)^2}\right)$	$Y = \exp(X_0) \cdot$ $\times \exp(-(b_1 + b_2/X_0)) \cdot t^{-b_3})$	Cieszewski (2004)	M4
Hossfeld (1822): $Y = \frac{a_1}{1 + a_2 \cdot t^{-a_3}}$	$a_1 = X$	$X_0 = Y_0 \cdot \left(1 + b_2 \cdot t^{-b_3}\right)$	$Y = Y_0 \cdot \frac{1 + b_2 \cdot t_0^{-b_3}}{1 + b_2 \cdot t^{-b_3}}$	Cieszewski and Bella (1989)	M5
	$a_2 = X$	$X_0 = t_0^{-b_3}\left(\frac{b_1}{Y_0} - 1\right)$	$Y = b_1/(1 - (1 - b_1/Y_0) \cdot (t_0/t)^{b_3})$	McDill and Amateis (1992)	M6
	$a_3 = X$	$X_0 = -\frac{Ln\left(\frac{(b_1/Y_0 - 1)}{b_2}\right)}{Ln(t_0)}$	$Y = \frac{b_1}{1 + b_2 \cdot t^{-X_0}}$	Ni and Liu (2008)	M7
	$a_1 = b_1 + X$ $a_1 = b_2/X$	$X_0 = \frac{1}{2}(Y_0 - b_1 \pm \sqrt{(Y_0 - b_1)^2 + 4 \cdot b_2 \cdot Y_0 \cdot t_0^{-b_3}})$	$Y = \frac{b_1 + X_0}{1 + b_2/X_0 \cdot t^{-b_3}}$	Cieszewski and Bella (1989)	M8
Bertalanffy–Richards (Bertalanffy 1949, 1957; Richards 1959): $Y = a_1 \cdot (1 - \exp(-a_2 \cdot t))^{a_3}$	$a_1 = X$	$X_0 = \frac{Y_0}{\left(1 - \exp(-b_2 \cdot t_0)^{b_3}\right)}$	$Y = Y_0 \cdot \frac{(1 - exp(-b_2 \cdot t))^{b_3}}{(1 - exp(-b_2 \cdot t_0))^{b_3}}$	Clutter et al. (1983)	M9
	$a_2 = X$	$X_0 = -Ln\left(1 - (Y_0/b_1)^{1/b_3}\right)/t_0$	$Y = b_1\left(1 - \left(1 - \left(\frac{Y_0}{b_1}\right)^{1/b_3}\right)^{t/t_0}\right)^{b_3}$	Clutter et al. (1983)	M10
	$a_3 = X$	$X_0 = \frac{Ln\left(\frac{Y_0}{b_1}\right)}{Ln(1 - exp(-b_2 \cdot t_0))}$	$Y = b_1\left(\frac{Y_0}{b_1}\right)^{\frac{Ln\left(1 - exp\left(-b_2 \cdot t\right)\right)}{Ln\left(1 - exp\left(-b_2 \cdot t_0\right)\right)}}$	Newnham (1988)	M11

Table 2 continued

Base function	Site parameters	Solution for X with initial values (t$_0$, Y$_0$)	Dynamic equation	References	Model
	$a_1 = \exp(X)$ $a_2 = b_2 + b_3/X$	$X_0 = \frac{1}{2}((Ln(Y_0) - b_2 \cdot L_0) \pm \sqrt{(Ln(Y_0) - b_2 \cdot L_0)^2 - 4 \cdot b_3 \cdot L_0})$ with $L_0 = Ln(1 - exp(-b_1 \cdot t_0))$	$Y = Y_0 \cdot \left(\frac{1-exp(-b_1 \cdot t)}{1-exp(-b_{12} \cdot t_0)}\right)^{(b_2 + b_3/X_0)}$	Cieszewski (2004); Krumland and Eng (2005)	M12

convention, a_1, a_2, and a_3 are used to denote parameters in base models, whereas b_1, b_2, and b_3 are employed for global parameters in ADA and GADA formulations.

Development of growth models including environmental data

Stand productivity depends on basal area and site quality, which in turn depends on climate, soil and physiography; these site factors can thus be used to predict the growth capacity of forests (Oliver and Larson 1996). In this study, the relationship between the basal area and dominant height projection functions and the site variables described in Table 1 were evaluated. For this purpose, linear, allometric and logarithmic structures (1–3) were tested, incorporating a single environmental variable in each parameter in order to reduce multicollinearity (Pérez-Cruzado et al. 2014):

$$b_i = c_{i1} + c_{i2} \cdot Z_i \tag{1}$$

$$b_i = c_{i1} \cdot ln\, Z_i + c_{i2} \tag{2}$$

$$b_i = c_{i1} \cdot Z_i^{c_{i2}} \tag{3}$$

where b_i is the expansion of the parameter of the previous model (Table 2: b_1, b_2, or b_3 in ADA and GADA formulations), c_{i1} and c_{i2} are the new model parameters and Z_i is the environmental variable (Table 1) which is being incorporated in the model.

Stand basal area prediction function

The basal area dynamic equation requires a value of basal area at a given age in order to be used for prediction. When this variable is unknown, a prediction function is needed to predict basal area from other stand variables such as plantation age, stand density and site productivity. The basal area growth model of this study is therefore composed of two equations: one for stand basal area projection (as explained in a previous section) and another for prediction.

To ensure compatibility between basal area projection and prediction functions: (1) the prediction function used should be obtained from the base growth model from which the projection function is derived, (2) the site-specific parameter of the prediction function should be related, in linear or non-linear form, to stand variables that do not vary over time (e.g. site index) and (3) the non-site-specific parameters of the base equation must have the same value for both the initialization and projection functions. Compatibility implies that, for a given stand basal area curve obtained from the prediction function, irrespective of which point on the curve is used as the initial condition value in the projection function, the estimated stand basal area will always be a point on that curve.

Additionally, this work also tests the inclusion of environmental factors (climate, soil and physiography variables) in both basal area prediction and projection functions. This is carried out by relating some parameters in linear or non-linear form with environmental variables, in order to explore the possibility of developing a site-dependent function with increased robustness.

Model fitting

The fitting of both projection functions was accomplished using the base-age invariant dummy variables method proposed by Cieszewski et al. (2000) which estimates site-specific effects under the assumption that data measurements always contain measurement and environmental errors (on both the left- and right-hand sides of the model) that must be modelled. Autocorrelation among residuals in the projection functions was expected to be very low in this work because only three inventories were carried out, therefore they were not modelled. This absence of autocorrelation was confirmed by graphical inspection and using the Durbin and Watson's test (1951).

Dominant height and basal area projection functions were fitted simultaneously using the seemingly unrelated regression technique for non-linear models (NSUR) implemented in Model Procedure of SAS/ETS® (SAS Institute Inc. 2004a). This method allows the correlation between residuals of both variables to be taken into account—correlation between both variables being expected since it is reasonable to assume that trees within a plot are ecologically interdependent—which usually results in an increase in parameter estimation efficiency and consistency. The method was accomplished in two steps: (1) separate fitting of each of the two projection functions and selection of the best models, (2) simultaneous re-fitting of the two best equations from the previous step.

In order to maintain compatibility between basal area projection and prediction functions, each parameter estimated in the projection equation (non-site-specific parameters) was substituted into the prediction equation and the latter then fitted individually to obtain estimates of the remaining parameters (site specific parameters). This methodology was selected because it gives priority to the projection function, it being the parameter which is most frequently used to project basal area when initial stand condition can be obtained from a forest inventory (Tomé et al. 2001; Barrio-Anta et al. 2006; Castedo-Dorado et al. 2007).

In addition, several models which included other stand variables and parameters in the base function, and various other growth models were also tested so as to determine the most accurate basal area prediction equation. The best predictor stand variables of basal area for inclusion in the model were found through correlation analysis using Corr Procedure of SAS/STAT® (SAS Institute Inc. 2004b). The presence of heterocedasticity was checked graphically, as well as using specific tests (Breusch and Pagan 1979; White 1980), and was corrected by weighted regression (Harvey 1976).

Model evaluation

The fitted models were graphically and numerically evaluated. Numerical analysis consisted in the calculation of goodness-of-fit statistics, the adjusted coefficient of determination (R^2_{adj}) and the root mean square error (*RMSE*) based on PRESS residuals. The expressions of the statistics are the following:

$$R^2_{adj} = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2} \cdot \frac{n-1}{n-p} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{n-p}} \tag{5}$$

where Y_i and $\hat{Y}_i$ are the observed and predicted values of the dependent variable respectively, $\bar{Y}$ is the average value, n is the total number of datasets and p represents the number of parameters included in the model.

The PRESS residual is the difference between the observed value and the predicted value where the observation in question is omitted, hence error prediction is more realistic (Myers 1986). The resulting statistics were designated as ${R^2_{\mathrm{adj}}}^{\mathrm{P}}$ and $RMSE^{\mathrm{P}}$.

Graphical analysis was accomplished by visual inspection of the observed residuals against estimated values for the detection of possible systematic discrepancies, and graphical overlaying of the curves of the projection functions on the observed trajectories was used to ensure the logical behaviour of models.

Practical use of dominant height projection function to estimate site quality from any given height-age pairing requires the selection of a base age to which site index will be referenced. The selection of a base age therefore becomes an important issue when only one observation of a new individual stand is available. The base age should be selected so that it is a reliable predictor of height at other ages. To address this consideration, different base ages and their corresponding observed heights were used to estimate heights at other ages (both forward and backward) for each plot. The results were compared with the observed values in each plot and the relative error in predictions (*RE*) was then calculated as follows:

$$RE\,(\%) = \sqrt{\frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2/(n-p)}{\bar{Y}}}\cdot 100 \tag{6}$$

where Y_i and $\hat{Y}_i$ are the observed and predicted values of the dependent variable respectively, $\bar{Y}$ is the average value, *n* is the total number of datasets and *p* represents the number of parameters included in the model.

Results and discussion

Dominant height and basal area projection functions

The estimated parameters and goodness-of-fit statistics based on PRESS residuals for individually-fitted dominant height and basal area projection functions are shown in Table 3. In the selection process, the models for both variables were analysed and compared using the statistical results, residuals analysis and the biological behaviour shown in the graphs of the model curves in relation to the observed plot data. Most of the models explained more than 90 % of the total variation although some resulted in no significant parameters, even after testing a wide range of initial values of the parameter in the fitting process of the model. With regard to dominant height, convergence was not found in the parameter estimation process with the GADA models M4 and M8.

Finally, in accordance with the established criteria, the model formulation M10 (Clutter et al. 1983), with a_2 as a specific site parameter, was selected for the two projection functions; dominant height and basal area. This model has also been found to be one of the best in other similar studies, for example, Barrio-Anta et al. (2008). A simultaneous fit of both models was carried out and the fitting statistics and parameter estimates are shown in Table 4. The models selected were ADA and polymorphic equations, albeit with a constant single asymptote (b_1 parameter), which is not a problem as long as growth curve behaviour is appropriate for the age range for which the model will be used (Bailey and Clutter 1974). In the resulting projection functions, all parameters were significant at the 1 % level. Dominant height and basal area models explained 98.37 and 96.08 % of observed variability respectively, while their respective $RMSE^{P}$ values were 0.41 m and 1.43 $m^2\ ha^{-1}$. The results of the specific tests and graphical analysis showed that there were no heteroscedasticity problems, nor trends in residues against estimated value graphs, and confirmed the absence of autocorrelation in the models.

Table 3 Parameters estimated and their approx. *p* values, results of Durbin–Watson's test (*D–W*), *p* value for testing positive ($\Pr < D\text{–}W$) and negative autocorrelation ($\Pr > D\text{–}W$) and fit statistics based on PRESS residuals $^{(\mathrm{P})}$ for dominant height and basal area projection functions tested

Variable	Model	b_1	b_2	b_3	*D–W*	$\Pr < D\text{–}W$	$\Pr > D\text{–}W$	$RMSE^{\mathrm{P}}$	$R^{2\mathrm{P}}_{\mathrm{adj}}$
Ho	M1	–	10.382 (0.1277)	0.128 (0.0924)	2.809	0.742	0.258	0.4415	0.9812
	M2	1478.38 (0.5589)	–	0.220 (0.0035)	2.866	0.810	0.190	0.4097	0.9838
	M3	202.635 (0.3311)	4.834 (<0.0001)	–	2.591	0.441	0.559	0.7289	0.9488
	M5	–	42.786 (0.0716)	1.267 (<0.0001)	2.810	0.741	0.259	0.4454	0.9809
	M6	47.024 (<0.0001)	–	1.401 (<0.0001)	2.840	0.760	0.240	0.4025	0.9844
	M7	33.099 (<0.0001)	18.159 (<0.0001)	–	2.584	0.430	0.571	0.7456	0.9464
	M9	–	0.071 (0.1079)	1.290 (<0.0001)	2.810	0.740	0.260	0.4451	0.9809
	M10	35.988 (<0.0001)	–	1.460 (<0.0001)	2.842	0.763	0.237	0.4026	0.9844
	M11	566.892 (0.5795)	0.008 (0.5492)	–	2.979	0.935	0.065	0.4354	0.9817
	M12	0.114 (0.0105)	−1.131 (0.4544)	9.441 (0.0966)	2.891	0.831	0.169	0.4106	0.9837
G	M1	–	7.646 (<0.0001)	0.492 (0.0003)	2.203	0.012	0.9879	1.7253	0.9425
	M2	380.456 (0.1741)	–	0.609 (<0.0001)	2.484	0.220	0.780	1.3281	0.9659
	M3	107.58 (0.0029)	6.925 (<0.0001)	–	2.291	0.078	0.922	2.2906	0.8983
	M4	−17.213 (0.2774)	126.554 (0.1311)	0.764 (<0.0001)	2.423	0.152	0.848	1.4448	0.9596
	M5	–	111.770 (<0.0001)	2.569 (<0.0001)	2.256	0.023	0.977	1.8236	0.9358
	M6	61.984 (<0.0001)	–	2.695 (<0.0001)	2.494	0.245	0.755	1.4921	0.9570
	M7	42.129 (<0.0001)	112.26 (<0.0001)	–	2.388	0.223	0.777	2.3190	0.8960
	M8	7.197 (0.7762)	4331.18 (0.1472)	2.847 (<0.0001)	2.369	0.088	0.912	1.6531	0.9472
	M9	–	0.247 (0.0002)	3.297 (<0.0001)	2.226	0.016	0.984	1.7805	0.9388
	M10	66.052 (<0.0001)	–	3.667 (<0.0001)	2.490	0.236	0.764	1.4162	0.9612
	M12	0.388 (<0.0001)	−1.823 (0.4885)	24.453 (0.0348)	2.441	0.164	0.837	1.4904	0.9570

Table 4 Parameters estimated and their approx. *p* values, results of Durbin–Watson's test (*D–W*), *p* value for testing positive (Pr < *D–W*) and negative autocorrelation (Pr > *D–W*) and fit statistics based on PRESS residuals $^{(P)}$ of the simultaneous fit for the model selected

Variable	Model	b_1	b_3	*D–W*	Pr < *D–W*	Pr > *D–W*	$RMSE^P$	R^{2P}_{adj}
Ho	M10	48.056 (<0.0001)	1.357 (<0.0001)	2.841	0.771	0.230	0.4109	0.9837
G	M10	67.281 (<0.0001)	3.616 (<0.0001)	2.497	0.250	0.750	1.4247	0.9608

With respect to base age, it was observed that the age range from 3.5 to 4.5 years had the lowest relative error. Therefore, the age of 4 years was proposed as the base age to classify site productivity for this type of stand. At this reference age, the values of 5, 8, 11 and 14 m were established for the dominant height growth curves and 4, 14, 24 and 34 m^2 ha^{-1} for basal area growth curves, depending on site quality. Figure 1 shows the projection functions for dominant height (a) and basal area (b) based on the data in Table 4.

Development of growth models including environmental data

The individual projection functions (M10) were expanded using structures 1–3 and the different environmental variables (Table 1) producing good results in some cases. Finally, after simultaneous fitting of the basal area and the dominant height functions, five models which included the expansion of parameter b_3 (Table 5) were selected as the best models, in accordance with the criteria explained in the prevision section for projection functions.

The climate variables incorporated in the models are associated with warm temperatures—mean temperature (*TMW*) and mean of maximum temperatures (*TMAX*) both for the warmest month and mean summer temperature (*TSU*)—as well as summer precipitation (*PS*). The inclusion of these parameters confirms the fact that *E. nitens* growth is affected by climate factors in summer: Although annual total precipitation in the area is approximately 1,250 mm, well within the requirements for the species, which have been established as between 750 and 1,750 mm $year^{-1}$ (FAO 1981; Booth and Pryor 1991), rainfall in the study area is in fact considerably reduced in summer, which can affect tree growth,

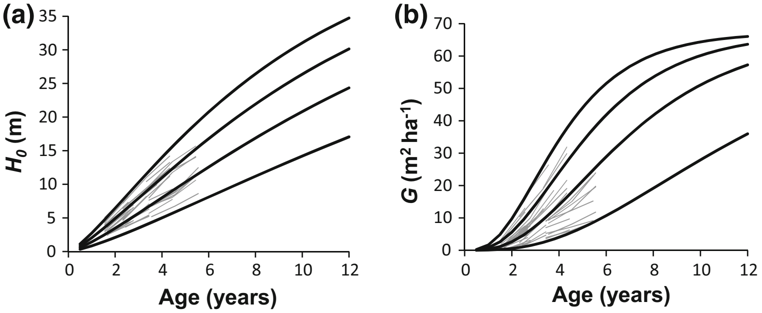

Fig. 1 **a** Dominant height (*Ho*) growth curves for values of 5, 8, 11 and 14 m for dominant height and **b** basal area (*G*) growth curves for values of 4, 14, 24 and 34 m^2 ha^{-1} for basal area, (both in *bold*) at a base age of 4 years, overlaid on the observed values over time (in *grey*)

Table 5 Parameters estimated, results of Durbin–Watson's test (D–W), *p* value for testing positive (Pr < DW) and negative autocorrelation (Pr > DW) and fit statistics based on PRESS residuals $^{(P)}$ for dominant height and basal area models including soil and climate variables

Model	Variable	Parameter	D–W	Pr < D–W	Pr > D–W	$RMSE^P$	R^{2P}_{adj}
OM	*Ho*	$b_1 = 22.638$ $b_3 = 0.152 \cdot OM$	2.553	0.360	0.640	0.5329	0.9726
	G	$b_1 = 55.786$ $b_3 = 8.534 – 0.359 \cdot OM$	2.711	0.420	0.580	1.2199	0.9712
SAND	*Ho*	$b_1 = 21.716$ $b_3 = 0.043 \cdot SAND$	2.580	0.161	0.839	0.6779	0.9557
	G	$b_1 = 57.152$ $b_3 = 2.420 + 0.035 \cdot SAND$	2.416	0.106	0.894	1.3836	0.9630
TMW	*Ho*	$b_1 = 38.438$ $b_3 = 0.086 \cdot TMW$	2.861	0.800	0.200	0.4110	0.9837
	G	$b_1 = 66.646$ $b_3 = 39.929 – 2.176 \cdot TMW$	2.482	0.207	0.793	1.3503	0.9648
TMAX	*Ho*	$b_1 = 35.191$ $b_3 = 0.066 \cdot TMAX$	2.873	0.818	0.182	0.4120	0.9836
	G	$b_1 = 58.427$ $b_3 = 30.268 – 1.185 \cdot TMAX$	2.342	0.061	0.939	1.2588	0.9694
TSU	*Ho*	$b_1 = 36.723$ $b_3 = 0.092 \cdot TSU$	2.861	0.798	0.202	0.4120	0.9836
	G	$b_1 = 65.726$ $b_3 = 37.844 – 2.173 \cdot TSU$	2.493	0.226	0.774	1.3327	0.9657
PS	*Ho*	$b_1 = 47.671$ $b_3 = 0.009 \cdot PS$	2.830	0.746	0.254	0.3995	0.9846
	G	$b_1 = 66.688$ $b_3 = -27.881 + 0.215 \cdot PS$	2.461	0.175	0.825	1.2934	0.9676

OM organic matter content of the soil (%), *SAND* sand content of the soil (%), *TMW* mean temperature of the warmest month (°C), *TMAX* mean of maximum temperatures of the warmest month (°C), *TSU* mean summer temperature (°C), *PS* summer precipitation (mm)

as has been shown in another study on the same permanent sample plots (González-García et al. 2015). Moreover, higher summer temperatures increase tree evapotranspiration, which together with the reduction in soil water content, means that growth is likely to be negatively affected in this season.

The soil variables included in the models were organic matter content (*OM*) and sand content (*SAND*), which emphasizes the significance of these variables for this kind of plantation in the distribution area, and confirming the soil requirements of the species, which shows better development in well drained loamy soils (FAO 1981). The high values of organic matter content in our soils (8–22 %) is the result of complex interactions between vegetation, soil use and climate, which makes it difficult to determine a direct relationship between organic matter content and stand productivity.

As shown in Fig. 2, despite accuracy being high for all the models ($R^2_{adj} > 0.95$), in the model which includes sand content of the soil, the accuracy of the dominant height model decreased with respect to the equivalent model without environmental factors (Table 4)

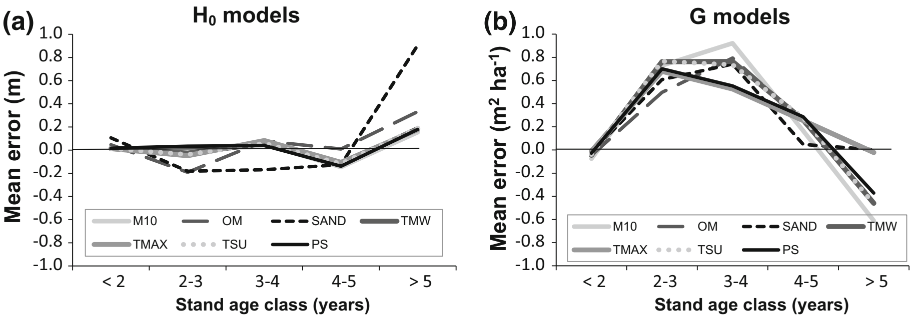

Fig. 2 Mean errors of dominant height (**a**) and basal area (**b**) estimation using the models developed. M10 is the simple model and the others are expanded models which include either organic matter content of the soil (*OM*), sand content of the soil (*SAND*), mean temperature of the warmest month (*TMW*), mean of maximum temperatures of the warmest month (*TMAX*), mean summer temperature (*TSU*) or summer precipitation (*PS*)

while, at the same time, the basal area function incorporating sand content was more accurate than that without. Nonetheless, for the models including climate variables, $R_{\mathrm{adj}}^{2\ \mathrm{P}}$ remained practically the same as in the model without environmental information with respect to dominant height function and rose slightly for the basal area equation. Generally, expanded models which include climate and soil variables are more robust due to them incorporating geographical variability (Nunes et al. 2011), and therefore generate more interesting results when contrasting conditions are available. Thus, although some the models including environmental data developed here have a lower accuracy than the corresponding models without site information, they can still be considered to generate fairly accurate growth curves of dominant height and basal area at the regional level because they can be adapted to incorporate short-term changes in climatic conditions. However, they must be used carefully because they are not suitable for predicting responses to global climate change (Nunes et al. 2011).

Furthermore, it is important to highlight that the interaction between tree growth and environmental factors is a complex one due to the fact that, for example, climate conditions have an impact on the physiological processes of the tree (Pallardy and Kozlowski 1979). As such, an extension of this study would be to take into account other tools, such as ecophysiological models, which will provide a better understanding of these relationships.

Basal area prediction function

The basal area prediction function was developed after the projection function. To ensure the compatibility of both equations, the Bertalanffy-Richards base model was used as the base equation (Table 2). The values of the parameters a_1 and a_3 were replaced by the value of their equivalent parameters, b_1 and b_3, in the derivative function (M10) (*Compatible function*). After correction of heterocedasticity, the model explained <40 % of observed variability (Table 6).

Other stand variables and formulations were also included in the base model to evaluate potential improvements in the equation prediction capacity. Dominant height was the variable which was most correlated to basal area, with a Pearson coefficient of 0.8613, followed by stand age and site index, with coefficients of 0.6639 and 0.3570 respectively.

Table 6 Parameters estimated and their approx. *p* values and fit statistics based on PRESS residuals $^{(P)}$ for the basal area prediction functions: compatible function, accurate function and the functions derived from the latter which includes site environmental parameters

Prediction function	Model		a_1	a_2	a_3	$RMSE^{P}$	R^{2P}_{adj}
$G = a_1(1 - exp(-a_2t))^{a_3}$	Compatible		67.281	0.2585 (<0.0001)	3.616	5.9604	0.3206
			a_1, a_3: fixed parameters M10				
$G = \exp\left(\frac{a_1+a_2Ho}{Ho+t}\right)$	Accurate		−17.429 (<0.0001)	5.440 (<0.0001)	–	3.6710	0.7390
$G = \exp\left(\frac{a_1+a_2Ho+a_3X}{Ho+t}\right)$	Site	$X = OM$	−14.022 (<0.0001)	5.508 (<0.0001)	−0.324 (0.0191)	2.8540	0.8459
		$X = TMW$	68.256 (0.0005)	5.621 (<0.0001)	−5.224 (<0.0001)	2.7627	0.8565
		$X = TMAX$	22.274 (0.0275)	5.620 (<0.0001)	−1.852 (<0.0001)	2.7238	0.8600
		$X = TSU$	50.187 (<0.0001)	5.609 (<0.0001)	−4.384 (<0.0001)	2.7404	0.8589
		$X = PS$	−75.431 (<0.0001)	5.653 (<0.0001)	0.384 (<0.0001)	2.8277	0.8497

OM organic matter content of the soil (%),*TMW* mean temperature of the warmest month (°C), *TMAX* mean of maximum temperatures of the warmest month (°C), *TSU* mean summer temperature (°C), *PS* summer precipitation (mm)

All were significant (p value <0.001), hence they were considered in the models tested. In contrast, the relation between the number of trees per hectare and basal area was not significant (p value >0.05) and therefore it was not taken into account in the models. Weighted regression (Harvey 1976) was applied to all the models due to the absence of homoscedasticity. Finally, due to the low accuracy of the base equation, an attempt to improve it was made by introducing slight modifications. Although this resulted in a great improvement in accuracy, compatibility between prediction and projection functions was not ensured when the modified prediction equations were used to calculate basal area. As a result it was decided that the best strategy in this case was to test other models and combinations of explanatory stand variables (age, dominant height and site index). Finally, the most accurate model was adapted from the Clutter model (1963) which includes dominant height and stand age as predictor variables (*Accurate function*). The adapted model explained 73.90 % of observed variability, with an $RMSE^{P}$ of 3.66 m^2 ha^{-1} calculated according to PRESS residuals, and showed a normal pattern after heterocedasticity correction. The improvement with respect to the compatible function was >50 % in R^{2P}_{adj}.

The basal area prediction functions including environmental factors (*Site functions*) are shown in Table 6. Five functions were selected according to fit statistics and their biological behaviour, in the same way as for the projection functions. Most of the variables tested (see Table 1) improved the accuracy of the base model, the most notable being the soil variable, *OM* and the climate variables *TMW*, *TMAX*, *TSU* and *PS*, which improved the R^{2P}_{adj} of the function by more than 13 %, in addition to increasing the flexibility of the model. These results support those obtained in the projection functions section, which emphasizes the importance of these factors for *E. nitens* growth in the region.

Growth and yield

The models developed in this research could play an important role in *E. nitens* short rotation woody crops plantations because they can help to optimize forest management strategies (i.e. indicating the optimal rotation of the stands) so that maximum advantage can be taken of plantations in the area. Additionally, the outputs which projection functions provide can be used as the inputs for biomass or volume models for a given age; essential tools for forest managers in this kind of stand.

Growth and biomass production of *E. nitens* woody crops were estimated for the site index classes determined in this study using the allometric above-ground biomass equation developed for such plantations (see González-García et al. 2013) at different stand ages. The results showed that at the stand age of 6 years, accumulated stand biomass varied from 110.72 Mg ha^{-1} for the highest site index ($SI = 14$ m) to 15.79 Mg ha^{-1} for the lowest ($SI = 5$ m).

Figure 3 shows the patterns of increment in stand biomass for the stands of different site quality index using mean annual increment (*MAI*) and Current Annual Increment (*CAI*). Optimal stand age for the harvest was determined using the point where *MAI* and *CAI* curves intersected, and is therefore different for each site index class, and ranged from 6 years for the highest site quality, to 12 for the lowest. These optimal rotation lengths are, of course, extrapolations, as are the fitted curves presented in Fig. 1, since they concern stand ages not included in the supporting dataset. The average biomass yield, expressed using *MAI*, at the end of the projected rotation was between 3.25 and 18.45 Mg ha^{-1} $year^{-1}$, according to site quality, these yields being in the same range or above that of the highest quality sites in other short rotation species in Europe (Laureysens et al. 2004; Fischer et al. 2005; Trnka et al. 2008), which have shown good growth responses in the study area. Other results for *E. nitens* short rotation crops in New Zealand (Sims et al.

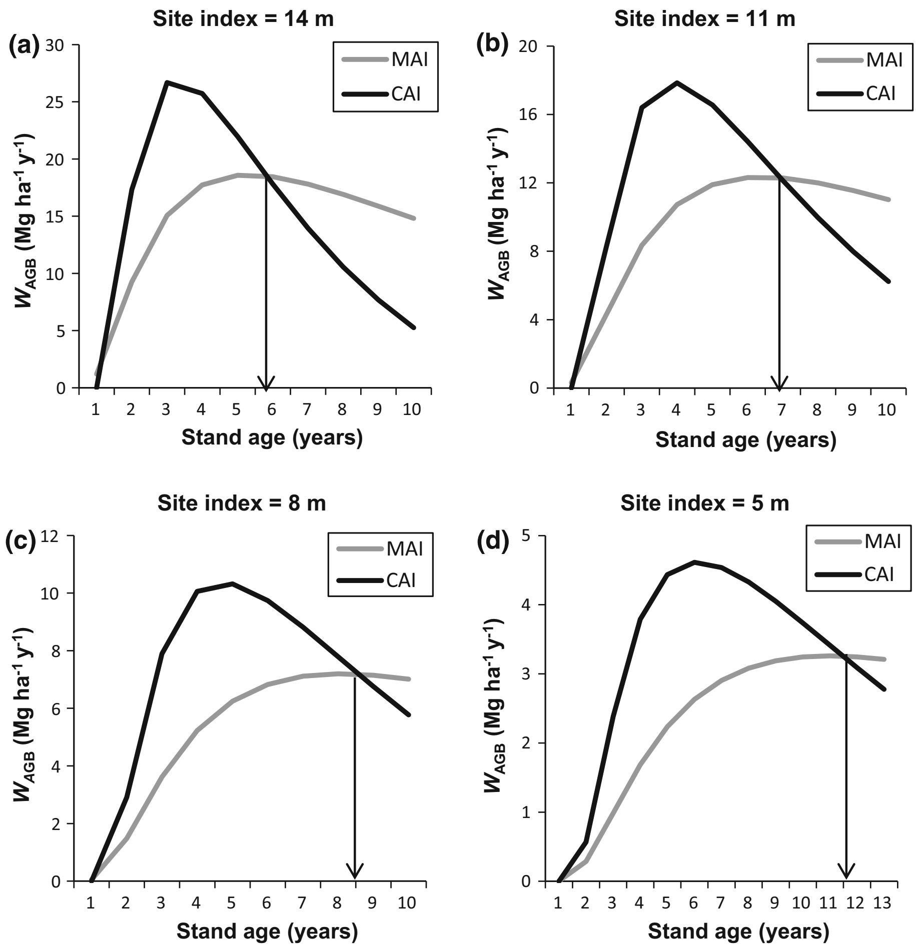

Fig. 3 Patterns of growth and stand biomass production for *E. nitens* woody crops. *MAI* is the Mean Annual Increment (Mg ha^{-1} year^{-1}) and *CAI* is the Current Annual Increment (Mg ha^{-1} year^{-1}) of above-ground biomass (W_{AGB}). The point where *MAI* and *CAI* curves intersect defines the optimal rotation age of the stand

2001) showed yield range to be from 3 to 7 Mg ha^{-1} year^{-1}, in line with the worst site qualities in the present work. Furthermore, the results obtained in this study are very similar to those found in a study using the dominant height GADA model developed by Pérez-Cruzado et al. (2013) from stem analysis of the same species. While their model, which was fitted for a stand density of between 1,100 and 1,600 trees ha^{-1}, presents site index curves of 8, 12, 16 and 20 m at a base age of 6 years, if the results are interpolated to the reference age of 4 years used in the present study the results for the two studies in relation to the dominant height model would be practically identical. The above-ground biomass (W_{AGB}) predictions for this growth model ranged from 7 to 36 Mg ha^{-1} year^{-1} depending on site, with an average of 17 Mg ha^{-1} year^{-1} for optimal rotation. Additionally, the productivity of W_{AGB} was 21.5 Mg ha^{-1} year^{-1} for the *E. nitens* static model developed taking into account a planting density of 2,400 trees ha^{-1} and a rotation of 11 years (Pérez-Cruzado et al. 2011a).

Conclusions

The best models obtained in this study for dominant height and basal area projection functions were polymorphic ADA models with single asymptote. The models provided accurate predictions for *E. nitens* short rotation woody crops.

The range of average biomass yield in *E. nitens* woody crop stands was from 3.25 to 18.45 Mg ha^{-1} y^{-1} at the end of the rotation, which was projected as between 6 and 12 years, depending on site quality.

This study also shows that stand growth can be predicted by including environmental factors in models, and that this produces good estimations which are useful in terms of suiting the model to small variations in site conditions.

Since *E. nitens* short rotation woody crops in the study zone are currently concentrated in a homogenous area where there is no great variability in climatic data, the future incorporation into the model of information about plantations in neighbouring areas, including the respective environmental data, would be of great value in increasing data variability and facilitating readjustments of the model.

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16 February, 2015

To Whom It May Concern:

I confirm that Marta González-García's article, "Application of a process-based model for predicting the productivity of Eucalyptus nitens bioenergy plantations in Spain" was accepted for publication by Global Change Biology Bioenergy on 11 February, 2015

It will soon be transferred publishing company, Wiley-Blackwell, for final proofing and corrections.

Best regards,
Rachel Shekar

Rachel Shekar

Executive Editor
GCB Bioenergy

ANNEX II. Resumen de la tesis y conclusiones

Debido a que el cuerpo general de la Tesis está en inglés por requerimientos académicos se presenta un resumen extendido en español. Este resumen se centra en la parte introductoria de la Tesis incluyendo los objetivos de la misma y en la discusión general de los resultados junto con las conclusiones finales obtenidas.

1. Justificación de la Tesis

Eucalyptus nitens es una especie con características apropiadas para la producción de biomasa en el noroeste de España. Las plantaciones de eucalipto en este área han contribuido firmemente al desarrollo del medio rural (Vázquez et al., 1997). Por otra parte, Galicia, ubicada en el extremo noroeste del país, posee terrenos actualmente inutilizados y colonizados por matorral con bajo valor ecológico y/o superficies agrícolas abandonadas (DGCN, 2012).

El interés por el fomento de las energías renovables con el objetivo de frenar el cambio climático y reducir la dependencia energética junto con los beneficios sociales asociados al uso de la biomasa forestal han provocado que en los últimos años las plantaciones bioenergéticas de *Eucalyptus* se hayan extendido por el noroeste de España.

La presente Tesis Doctoral se centra en el estudio de estas masas para proporcionar las herramientas y la información necesaria para llevar a cabo una gestión forestal sostenible.

2. El uso del eucalipto como cultivo energético en el noroeste de España

La biomasa es el material biológico almacenado en las plantas a través del proceso de la fotosíntesis que se compone fundamentalmente de carbohidratos donde los más importantes son la celulosa, la hemicelulosa y la lignina.

La biomasa puede clasificarse en función de la naturaleza del material en plantas herbáceas, plantas leñosas (biomasa lignocelulósica), plantas acuáticas y residuos orgánicos producidos por animales (McKendry, 2002).

Las biomasa lignocelulósica es aquella que posee un alto contenido en celulosa y lignina (Shelly, 2008), es decir las especies leñosas o arbóreas. Esta biomasa puede ser de dos tipos a su vez: biomasa productiva generada en plantaciones energéticas o biomasa residual proveniente de distintas actividades forestales como claras, podas, cortas finales o residuos del procesado de la madera (Long et al., 2013).

El aprovechamiento de la biomasa residual posee múltiples ventajas ya que se obtiene un rendimiento de un residuo sin o con escaso valor que abandonado en el bosque puede contribuir a la propagación de incendios, plagas o enfermedades (Shelly, 2008; Soliño, 2010). Sin embargo, estos residuos pueden ser insuficientes para cubrir la demanda energética en el futuro en algunas regiones y por ello se recurre a la biomasa productiva cuya disponibilidad es más segura si se realiza una adecuada planificación de los recursos.

Los cultivos energéticos leñosos son especies de rápido crecimiento gestionados en altas densidades de plantación y turnos cortos para intentar obtener la mayor producción de biomasa en el menor intervalo de tiempo (Mckay, 2011). Estos cultivos se conocen en inglés como Short Rotation Forestry (*SRF*), Short Rotation Woody Crops (*SRWC*) o Short Rotation Coppice (*SRC*) cuando se emplea el rebrote del cultivo durante los siguientes turnos eliminando con ello los costes de plantación.

La producción de biomasa mediante *SRWC* requiere una gestión intensiva donde para aumentar la productividad de la plantación se requiere llevar a cabo la selección de la especie, variedad o clon, la densidad de plantación, el turno de corta e implementar técnicas culturales como fertilización, riego o control de malas hierbas (Mitchell, 1995). Los híbridos de chopo (*Populus* spp.), los sauces

(*Salix* spp.) y las especies del género *Eucalyptus* son los cultivos energéticos leñosos más comúnmente empleados debido a sus buenos crecimientos y sus características favorables para producción de energía (Armstrong et al., 1999; Sims et al., 2001; Sochacki et al., 2007).

El género *Eucalyptus*, originario de Australia, ha sido extendido por numerosos países alrededor del mundo (Rockwood et al., 2008). Su aprovechamiento ha estado centrado en la industria de pasta de papel, los productos sólidos o la obtención de leñas. Sin embargo, en los últimos años con el auge de las energías renovables se ha producido un aumento en el uso del eucalipto para bioenergía (Rockwood et al., 2008; Stanturf et al., 2013). Este género presenta múltiples ventajas para este propósito ya que posee un rápido crecimiento siendo adecuado para desarrollarse en turnos cortos, tolera un amplio rango de tipos de suelos y presenta gran capacidad para crecer en suelos con bajo contenido en nutrientes (Leslie et al., 2012; Mughini et al., 2014; Rockwood et al., 2008; Stanturf et al., 2013).

Eucalyptus nitens (Deane & Maiden) Maiden fue introducido en el noroeste de España como alternativa a *Eucalyptus globulus* Labill., la principal especie de eucalipto usada en el norte de la península, debido a su resistencia a las bajas temperaturas (Booth y Pryor, 1991; Tibbits y Reid, 1987). Esta especie ha demostrado obtener altas productividades en el norte de España (Pérez-Cruzado et al., 2011; Pérez-Cruzado y Rodríguez-Soalleiro, 2011) obteniendo mejores producciones en bioenergía que otras especies de eucalipto como *E. globulus*, *E. viminalis*, *E. regnans* o chopo, además de presentar un alto poder calorífico (Pérez et al., 2011). Sin embargo, la principal desventaja de esta especie es su baja capacidad de rebrote que podría estar asociada a la procedencia McAlister (Sims et al., 2001, 1999).

3. La modelización de las plantaciones energéticas

El desarrollo de herramientas que cuantifiquen la producción de biomasa es esencial en la gestión e investigación forestal. Los estudios de la productividad del ecosistema, del flujo de energía y nutrientes y el ciclo de carbono requieren disponer de información sobre la producción de biomasa (Burkhart y Tomé, 2012). Adicionalmente, en plantaciones bioenergéticas donde todos los componentes del árbol, incluyendo las fracciones de copa, son aprovechados para la producción de energía, la biomasa es la variable que determina la productividad de la plantación y por ello es fundamental disponer de modelos o herramientas que permitan realizar una estimación precisa de la misma.

Los modelos de crecimiento forestales describen la evolución de un individuo o una masa en el tiempo. Son herramientas muy útiles en la gestión forestal y junto con los modelos de producción permiten conocer la biomasa en un momento determinado del desarrollo de la plantación y con ello apoyar la toma de decisiones.

Los modelos pueden clasificarse en empíricos, basados en datos experimentales, o mecanísticos, los cuales incluyen procesos fisiológicos relacionados con el crecimiento del árbol. Los modelos empíricos son los más usados frecuentemente en gestión forestal (Pretzsch, 2010) pero presentan limitaciones ya que su rango de aplicación es reducido (Fontes et al., 2010). Por otra parte, los modelos de procesos son modelos mecanísticos que tienen en cuenta la fisiología de las plantas considerando procesos como la fotosíntesis o la respiración que dependen a su vez de condiciones ambientales (Landsberg y Sands, 2010). Estos modelos son valorados desde el punto de vista forestal sin embargo en ocasiones se consideran complejos debido a la multitud de variables que requieren (Bartelink y Mohren, 2004).

Las plantaciones energéticas implican una mayor extracción de nutrientes que las plantaciones tradicionales para madera o pasta (Nguyen Thé et al., 2010) debido a sus altas densidades de plantación, turnos cortos y la cosecha de todos los componentes del árbol en su aprovechamiento. Esto puede producir la reducción de la fertilidad del suelo y por ello su potencial productivo en el futuro puede verse comprometido (Raulund-Rasmussen et al., 2008). Por tanto, es fundamental la realización de un análisis nutricional de las plantaciones que permita cuantificar la extracción de nutrientes al final del turno para llevar a cabo su reposición y evitar la degradación edáfica.

Por otra parte, la estimación del contenido de carbono en las plantaciones ha adquirido importancia en los últimos años debido al papel que juegan los bosques en la mitigación del cambio climático (Ruiz-Peinado et al., 2012). Esta cuantificación adquiere importancia en los cultivos energéticos ya que uno de los incentivos de su uso es la captura del CO_2 atmosférico para reducir el efecto invernadero.

Complementariamente con el resto de cuestiones, desde el punto de vista económico, el estudio de las características energéticas de la biomasa para conocer el potencial energético de las plantaciones bioenergéticas es fundamental.

4. Objetivos de la tesis

El objetivo principal de la Tesis Doctoral fue evaluar la productividad de las plantaciones de *Eucalyptus nitens* de turno corto para la producción de bioenergía en el noroeste de España.

Los objetivos específicos fueron los siguientes:

- Desarrollar herramientas predictivas para estimar la producción de biomasa aérea y volumen a nivel de árbol y de masa (**Capítulo 2**).
- Estudiar el crecimiento de las plantaciones y su productividad considerando la influencia de factores ambientales mediante el uso de

distintos modelos: un modelo dinámico de crecimiento incorporando variables ambientales (**Capítulo 3**) y un modelo de procesos que evalúa distintas estrategias de gestión (**Capítulo 4**).

- Evaluar el contenido de nutrientes y carbono de acuerdo con la productividad del sitio además de cuantificar el potencial energético de la biomasa (**Capítulo 5**).

5. Principales resultados y discusión

La biomasa leñosa es una de las fuentes de energía renovable con mayor potencial en la UE, que contribuye a alcanzar los objetivos políticos y ambientales en el consumo total de energía además de producir otros beneficios económicos y sociales. Dentro de este tipo de biomasa, *SRWC* y específicamente la especie *E. nitens* tiene un gran potencial en el noroeste de España (Pérez-Cruzado et al., 2011; Pérez-Cruzado y Rodríguez-Soalleiro, 2011) por lo que puede ser empleada para la producción bioenergética en este área.

El desarrollo de herramientas de modelización así como información adicional generada a partir de los datos recogidos en las plantaciones energéticas es esencial para una gestión sostenible y económicamente viable de los cultivos energéticos de *E. nitens*.

Los resultados del **Capítulo 2**, centrados en el desarrollo de herramientas de estimación de la producción, mostraron que la ecuación de biomasa fue el método más preciso para estimar la fracción del fuste, aunque cualquiera de las metodologías estudiadas en dicho capítulo podría ser aplicada con buenos resultados. Por otra parte, para la fracción de copa el modelo de *BEF* y la ecuación de biomasa proporcionan las mejores predicciones mientras que a su vez esta última fue la mejor herramienta de predicción para la biomasa aérea. En ambas fracciones, copa y biomasa aérea, el *BEF* constante subestimó la producción al igual que ocurrió en otros estudios de plantaciones jóvenes (Brown y Schroeder, 1999; Fang et al., 1998) y por tanto no se recomienda el uso de esta metodología cuando sea posible emplear otros métodos ya que puede provocar errores considerables (Guo et al., 2010; Tobin y Nieuwenhuis, 2007).

Las mejores variables predictoras en las ecuaciones de biomasa a nivel de árbol fueron el diámetro normal y la altura de la copa viva para la fracción de biomasa de copa y el diámetro normal y la altura total para la biomasa de fuste. Resultados similares han sido obtenidos en otros estudios (Sochacki et al., 2007; Zewdie et al., 2009). Para las ecuaciones de biomasa a nivel de masa, las variables que proporcionaron la mayor precisión fueron la altura dominante y el área basimétrica. En la evaluación del *BEF* de árbol la altura total fue la variable que presentó una mayor relación con la copa y el árbol completo, al igual que ocurrió en otros estudios previos (Sanquetta et al., 2011), seguido por el diámetro y la edad del árbol. Por otra parte, el valor del *BEF* del fuste a nivel de árbol se mantuvo constante cuando se evaluaron distintas variables de árbol. Finalmente a nivel de masa, la altura dominante, el diámetro medio cuadrático, el área basimétrica y la edad presentaron la mayor relación con el *BEF*, cuyos valores tendieron a estabilizarse con la edad de la masa (Sanquetta et al., 2011; Soares y Tomé, 2012).

Por tanto, la selección de las herramientas para predecir la producción en plantaciones energéticas de *E. nitens* a nivel de árbol o de masa (ecuaciones de biomasa simplificadas o precisas, *BEF* constantes, modelos de *BEF* o modelos de volumen) se realiza en función de las variables disponibles y del nivel de precisión requerido (**Capítulo 2**).

El modelo seleccionado para las funciones de proyección de altura dominante y área basimétrica del modelo dinámico ajustado en el **Capítulo 3** fue un modelo ADA polimórfico con una asíntota constante. Dicho modelo ha sido empleado previamente para el ajuste de modelos de crecimiento de otras especies como *Populus* spp. (Barrio-Anta et al., 2008). En esta Tesis, las curvas de calidad de estación se establecieron para valores de altura dominante de 5, 8, 11 y 14 m a la edad de referencia de 4 años (índice de sitio) y el turno óptimo proyectado estuvo entre 6 y 12 años en función también de la calidad de estación. El crecimiento medio de la biomasa aérea obtenido osciló entre 3 y 18 Mg ha^{-1} año^{-1} al final del turno. Estos rangos de producción son muy similares a los obtenidos por Pérez-Cruzado et al. (2013) en el modelo GADA de altura dominante ajustado para masas de esta especie en la región con densidades de plantación inferiores (< 1500 pies ha^{-1}) a las estudiadas en esta Tesis.

En los últimos años, la incorporación de variables ambientales en los modelos forestales se han convertido en un factor clave (Bravo-Oviedo et al., 2011; Nunes et al., 2011). El modelo dinámico ajustado (**Capítulo 3**) estudió la posibilidad de incluir variables ambientales lo cual mostró un nivel predictivo similar al modelo que no las incorporaba. Además, se ha demostrado que la incorporación de estas variables en los modelos da lugar a funciones más flexibles y robustas ya que pueden tener en cuenta pequeñas variaciones en las condiciones ambientales (Nunes et al., 2011) por lo su incorporación puede considerarse un aspecto importante. Las variables edáficas materia orgánica y contenido de arena y las variables climáticas relacionadas con la temperatura y precipitación en verano fueron las variables seleccionadas para el modelo de crecimiento. Por otra parte, se seleccionó una estructura lineal de expansión de los parámetros para la incorporación de dichas variables en el modelo a diferencia de otros estudios similares donde existía una alta variabilidad ambiental y se tuvieron en cuenta otro tipo de estructuras (Pérez-Cruzado et al., 2014).

Para la función de inicialización de área basimétrica se seleccionaron la altura dominante y la edad de la masa como variables predictivas (**Capítulo 3**). La función seleccionada explicó más del 50 % de la variabilidad de los datos comparándola con la ecuación base compatible de la función de proyección de área basimétrica del modelo de crecimiento. La precisión y la robustez de la función de inicialización de área basimétrica se vieron incrementadas con la incorporación de las variables ambientales, siendo dichas variables muy similares a las citadas anteriormente para el modelo de crecimiento.

En el **Capítulo 4** se observó una buena relación entre los valores observados y los predichos por el modelo 3-PG para las variables productivas lo que indicó que la parametrización realizada para el modelo fue adecuada. A pesar de que el modelo fue capaz de estimar el crecimiento de la masa para un amplio rango de sitios, las mejores predicciones fueron para masas de productividad media lo que puede atribuirse a la limitación de datos disponibles y a las incertidumbres en relación con la profundidad y el contenido de agua en el suelo (Landsberg y Sands, 2010).

Las masas con densidades de plantación de 3000 pies ha^{-1} produjeron un crecimiento medio en biomasa similar a aquellas con mayores densidades de plantación (**Capítulo 4**), obteniendo un 20 % de incremento en el diámetro medio del fuste además de menores costes asociados a su producción. Por tanto, estos resultados sugieren que una menor densidad de plantación puede ser más adecuada para plantaciones bioenergéticas encontrándose dichas densidades de plantación en el mismo rango que otros estudios de *Eucalyptus* (González et al., 2011; Sims et al., 1999). Adicionalmente, se obtuvo un turno óptimo que osciló entre 6 y 8 años. Sin embargo, aunque el máximo crecimiento medio se obtuvo entorno a los 8 años, el rendimiento es prácticamente idéntico al obtenido a los 6 años por lo que el turno más corto de 6 años parece más apropiado al reducir el tiempo de cosecha (**Capítulo 4**). Estos turnos, que pueden asociarse a calidades de sitio medias o altas están en concordancia con los resultados obtenidos en el modelo dinámico de crecimiento (**Capítulo 3**) donde el turno óptimo fue de 6, 7 y 9 años para las calidades de estación I, II y III respectivamente.

La productividad potencial de las plantaciones estuvo afectada por la disponibilidad de agua los meses de verano, principalmente la precipitación y en menor medida la temperatura mínima y máxima y el déficit de presión de vapor

(*DPV*), aunque la reducción en la disponibilidad de agua no puede compararse con los periodos de sequía de las zonas mediterráneas donde la supervivencia de las plantaciones puede verse afectada (**Capítulo 4**). Este hecho se encontró también en los modelos empíricos cuando se incluyeron las variables climáticas en el modelo expandido (**Capítulo 3**) y por tanto remarca la importancia del efecto del déficit hídrico para el desarrollo de las plantaciones como ya fue apuntado previamente para esta especie en otros países como Chile o Australia (Rodríguez et al., 2009; White et al., 1996). Al mismo tiempo, los resultados obtenidos en el **Capítulo 4** mostraron que la producción de biomasa aérea está sobreestimada en aproximadamente un 12 % cuando en lugar del clima medio se utilizó el clima real. Este hecho, que también ha sido demostrado en otros estudios donde se emplea el modelo 3-PG (Almeida et al., 2010) resalta la importancia del uso de clima real, cuando esté disponible, para evitar errores en las predicciones.

Los modelos de crecimiento desarrollados en esta Tesis (**Capítulos 3** y **4**) obtuvieron rangos de precisión adecuados y son apropiados para la toma de decisiones. A pesar del hecho de que los modelos de procesos pueden considerarse herramientas más realistas porque tienen en cuenta los procesos fisiológicos que están detrás del crecimiento de los árboles, requieren una gran cantidad de datos específicos para su uso. Por ello, la decisión de usar este modelo (**Capítulo 4**) o el modelo de crecimiento dinámico (**Capítulo 3**) depende de los datos disponibles sobre la plantación, la información de salida requerida y la precisión deseada.

Los cultivos energéticos presentan un impacto en el suelo debido a la extracción de biomasa que podría afectar al potencial productivo del terreno en el futuro. La evaluación nutricional obtenida en el **Capítulo 5** mostró que las hojas y la corteza son los componentes con la mayor concentración de nutrientes (N, P, K, Mg) excepto para el Ca, donde la corteza y las ramas son los componentes principales. Estos patrones de distribución de los nutrientes también aparecen en otros estudios de *Eucalyptu*s en la región (Balboa, 2005; Brañas et al., 2000; Rodríguez da Costa, 2010; Rodríguez-Soalleiro et al., 2004). Las plantaciones estudiadas estuvieron dentro de los rangos típicos para el N, K y Ca, aunque algunas de las plantaciones se encontraron por debajo de ellos. Los valores de P sobrepasaron dichos rangos y obteniéndose concentraciones más altas que en otros estudios para la misma especie en esta región (Rodríguez da Costa, 2010) lo que puede justificarse por la fertilización que se lleva a cabo tras la plantación. Por otra parte, se presenta una clara deficiencia de Mg y bajos valores de Ca edáficos, asociados a la baja disponibilidad de estos elementos en los suelos de esta región (Balboa, 2005; Calvo de Anta, 1992).

El fuste, componente mayoritario al final del turno es la fracción con mayor contenido de P, K, Mg y Na mientras que por otra parte el N y el Ca se almacenan principalmente en las hojas y la corteza respectivamente (**Capítulo 5**). Adicionalmente los nutrientes extraídos con la biomasa aérea de acuerdo con la calidad de estación (**Capítulo 3**) fueron 243-706 kg N, 44-122 kg P, 131-375 kg K, 121-329 kg Ca, 25-67 kg Mg y 29-86 kg Na por ha (**Capítulo 5**). Los nutrientes extraídos deberían estimarse de manera específica de acuerdo con la producción de biomasa real y el ciclo de nutrientes para ser reemplazados en los siguientes turnos y así mantener la productividad del suelo.

Desde el punto de vista del cambio climático se considera importante la estimación del carbono almacenado en el suelo y la biomasa de las plantaciones (Ruiz-Peinado et al., 2012). Los resultados del análisis de carbono especificado en el **Capítulo 5** mostraron una concentración contante en todos los componentes estudiados. Las hojas presentaron la mayor concentración de C, sin embargo la madera fue el componente mayoritario en dicho elemento. El contenido medio de C en la biomasa aérea fue entre 2 y 9 Mg C ha^{-1} año^{-1} en función de la calidad de estación. Estos resultados resultaron inferiores que los obtenidos para plantaciones más maduras en la región (Pérez et al., 2006; Rodríguez da Costa, 2010).

El estudio de las propiedades energéticas es de gran importancia en el uso de los cultivos leñosos como biocombustibles con el fin de estimar el potencial energético que estos puede generar. Las plantaciones bioenergéticas de *E. nitens* obtuvieron un poder calorífico constante con un valor medio de *NCV* de 18.32 MJ kg^{-1} (**Capítulo 5**), que es superior a otras especies de *SRWC* como el chopo y el sauce (McKendry, 2002) y un contenido de cenizas medio < 1 %, que es inferior a los cultivos herbáceos y otras especies como *E. globulus* (Jenkins et al., 1998; Pérez et al., 2011, Senelwa y Sims, 1999).

Los resultados obtenidos en esta Tesis proporcionan información valiosa para los gestores forestales y las industrias regionales y por tanto contribuirá a promover las inversiones en el sector de la bioenergía. Esto a su vez podría contribuir considerablemente a satisfacer la demanda energética en la región en el futuro, reducir la dependencia en combustibles fósiles, crear empleo y proporcionar una alternativa para los terrenos marginales o abandonados.

6. Conclusiones

- ✓ Los **métodos para la estimación de la biomasa y el volumen** desarrollados en esta Tesis permiten determinar en cualquier momento a lo largo del turno la producción de las plantaciones bioenergéticas de *E. nitens* de forma sencilla a partir de variables de árbol o de rodal. Las ecuaciones de biomasa son el método más preciso para la estimación de la biomasa del fuste aunque podría ser aceptable el uso de cualquiera de las metodologías estudiadas. Por otra parte, el uso de *BEF*s constantes debe evitarse siempre que sea posible en la fracción de copa y en la biomasa aérea ya que subestiman la producción y por ello deberían emplearse otras metodologías disponibles como las ecuaciones de biomasa o los modelos de *BEF*s.

- ✓ El **modelo dinámico de crecimiento** de rodal aquí presentado resulta una herramienta de gran utilidad para la planificación y gestión de las masas de *E. nitens*. Dicho modelo se compone de funciones de transición para la proyección en el tiempo del área basimétrica y la altura dominante (esencial para la definición de la **calidad de estación** a partir del índice de sitio) y funciones de salida para la estimación del volumen y la biomasa aérea.

✓ La inclusión de **variables ambientales** en el modelo dinámico de crecimiento da lugar a funciones con una precisión similar al obtenido sin considerar estas variables además de convertirse en funciones más robustas y flexibles frente a pequeños cambios ambientales dentro de los rangos estudiados.

✓ El **modelo de procesos** ajustado en esta Tesis ha constatado la importancia de los factores climáticos en el crecimiento de estas plantaciones especialmente la precipitación durante los meses de verano. Asimismo, este modelo aplicado a una mayor escala mediante el análisis espacial con herramientas GIS, muestra las diferencias productivas de las masas forestales en función de la variabilidad climática presente en el área de estudio. El uso de datos climáticos medios anuales en lugar de datos reales está desaconsejada debido a que la producción se ve claramente sobrestimada.

✓ La **evaluación y cuantificación del contenido nutricional** de los distintos componentes arbóreos muestra el impacto nutricional que puede suponer la extracción de la biomasa aérea de los cultivos energéticos al final del turno en función de la calidad del sitio. Adicionalmente a la evaluación nutricional, el contenido de carbono y el poder calorífico junto con otras variables energéticas resultan información esencial para la gestión sostenible y rentable de las plantaciones energéticas.

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ANNEX III. Abbreviations

3-PG	Physiological Principles Predicting Growth
3-PGS	Physiological Principles Predicting Growth Spatial
ADA	Algebraic Difference Approach
AGB	Above-ground biomass
AWS	Automatic weather stations
BEF	Biomass Expansion Factor
CAI	Current Annual Increment
CMI	Current Monthly Increment
D	Mean diameter at breast height
d	Diameter at breast height
dg	Quadratic mean diameter
D-W	Durbin Watson’s Test
EF	Model Efficiency
FC	Fixed Carbon
FR	Fertility Rate
G	Stand basal area
GADA	Generalized Algebraic Difference Approach
GCV	Gross Calorific Value
GIS	Geographic information system
H	Mean total height
H_0	Dominant height
h	Total height
h_v	Height of the live crown
IC	Condition number
LAI	Leaf Area Index
MAI	Mean Annual Increment
N	Stocking or number of trees per hectare
NCV	Net Calorific Value
OM	Organic matter
PS	Summer precipitation
R^2	Coefficient of determination
R^2_{adj}	Adjusted coefficient of determination
RE	Relative error
RMSE	Root mean square error
SI	Site index
SLA	Specific Leaf Area
SRC	Short Rotation Coppice
SRF	Short Rotation Forestry
SRWC	Short Rotation Woody Crops
SW	Soil Water
t	Stand or tree age
TMAX	Mean of maximum temperatures of the warmest month
TMW	Mean temperature of the warmest month
TSU	Mean summer temperature
V	Over-bark stemwood volume
VM	Volatile Matter
VPD	Vapour pressure deficit