UNIVERSIDAD DE OVIEDO

Departamento de Biología de Organismos y Sistemas

Programa de Doctorado: “Recursos Biológicos y Biodiversidad”

“Modelización del crecimiento y producción de las masas de monte bajo de *Castanea sativa* Mill. en el noroeste de España”

“Growth and yield modelling for *Castanea sativa* Mill. coppice stands in northwestern Spain”

TESIS DOCTORAL

María Menéndez Miguélez

Oviedo 2015

Vicerrectorado de Internacionalización
y Postgrado
Universidad de Oviedo

ASTURIAS
CAMPUS DE EXCELENCIA
INTERNACIONAL
AD FUTURUM

RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis	
Español/Otro Idioma: “Modelización del crecimiento y producción de las masas de monte bajo de *Castanea sativa* en el noroeste de España”	Inglés: “Growth and yield modelling for *Castanea sativa* Mill. coppices stands in northwestern Spain”

2.- Autor	
Nombre: MARÍA MENÉNDEZ MIGUÉLEZ	DNI/Pasaporte/NIE:
Programa de Doctorado: RECURSOS BIOLÓGICOS Y BIODIVERSIDAD	
Órgano responsable: UNIVERSIDAD DE OVIEDO	

RESUMEN (en español)

Hablar de castaño en el noroeste de España, y especialmente en Asturias, significa mucho más que hablar de una de las principales frondosas, por no decir la más importante de todas ellas en cuanto a superficie. La puesta en valor de esta especie necesita el desarrollo de herramientas de gestión que permitan planificar las actuaciones para obtener el máximo rendimiento de estas masas.

Con este objetivo principal se realizado esta tesis en la que se ha desarrollado un modelo estático de crecimiento para las masas de monte bajo de castaño en el noroeste de España. Para ello se ha establecido una red de 70 parcelas permanentes instalada en rodales regulares de monte bajo de castaño, representando toda la variabilidad en cuanto a edades, densidades y calidades de estación, para que los modelos desarrollados sean fiel reflejo de la realidad.

Se ha modelizado la biomasa arbórea en tres niveles (árbol individual, cepa y masa) para estimar su cálculo de acuerdo con el grado de detalle de la información disponible. Se aseguró la aditividad de los diferentes sistemas mediante *Nonlinear Seemingly Unrelated Regression* (NSUR).

Se apearon 203 árboles tipo (incluidos los árboles dominantes) para la estimación de los volúmenes de árbol individual y la posterior evaluación de varias funciones de perfil. Estos análisis permitieron desarrollar un sistema compatible formado por una función de perfil, una ecuación de volumen total y una ecuación de volumen comercial.

Se ha desarrollado un sistema de calidad de estación mediante el análisis de tronco en los árboles dominantes apeados y la posterior evaluación de cuatro ecuaciones dinámicas de índice de sitio obtenidas mediante la metodología de generalización de ecuaciones en diferencias algebraicas (GADA). El modelo de Cieszewski (2002) con dos parámetros dependientes de la estación fue finalmente seleccionado entre los modelos evaluados.

Se han calculado también otras relaciones dasométricas a nivel de masa de interés como dos modelos de evolución de densidad debido al estado selvícola heterogéneo de las masas que forzó a dividir la muestra en dos grupos (alta y baja densidad), ecuaciones para la predicción del diámetro medio cuadrático, una tarifa de volumen total, una tarifa de cubicación con clasificación de productos y ecuaciones de biomasa para diferentes componentes dependientes de altura dominante y densidad.

Todas estas herramientas pueden ser utilizadas directamente o a través de las tablas de producción y los diagramas de manejo de densidad en los que se han implementado. Se han desarrollado 8 tablas de producción correspondientes a dos posibles densidades (alta y baja) y cuatro calidades de estación a la edad de referencia de 22 años (10, 14, 18 y 22 m). Se han diseñado tres diagramas de manejo de densidad que pueden ser utilizados para proponer esquemas selvícolas para la producción de madera de calidad, estimación de biomasa o incluso stocks de carbono.

FOR-MAT-VOA-010-BIS

Finalmente, para comprender mejor el conjunto del monte bajo de castaño en el noroeste de España, se ha evaluado la influencia de los factores ambientales y nutrientes del suelo en su capacidad productiva, mejorando así también el conocimiento que se tenía hasta ahora de esta especie.

RESUMEN (en Inglés)

Chestnut in northwestern Spain, and especially in Asturias, is not simply another broadleaf species, rather it is the most important of all of them regarding area covered. The enhancement of this species requires the development of management tools that allow actions to be planned in order to get the best performance from these stands.

With this mean objective, a static growth model for chestnut coppice stands in northwestern Spain was developed in this thesis. For this purpose, a network of 70 permanent plots was established in regular coppice stands, representing the existing range of ages, densities and sites to develop models that closely reflect reality.

Stand aboveground biomass was fitted at three levels (individual tree, stool and stand) according to the degree of detail of the information available, ensuring additivity of the different systems using Nonlinear Seemingly Unrelated Regression (NSUR).

Data coming from 203 felled trees (including dominant trees) were used to estimate individual tree volumes and the subsequent evaluation of different taper functions. These analysis afford to develop a compatible system formed by a taper function, a total volume equation and a merchantable volume equation.

A site quality system has been developed from stem analysis data in the dominant felled trees and the later evaluation of four dynamic models developed applying the generalized algebraic difference approach (GADA). Cieszewski model (2002) with two site specific parameters was finally selected from the evaluated models.

Other interesting dasometric relations at stand level were also estimated, two models of density evolution due to the heterogeneous silvicultural state of the stands that force to divided into two groups (high and low density) the data, equations for predicting mean square diameter, a total stand volume equation, a merchantable stand volume equation and stand biomass equations for different components from dominant height and stand density.

All these tools can be directly used or through the yield tables and the stand density management diagrams (SDMDs) in which they were implemented. Eight yield tables corresponding to two different stand densities (high and low) and four site qualities at a reference age of 22 years (10, 14, 18 and 22 m) were developed. Stand density management diagrams were designed to propose silviculture schemes for high quality wood production, biomass estimation or carbon stocks even.

Finally, the influence of environmental factors and soil nutrients in explaining the productivity was evaluated in order to better understand the ensemble of chestnut coppice stands in northwest Spain, improving also the knowledge we had of this species up to now.

SRA. PRESIDENTA DE LA COMISIÓN ACADÉMICA DEL PROGRAMA DE DOCTORADO EN RECURSOS BIOLÓGICOS Y BIODIVERSIDAD.

Los trabajos llevados a cabo para la realización de esta Tesis Doctoral han sido financiados mediante el siguiente proyecto de investigación:

- ✓ "Proyecto Singular Estratégico VALOCAS: Valorización Forestal e Industrial del Castaño en España" (PSE VALOCAS 2009-2012) desarrollado por el Centro Tecnológico Forestal y de la Madera de Asturias (CETEMAS). Proyecto financiado por el Ministerio de Ciencia e Innovación de España (MICIN) y por el Plan de Ciencia Tecnología e Innovación del Principado de Asturias (PCTI).

Los datos utilizados para la validación de los modelos han sido proporcionados por la Universidad de Oviedo mediante la realización del siguiente proyecto de investigación:

- ✓ "Caracterización, cuantificación y zonificación de los residuos de castaño como recurso de biomasa". Proyecto financiado por la Fundación Asturiana de la Energía (FAEN).

El autor ha sido financiado mediante un contrato en el Centro Tecnológico Forestal y de la Madera de Asturias (CETEMAS).

AGRADECIMIENTOS

Quisiera dar las gracias a todas las personas que, de alguna u otra forma, me han ayudado en esta etapa de tesis que ahora termina. Soy consciente que es muy difícil considerar a todos porque habéis sido muchos a lo largo de estos años. Espero sinceramente no haberme olvidado de nadie y pido perdón de antemano a quienes no hayan sido nombrados en este texto.

En primer lugar, quisiera dar las gracias al Dr. Juan Majada, Director Científico del Centro Tecnológico Forestal y de la Madera de Asturias, por darme la oportunidad de formar parte del equipo del CETEMAS y de realizar esta tesis, así como por todos estos años de aprendizaje y apoyo continuo a mi trabajo y a toda la línea de investigación del castaño.

Gracias a mis directores, la Dra. Elena Canga y el Dr. Pedro Álvarez, por haber aceptado la batuta de esta tesis doctoral, por vuestra dedicación y el trato recibido en todo momento, así como por haberme enseñado cómo funciona todo este mundo de la investigación. Gracias Elena por haberme enseñado que la modelización es algo más que un montón de números e interminables programas de SAS, por tu rigor, tu apoyo, tu paciencia ante las miles de preguntas que se me han planteado y por guiarme a lo largo de este tiempo procurando siempre que todo el trabajo estuviera lo mejor posible. A Pedro, por compartir conmigo desde el primer minuto todos tus conocimientos sobre nuestro querido castaño, por haberme enseñado que hay un mundo más alla de la modelización y que el bosque tiene un entramado mucho más complejo de lo que imaginamos, por nuestras discusiones en el despacho intentando llegar a un acuerdo de cómo expresar de la mejor manera posible la idea que ambos teníamos en mente y por tu apoyo y confianza. Gracias a los dos por todo el esfuerzo a lo largo de estos años, por aportar mejoras constantes en cada parte y por todas esas horas extras que habéis tenido que hacer para que esta tesis llegara finalmente a buen puerto.

No puedo dejar pasar esta oportunidad para agradecerles a Jean Lemaire, Gilles Pichard y todo el *Groupe de travail châtaignier* de Francia por haberme permitido formar parte del mismo y aprender de personas que llevan tantísimos años trabajando con castaño. Ha sido un verdadero privilegio para mí que hayais compartido todos vuestros conocimientos y experiencia conmigo. Ojalá pueda en algún momento de mi vida llegar a saber, aunque sea una décima parte, de lo que vosotros conocéis de esta especie.

Debo mencionar y agradecer también a los Drs. Marcos Barrio, profesor de la Escuela Politécnica de Mieres, y Fernando Castedo, profesor de la Escuela Superior y Técnica de Ingeniería Agraria de la Universidad de León, su inestimable ayuda en temas de modelización, sus enseñanzas y su predisposición a resolver cualquier duda que me ha surgido durante este trabajo. También le agradezco a la Dra. Asunción Cámara Obregón su apoyo y ayuda desde que dirigió mi Proyecto Fin de Carrera de Ingeniero Técnico Forestal, sus enseñanzas y ánimos han sido muy importantes desde el principio.

Una red de parcelas como la que se ha establecido en esta tesis no hubiera sido posible sin la ayuda del personal del Servicio de Montes del Principado de Asturias (técnicos, guardas….). Gracias por ello y por vuestro interés en las herramientas de selvicultura que se han desarrollado.

No puedo olvidar agradecer en estas líneas a todas las personas que forman y formaron parte del CETEMAS, SERIDA y SERPA los buenos momentos que hemos vivido. Cada uno habéis enriquecido a vuestra manera el día a día de esta tesis. Gracias a Eloy y los Drs. Mónica Meijón, Isabel Feito, Ângelo Kidelman y Marta Ciordia por las animadas conversaciones a la hora del café en las que cualquier problema pasaba a segundo plano. Ernesto, Manu, Miguel, Juan Carlos y Alba, sin vosotros no hubiera sido posible llevar a cabo todo el trabajo de campo que esta tesis ha necesitado, a pesar de la lluvia, la nieve y el frío; vuestra manera de trabajar y experiencia me han enseñado muchas cosas del mundo forestal. Gracias Ronnie por tu inestimable ayuda con el inglés y por revisar tan concienzudamente siempre los trabajos sin perder nunca la sonrisa. Gracias a mis compañeras de despacho: Marta, Sandra y Andrea, hemos compartido largas horas de trabajo pero vuestra ayuda y apoyo ha sido constante. Fran, gracias por tu confianza y apoyo, ha sido duro pero siempre has tenido una palabra de ánimo cuando la he necesitado. Lu, Gely y Carol ¡qué puedo deciros que no sepáis ya! Gracias por vuestra amistad y todos los buenos momentos vividos juntas, dentro y fuera del trabajo; siempre habéis sido un gran apoyo desde el primer día en que empecé esta andadura y mucho más en los últimos meses.

A Óscar Garcia, Brenda Janzen, Paul Sanborn, Darwin Coxson, Kathy Lewis, Chris Opio, Philippe Henry, Scott Green, Marlina Hawes y al resto del personal del *Ecosystem Science and Management Program (University of Northern British Columbia, UNBC)*, por la dedicación, el buen trato y la acogida recibida durante mi estancia en Canadá. Gracias a Hosly Garcia por enseñarme ese otro Prince George y esa otra Canadá, por tu amistad, por compartir conmigo tantas horas de largas conversaciones con nuestra taza de café, por tus risas, tus historias, tus consejos sobre lugares que no podía dejar de conocer antes de marcharme y por haberme hecho sentir una más de vuestra familia. Si por algo son conocidos los canadienses, a parte de por sus impresionantes paisajes, lagos y bosques, es por su hospitalidad y lo he podido comprobar de primera mano, ya que desde el momento que puse un pie en ese impresionante país me recibisteis con los brazos abiertos. Gracias por esos tres meses inolvidables.

También debo mencionar a todos los alumnos que participaron en el trabajo y que realizaron sus Proyectos Fin de Carrera o Fin de Grado. Maxi, Antolín, Cova, Marta, Quique, Raúl e Iván, gracias por los buenos momentos en campo y en los laboratorios, a cambio me llevo nuevos amigos.

Gracias a vosotros, los amigos de toda la vida y los que os habéis convertido en grandes amigos estos últimos años, destacando a Silvia, Raque, César, Tere y Vane; mi querido "point pattern group": Antonio, Diana, Toni y los Drs. Eugenia Iturritxa, Nuria Bonada y Carlos Campillo; mis amigos de aventuras en monte bajo con los que la mejor respuesta siempre es "it depends…": Giulia, Admir, Oscar y el Dr. Walter Mattioli; y los Drs. César Pérez y Fernando Pérez. Todos habéis hecho que el esfuerzo y las largas horas de trabajo en esta tesis hayan sido más llevaderas. Gracias por ser como sois, únicos e irrepetibles cada uno en lo vuestro, por haber entendido mis ausencias a lo largo de estos años, por haber tenido siempre una palabra de ánimo cuando lo necesitaba y por haberme sacado de mi "encierro" tantas veces.

Y, por supuesto, a mi familia, especialmente a mis padres y a mi hermano. Gracias por vuestra comprensión y paciencia infinita, por haberme animado a que siguiera adelante por muy grandes que fueran las piedras que me encontraba en el camino y por no haber dudado nunca que esta tesis vería la luz. Habéis sido un pilar fundamental durante todos estos años y no podría haber sido posible sin vosotros. Mamá, papá, Alex ¡GRACIAS! Creo que por mucho que os lo diga no llegaré nunca a agradeceros lo suficiente todo vuestro apoyo. Sois ejemplo de sencillez, cariño, paciencia, coraje, comprensión y ayuda. Sólo espero poder algún día poder parecerme a vosotros.

Por último y muy especialmente a mis abuelos, por vuestro cariño incondicional, por todo el tiempo que pasamos juntos y todas las cosas que aprendí de vosotros. Aunque ya no estáis aquí quiero dedicaros este trabajo especialmente a vosotros porque me hubiera gustado que lo hubierais visto, seguro que os habría encantado.

Gracias a tod@s

A mi familia

Elijo elegir
Y elijo la condición del árbol.
Porque come luz.
¡Qué delicia desayunar
transparencia,
almorzar lucidez
cenar ocasos anaranjados!
Y con ellos construir el verdor
y la sombra
y la rara nube que es toda copa
donde se esconde el canto de
los pájaros.
Ahora no puedo,
pero cuando lo deje,
seré lo que he elegido.

Joaquín Araújo-Árbol

General Index

Table index

Results

Introduction

1.Introduction

1.1 The tree species studied: *Castanea sativa* Mill.

Sweet chestnut (*Castanea sativa* Mill.) is the only native species of the *Castanea* genus in Europe. It extends across 15 countries in Central and Mediterranean Europe, covering over 2.5 million ha (Bourgeois *et al*., 2004; Conedera *et al*., 2004; Konstantinidis *et al*., 2008). This species demonstrates an outstanding evolutionary history with respect to other European forest species (Mattioni *et al*., 2008) and chestnut forests have been recognized as a habitat of interest in the European Natura 2000 network. This action guarantees the continuation of these natural habitats, reduces their degradation and favours biodiversity and at the same time takes into account economic, social, cultural and regional demands with relation to the species (CEE Directive 92/43, 1992).

Current knowledge regarding the biogeographic origin of *Castanea* genus is still quite limited, althought it is assumed to have originated in Asia during the Tertiary Period, and then progressively spread eastwards giving rise to the American chestnut, *Castanea dentata* (Marsch.) Borkh., and westwards resulting in the European chestnut – *Castanea sativa* – (Zohari and Hopf, 1988). It was, though, not simply a natural dispersion, it was in fact introduced into many areas by humans who grewselected grafts in orchards for the valuable nuts or in coppices form for wood production (Fernández-Cruz and Fernández-López, 2012). These processes gave rise to the present natural range of the species (Pitte, 1986; Conedera *et al*., 2004), although its origin in the Iberian populations is uncertain. In spite of this, recordings of fossil pollen suggest that the Northern Spain and Southern Galicia genetic pools originated during the Last Glacial Maximum from conserved populations located in two refugia: one in Northern Portugal and Galicia (Spain), and the other on the Cantabrian coast – from the Picos de Europa (Asturias, Spain) to the French Basque region (Krebs *et al*., 2004). The production of good quality fruits made chestnut into one of the principal sources of food for human populations, especially those from rural areas (Fineschi *et al*., 2000; Fernández-Cruz and Fernández López, 2012).

Sweet chestnut in Spain is estimated to cover over 272,400 ha, 154,500 of which correspond to pure chestnut stands, i.e. where chestnut is the dominant tree species (chestnut tree cover rate, CTR ≥60%). It is the most important forest species in Northwest Spain, and accounts for 100,000 ha, mainly as coppice stands (DGCN, 2013) which accounts for over 95% of the area with potential for chestnut coppice stands in Spain.

The potential growth of chestnut is influenced by many factors, the most important being those related to water (Lemaire, 2008a). Mean annual temperature is also a key factor, with an optimal range of 9-12°C required for adeguate growth of the species. Solignat (1977) showed a minimum annual rainfall of 700 mm to be necessary for appropriate growth of the species, whereas Bourgeois *et al*. (2004) noted that the most productive stands in France are located in areas with values of mean annual rainfall ≥800 mm. In Spain, rainfall is always over 600 mm year^{-1} (López, 1991), such that Spanish chestnut coppice stands are located in optimal areas with regard to the rainfall regime. That said, in relation to adeguate growth of this species, it is the homogeneous distribution of the rainfall during the year, with no more than three months of unfavourable conditions (drought) which is the key aspet rather than the specific total rainfall value (CEMAGREF, 1987; Pichard, 1994; Sevrin, 1994). In addition, very wet spring months are detrimental to the species as it can favour the development of chestnut ink (*Phytophthora cambivora* (Petri.) Buissman and/or *Phytophthora cinnamoni* Rands) and armilaria (*Armillaria mellea* (Vahl.) Kummer), or cause the suffocation of roots in soils with an insufficient drainage (Bourgeois *et al*., 2004). Regarding altitude and exposure, chestnut is preferably located in areas protected from cold and drought, being found from sea level up to 1,200 m – such as in the Pyrenees – or 1,600 m as in the Sierra Nevada (Bourgeois *et al*., 2004), although best performance for wood production is between 500 and 1000 m (Ruíz de la Torre, 2006). Various factors related to soil also influence growth. Chestnut is a calcifuges species that grows optimally in porous deep soils, silty-sandy or silty in structure, with a pH between 4.5 and 6.5, and which exhibits no hydromorphy of any kind in the first 50-60 cm and has a usable water reserve of at least 100 mm (Pichard, 1994; Bourgeois *et al*., 2004; Lemaire, 2008a).

Chestnut fruit or wood production can be reduced as a consequence of plagues and diseases, principally chestnut blight (*Cryphonectria parasitica* (Murril.) M.E. Barr.) and ink disease (*Phytophthora cambivora* (Petri) Buissman and/or *Phytophthora cinnamoni* Rands.) and, since some years ago, the plague of chestnut gall wasp (*Dryocosmus kuriphilus* Yasumatsu). Less common problems that can affect chestnut include anthracnose (*Mycosphaerella maculiformis* (Person) Schroet.) and root putrefaction caused by the fungus *Armillaria mellea* (Vahl.) Kummer (Cobos, 1989; Mansilla *et al*., 1999; García-Benavides and Monte, 2005).

Chestnut blight is considered the most serious phytosanitary problem for chestnut worldwide and is included in the A2 list of EPPO (European Plant Protection Organization) as a quarantinable disease, as well as in Annex II, Part A, Section II of the Directive 2000/29 of the European Union regarding the protection measures against the introduction or spread of organisms which damage plant material into the European Union. In Spain, however, Castilla y León is the only autonomous community that has a law, implemented in 2005, regading the transport and commercialisation of chestnut wood (MAM 510, 2007). *Cryphonectria parasitica* is not able to infect healthy cortical tissue, only spreading through injuries caused by thinnings, cracks, etc. (Heiniger and Rigling, 1994; Milgroom and Cortesi, 2004). Currently, there are no effective phytosanitary products against this infection although various control measures are being tested, such as hybridization of *Castanea* species and the inoculation of hypovirulent families, which provide the most viable solutions for chestnut blight control in the mid-term.

Chestnut ink disease is caused by *Phytophtora cinnamomi* Rabds. and *Phytophtora cambivora* Buissman, two saprophytic fungus that live on organic matter particles in the top 20-30 cm of soil. This pathogen causes necrotic inner bark lesions that exude a blackish-blue substance, hence its name, particularly in the collar region as well as causing root-rot. Ink disease may result in death when the collar region is completely affected or when most of the roots have died (Turchetti and Maresi, 2000; Fonseca *et al*., 2004). Soil conditions and the interaction between site factors and cropping practices can contribute to disease incidence (Portela *et al*., 1998), since water accumulation caused by soil compaction stimulates the establishment, spread and longevity of *P. cinnamomi* (Fonseca *et al*., 2004). The most effective control of the disease is based on preventive measures, which can be applied at a regional scale to increase their effectiveness (Martins *et* *al*., 2007). Nevertheless, there have been various approaches to controlling ink disease, through biological control using ectomycorrhizal fungi (Branzanti *et al*., 1998) and artificial hybridization of *C. sativa* and the Asiatic species – *Castanea crenata* Blume and *Castanea mollissima* Sieb. et Zucc. – (Craddock and Bassi, 1999; Fernández-Cruz and Fernández-López, 2012). In 1998 the Lourizán Forest Research Centre (Spain) initiated a program for the identification, clonal propagation and selection of clones resistant to *Phytophtora spp*. for timber production (Fernández-López *et al*., 1992, 1995, 2008; Miranda-Fontaíña and Fernández-López, 2001; Miranda-Fontaíña *et al*., 2007). The result of these studies was the endorsement of 32 clones from the ollection of the Lourizán Forest Research Centre as basic material for chestnut timber production (BOLETÍN OFICIAL DEL ESTADO, 2007).

One of the most recent plagues to invade Europe has been *Dryocosmus kuriphilus* Yasumatsu, which is a global pest of the *Castanea* genus commonly known as the chestnut gall wasp (Avtzis and Matoŝević, 2013; Battisti *et al*., 2013). One of the principal explanations for the success of this pest is a direct consequence of its *modus vivendi*: even a single female is capable of establishing a population (Nohara, 1956; Askew, 1984). In addition, the minute eggs and first instars grow inside the chestnut buds, rendering this species practically undetectable at these stages (Panzavolta *et al*., 2011). By attacking vegetative buds this insect disrupts twig growth and reduces fruiting, producing losses of up to 70% (Dixon *et al*., 1986; EPPO, 2005). Due to this stress, chestnut trees exhibit a gradual decline in biomass combined with a decline in attractiveness and aesthetic value (EFSA, 2010).

Chestnut wood is one of the most versatile and appreciated woods grown in Europe (Bourgeois *et al*., 2004). It combines a pleasant appearance, high durability, good mechanical properties and very interesting technical characteristics. It is also characterized by high growth rates (Fonti *et al*., 2002b; Cantiani, 1965 in Tani *et al*., 2003), i.e. a mean volume increment of between 3.9 and 18.6 m^3 ha^{-1} $año^{-1}$ at 33 years – depending on the site quality – according to the yield tables previously available in Asturias (Cabrera and Ochoa, 1997). It is a ring-porous species with the border between latewood – a wider area with smaller and diffused vessels –, and early wood – a narrow area with large vessels – of consecutive rings being easily discernible. Chestnut timber is suitable for a wide range of natural products ranging from the more innovative (parquet floor, laminated, veneer, lumber, non-structural Glulam and solid wood panels) to the more traditional ones (poles, fences, vineyard stakes, energy) (Fonti *et al*., 2002b; Bourgeois *et al*., 2004; Fonti and Giudici, 2005). In addition, while chestnut wood has been used for years as one of the main options for different types of constructions and structures, it is important to carry out tests and studies of its structural characterization (Faggiano *et al*., 2010; Nocetti *et al*., 2010; Vega, 2013) for its inclusion in the Spanish visual grading Standard (UNE 56546, 2013). The most technological limitation of the wood is ring shake, a type of wood fracture arising parallel to the annual growth rings in the tangential plane of the stem (Chanson *et al*., 1989) which occurs after felling or cross cutting (Fonti *et al*., 2002; Bourgeois *et al*., 2004). Several studies previously carried out have shown that this defect is due to a number of factors, including age, size, forestry intervention (thinning and cuttings), soil fertility and chemistry and a possible genetic disposition (Fonti *et al*., 2002a-b; Becagli *et al*., 2002-2004; Bourgeois *et al*., 2004). This defect, mainly in the basal portion of stems, leads to the discarding of much of the material, and in the worst case, its incidence is so high that only a few logs from a stand can actually be taken to the sawmill (Fonti *et al*., 2002b; Pina and Romagnoli, 2010).

1.2 Coppice stands

Silviculture defines coppice stands as a beneficial method which ensures the regeneration of the main stand from stump or root shoots, applying the same terminology to the resultant stands, formed mostly by saplings (Serrada *et al*., 2008).

Coppices are the most usual system form in chestnut areas dedicated to wood production. They are considered anthropogenic forest patches in which chestnut is the dominant species. The great sprouting capacity of this species, the thicknesses of tree cover and allelopathies generated by tannins presented along almost the entire surface of the tree cause, in many cases, chestnut to be present as monospecific stands, the presence and development of other species being inhibited by these factors (Ruíz de la Torre, 2006).

Nevertheless, these general concepts are slightly variable in relation to chestnut coppice stands in Asturias. In this region, chestnut can be found in pure stands such as those defined by Ruíz de la Torre (2006), although it is also quite often found it associated with other hardwoods such as oak (*Quercus robur* L.) or birch (*Betula sp.*) in areas in the interior, or with eucalyptus (*Eucalyptus globulus* Labill.) on the coast.

Most areas occupied by chestnut in the northwest do not have a clear production purpose. Currently many of these stands are virtually abandoned and have no intensive management. While it is true that for many years firewood has been extracted by local people to a greater or lesser extent depending on the area, there has been no exploitation to obtain several different products in the different life stages. The Regional Public Administration itself recognises the current abandonment and deterioration of chestnut stands in Asturias, and the importance of research initiatives, awareness and divulgation to promote information about this important species in the region. These facts combined with the need to carry out studies to develop different management tools adapted to several chestnut stands in the near future.

In the traditional chestnut culture, the management practice for timber production was mainly coppicing, i.e. a short rotation (12 to 25 years) management system, in which timber assortments were frequently characterized by relatively low economic value because of the small average size of the shoots at the end of the cutting cycle, usually without any thinnings (Manetti *et al*., 2001; Vogt *et al*., 2006; Seci *et al*., 2013). This lack of thinnings and clear cuttings is one of the main problems of management in chestnut coppice stands because it greatly limits the diameter development of the shoots.

In contrast, in recent years, new management schemes based on longer rotations and selective thinnings, according to site condition and socio-economic context, have been developed experimentally with the aim of increasing timber value (Amorini and Manetti, 2002; Lemaire, 2009). This selection is carried out to concentrate the growth into the most vigorous shoots with the best form and allows not only financial profit in a much shorter period of time, but also helps to improve the health status of the stand and the tolerance of individual trees to chestnut blight (Bourgeois *et al*., 2004).

The maintenance of stability and perpetuity of these chestnut stands requires the implementation of the appropriate silvicultural treatments in order to optimize the productive capacity and to establish the ecological balance. However, it is not only important to maintain the stability of these stands, but it is also necessary to develop new tools, models and methodologies for their management that allow actions to begin to be taken in these stands.

1.3 Growth modelling

One of the main objectives of forest research is the thorough knowledge of the different patterns and processes in growth and yield of forest species, both as individual trees and in terms of stand. In this sense, several growth models have been developed to represent the natural dynamic of forest stands and to explain processes, such as mortality or growth, or variations in the composition and structure of the stands (Burkhart and Tomé, 2012).

The main aim of growth models is to establish, based on equation systems, the evolution over time of one or more dendrometric (from individual trees) or dasometric (from stands) variables which are defined in the study system in order to facilitate the selection of the best management option depending on previously defined aims (Diéguez-Aranda *et al*., 2009).

Several studies have been carried out in recent years in countries such as France, Germany, Italy and Portugal to better understand the behaviour and evolution of chestnut, both in coppice stands and in high forest. In Portugal, biomass equations have been developed for high forest (Patricio *et al*., 2005); growth, soil and foliar chemical studies have also been carried out in the north of the country for mixed stands of *Castanea sativa* Mill. and *Pseudotsuga menziesii* (Mirb.) (Nunes *et al*., 2011); and studies of litterfall and litter decomposition in coppice stands (Patricio *et al*., 2012). In Italy, Angelini *et al*. (2010) developed models for height growth, site index and volume estimation in chestnut coppice stands. Furthermore, a site index model has also been developed in Bulgaria from a guide curve (Zlatanov *et al*., 2012) although, unfortunately, this model has the disadvantage of not specifying whether the study was carried out in coppice stands or in high forest. Hein *et al.* (2014) have also developed site index curves, height growth and crown models for chestnut in Germany, another country in which chestnut is a very important forest species. In France, the cultural and traditional importance of chestnut has led to numerous studies related to its growth, development and management in coppice stands, giving rise to site index curves (Bourgeois *et al*., 2004; Lemaire, 2008b), silvicultural management plans (Lemaire, 2008d), yield tables for different silvicultural management plans (Lemaire, 2008b) and volume equations (Bourgeois *et al*., 2004; Lemaire, 2008c).

Modelling studies for chestnut coppice stands in Asturias are reduced to tree volume, current annual increment, total height, crown diameter, site index equations and yield tables (Cabrera, 1997; Cabrera and Ochoa, 1997). Afif-Khouri *et al*. (2011) have also studied stands in Asturias with respect to the influence of edapho-climatic factors on site index, as defined Cabrera and Ochoa (1997). The first two works cited above carried out in temporal plots established in chestnut coppice stands in the region. The drawback of temporal plots is the impossibility of returning to them for successive measuremenys. Duplicate measurements are necessary to develop dynamic models to assess stand evolution and to check that static models developed in the first step do in fact properly describe this type of stand.

1.4 Network of permanent plots

The information used in this thesis comes from an experimental network of 70 circular permanent plots (15 m radius) established by the Forest and Wood Technology Research Centre (CETEMAS) in chestnut coppice stands located throughout the area of distribution of the species in Northwest Spain. This network was designed to represent the existing range of ages, stand densities and sites of this species. Further information regarding the permanent plots and the stand characteristics, as well as data collection, is fully explained in the different chapters.

The study of these stands has reinforced knowledge of the current situation of abandonment and strengthens the need for appropriate management in order to obtain the best performance possible. Chestnut coppice stands in Northwest Spain are characterized by high densities, from a stock point of view, with a mean value of 162 m^3 ha^{-1} (DGDRPF, 2012). The high number of shoots coming from the same stool is the result of the great sprouting ability of this species combined with the absence of thinnings. These two aspects, along with the fact that canker is a problem in the area, establish the necessity for again beginning the intensive management of this type of stand in order to take advantage of their great potentially in Northwest Spain.

The establishment of this network was the baseline for this thesis and will be the study area for future lines of research resulting from the work begun in the present thesis. Some of these potential lines of research are: dynamic models, analysis of different thinning intensities, canker evolution, spatio-temporal competition, management scenarios, conversion from coppice to high forest, etc.

1.5 References

Afif-Khouri E, Álvarez-Álvarez P, Fernández-López MJ, Oliveira-Prendes JA, Cámara-Obregón A. 2011. Influence of climate, edaphic factors and tree nutrition on site index of chestnut coppice stands in north-west Spain. Forestry 84, 4: 385-396. doi: 10.1093/forestry/cpr025.

Amorini E, Manetti MC. 2002. Selvicoltura nei cedui di castagno. Sostenibilità della gestione e produzione legnosea di qualità. In: Ciancio O, Nocentini S: Il bosco ceduo in Italia. A.I.S.F., Firenze: 219-248.

Angelini A, Mattioli W, Merlini P, Corona P, Portoghesi L. 2013. Empirical modelling of chestnut coppice yield for Cimini and Vicani mountains (Central Italy). Annals of Silvicultural Research 37: 7–12. doi:10.12899/ASR-749.

Askew RR. 1984. The biology of gall wasps. In: Anantha-Krishnan RN (ed): Biology of Gall Insects. Oxford and IBH Publishing Co., New Delhi, Bombay, Calcuta, pp. 223-271.

Becagli C, Amorini E, Manetti MC. 2002-2004. Incidenza della cipollatura in popolamenti di cedui di castagno da legno del Monte Amiata. Annali CRA-Istituto Sperimentale Selvicoltura 33 : 245-256.

BOLETÍN OFICIAL DEL ESTADO. 2007. Resolución del 25 de Octubre de 2007 de la Dirección General de Agricultura, por la que se publica la ampliación del Catálogo de materiales de base de diversas especies forestales de reproducción de las categorías identificada, cualificada y controlada. BOE núm. 27 del 13/11/2007.

Bourgeois C, Sevrin É, Lemaire J. 2004. Les guides du sylviculteur. Le châtaignier un arbre, un bois. Deuxième édition. Institut pour le Développement Forestier.

Branzanti MB, Rocca E, Pisi AM. 1998. Biological control of chestnut ink disease with ectomycorrhizal fungi. Abstract from 2nd International Congress on Mycorrhiza, Uppsala, Sweden, July 5-10.

Burkhart HE, Tomé M. 2012. Modelling Forest Trees and Stands. Springer, 471 pp.

Cabrera M. 1997. El monte bajo de castaño en Asturias: alternativas selvícolas. Tesis doctoral. Escuela Superior de Ingenieros de Montes. Universidad Politécnica de Madrid.

Cabrera BM, Ochoa F. 1997. Tablas de producción de castaño (*Castanea sativa* Mill.) tratado en monte bajo, en Asturias. In II Congreso Forestal Español-Irati 97. Puertas F., Rivas M. (eds). Pamplona, Spain, pp 131-136.

CEE. 1992. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. The Council of the European Communities, OJ L, 21 May 1992.

CEMAGREF. 1987. Guide technique du forestier méditerranéen français.

Chanson B, Leban JM, Thibaut B. 1989. La Roulure du châtaignier. For. Mediterr. 11: 15-32.

Cobos P. 1989. Fitopatología del Castaño (*Castanea sativa* Miller). Boletín Sanidad Vegetal Plagas. Fuera de Serie 16: 129 pp.

Conedera M, Krebs P, Tinner W, Pradella M, Torriani D. 2004. The cultivation of *Castanea sativa* (Mill.) in Europe, form its origin to its diffusion on a continental scale. Vegetation History and Archaeobotany 13: 161-179. doi: 10.1007/s00334.004.0038.7.

Craddock JH, Bassi G. 1999. Effect of clonally propagated interspecific hybrid chestnut rootstocks on short-term graft incompatibility with four cultivars of Italian “Marrone”. Acta Horticulturae 494: 207-212.

DGCN. 2013. III Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España.

DGDRPF. 2012. Dirección General de Desarrollo Rural y Política Forestal. Cuarto Inventario Forestal Nacional, Asturias. Ministerio de Agricultura, Alimentación y Medio Ambiente, Madrid. 58 pp.

Diéguez-Aranda U, Rojo Alboreca A, Castedo-Dorado F, Álvarez-González JG, Barrio-Anta M, Crecente-Campo F, González-González JM, Pérez-Cruzado C, Rodríguez-Soalleiro R, López-Sánchez CA, Balboa-Murias MA, Gorgoso Varela JJ, Sánchez Rodríguez F. 2009. Consellería do Medio Rural, Xunta de Galicia. 268 pp + CD-Rom.

Dixon WN, Burns RE, Stange LA. 1986. Oriental chestnut gall wasps *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae). Entomology, Circular Nº287.

EFSA. 2010. Risk assessment of the oriental gall wasp, *Dryocosmus kuriphilus* for the EU territory and identification and evaluation of risk management options. EFSA Journal 8: 1619.

EPPO. 2005. Data sheets of quarantine perst- *Dryocosmus kuriphilus.* EPPO Bulletin 35: 422-424.

Faggiano B, Grippa M, Marzo A, Mazzolani F. 2010. Structural grading of old chestnut elements by bending and compression tests. World Conference of Timber Engineering 2010. Trentino, Italy.

Fernández-Cruz J; Fernández-López J. 2012. Morphological, molecular and statistical tools to identify *Castanea* species and their hybrids. Conservation Genetics 13: 1589-1600. doi: 10.1007/s10592-012-0408-0.

Fernández-López J, Pereira-Lorenzo S, Miranda-Fontaíña ME. 1992. Fog and substrate conditions for chestnut propagation by leafly cuttings. Symposium Proceedings Mass Production Technology for Genetically improved fast growing forest tree species. AFOCEL/IUFRO I: 379-383.

Fernández-López J, Miranda-Fontaíña ME, Pereira-Lorenzo S. 1995. Esquema de la producción de materiales clonales forestales y frutales de castaño híbrido (*Castanea crenata* x *Castanea sativa*). ITEA 91: 149-156.

Fernández-López J, Miranda-Fontaíña ME, Furones-Pérez P. 2008. Caracteres de selección en campo de clones de castaño híbrido (*Castanea crenata* x *Castanea sativa*) para la producción de madera. Cuadernos de la Sociedad Española de Ciencias Forestales 24: 39-43.

Fineschi S, Taurchini D, Villani F, Vendramin GG. 2000. Chloroplast DNA polymorphism reveals little geographical structure in *Castanea sativa* Mill. (*Fagaceae*) throughout southern European countries. Molecular Ecology 9: 1495-1503. doi: 10.1046/j1365-294x.2000.01029.x.

Fonseca TF, Abreu CG, Parresol BR. 2004. Soil compactation and Chestnut Ink Disease. Forest Pathology 34: 273-283. doi: 10.1111/j.1439-0329.2004.00371.x.

Fonti P, Giudici F, Conedera M. 2002a. La cipollatura nel legno di Castagno: un problema central per il rilancio della castanicoltura da legno di qualità. Schweizerische Zeitschrift für Forstwesen 153: 430-436. doi: 10.3188/szf.2002.0430.

Fonti P, Macchioni N, Thibaut B. 2002b. Ring shake in chestnut (*Castanea sativa* Mill.): State of the art. Annals of Forest Science 59: 129-140. doi: 10.1051/forest:2002007.

Fonti P, Giudici F. 2005. Reducing the Risk of Ring Shake in Chestnut. Proceedings of the IIIrd International Chestnut Congress. Acta Horticulturae 693: 733-741.

García-Benavides P, Monte E. 2005. Fitopatología del Castaño: el chancro y la tinta en la provincia de Salamanca. Salamanca: Excma. Diputación Provincial de Salamanca, 58 pp.

Hein S, Ehring A, Kohnle U. 2014. Wachstumskundliche Grundlagen der Wertholzproduktion mit der Edelkastanie (*Castanea sativa* Mill.) in Südwestdeutschland und im Elsass. Allgemeine Forst und Jagdzeitung 185. Jg 1/2: 1-16.

Heiniger U, Rigling D. 1994. Biological control of chestnut blight in Europe. Annual Review of Phytopathology 32: 581-599. doi: 10.1146/annurev.py.32.090194.003053.

Konstantinidis P, Tsiourlis G, Xofis P, Buckley GP. 2008. Taxonomy and ecology of *Castanea sativa* Mill. forest in Greece. Plant Ecology 195: 235-256.

Krebs P, Conedera M, Pradella M, Torriani D, Felber M, Tinner W. 2004. Quaternary refugia of the sweet chestnut (*Castanea sativa* Mill.): an extended palynological approach. Vegetation History and Archaeobotany 13: 145-160. doi: 10.1007/s00334-004-0041-z.

Lemaire J. 2008a. Autécologie du châtaignier : un fougueux qui craint la sécheresse! Forêt Enterprise 179: 18-24.

Lemaire J. 2008b. Estimer la potentialité de son taillis de châtaignier et y adapter les éclaircies. Forêt Enterprise 179: 14-17.

Lemaire J. 2008c. Des outils pour cuber ses taillis de châtaignier. Forêt Enterprise 179: 25-28.

Lemaire J. 2008d. Prendre en compte le risque de roulure dans la conduite des éclaircies dans les taillis de châtaignier. Forêt Enterprise 179: 49-52.

Lemaire J. 2009. Produttività dei cedui e trattamenti selvicolturali. In: Dossier Castagno: Selvicoltura e Cipollatura. Sherwood 151: 13-16.

López J. 1991. Dossier: Le châtaignier en Europe; Espagne: De la Galice à la Catalogne, une situation diversifiée. Forêt Enterprise 76, 4: 28-32.

MAM 510. 2007. Normativa autonómica sobre sanidad forestal. Boletín Oficial de Castilla y León Nº60, 26 marzo 2007.

Manetti MC, Amorini E, Becagli C, Conedera M, Giudici F. 2001. Productive potential of chestnut (*Castanea sativa* Mill.) stands in Europe. Forest Snow and Landscape Research 76 (3): 471-476.

Mansilla P, Pérez R, Pintos C. 1999. Plagas y enfermedades que dañan al castaño. Frutic. Prof. 107: 43-52.

Martins L, Castro J, Macedo W, Marques C, Abreu C. 2007. Assessment of the spread of chestnut ink disease using remote sensing and geostatistical methods. European Journal of Plant Pathology 119 : 159-164.

Mattioni C, Cherubini M, Micheli E, Villani F, Bucci G. 2008. Role of domestication in shaping *Castanea sativa* genetic variation in Europe. Tree Genetics & Genomics 4: 563-574. doi: 10.1007/s11295-008-0132-6.

Milgroom MG, Cortesi P. 2004. Biological control of chestnut blight with hypovirulence: a critical analysis. Annual Review of Phytopathology 42: 311-338. doi: 10.1146/annurev.phyto.42.040803.140325.

Nocceti M, Bacher M, Brunetti M, Crivellaro A, van de Kuillen JWG. 2010. Machine grading of Italian structural timber: preliminary results on different wood species. World Conference of Timber Engineering 2010. Trentino, Italy.

Nohara K. 1956. Considerations on the reproductive capacity of *Dryocosmus kuriphilus* Yasumatsu (*Hymenoptera*: *Cynipidae*). Scientific Bulletin Faculty of Agriculture Kyushu University 15: 441-446.

Nunes L, Coutinho J, Nunes LF, Castro Rego F, Lopes D. 2011. Growth, soil properties and foliage chemical analysis comparison between pure and mixed stands of *Castanea sativa* Mill. and *Pseudotsuga menziesii* (Mirb.) Franco, in Northern Portugal. Forest Systems 20 (3): 497-507. doi: 10.5424/fs/20112003-11104.

Panzavolta T, Bracalini M, Croci F, Campani C, Bartoletti T, Miniati G, Benedetti S, Tiberi R. 2012. Asian chestnutgall wasp in Tuscany: gall characteristics, egg distribution and chestnut cultivar susceptibility. Agricultural and Forest Entomology 14: 139-145. doi: 10.1111/j.1461-9563.2011.00551.x.

Patricio MS, Monteiro ML, Tomé M. 2005. Biomass equations for *Castanea sativa* high forest in the Northwest of Portugal. Proceedings of the Third International Chestnut Congress 727-732.

Patricio MS, Nunes, LF, Pereira EL. 2012. Litterfall and litter decomposition in chestnut high forest stands in northern Portugal. Forest Systems 21 (2): 259-271. doi: 10.5424/fs/2012212-02711.

Pichard G. 1994. La regeneration naturelle assistée du châtaignier en Bretagne. Une method désormaisé prouvée. Forêt de France 355: 27-29.

Pina S, Romagnoli M. 2010. Characterization of ring shake defect in chestnut (*Castanea sativa* Mill.) wood in the Lazio Region (Italy). Forestry 83 (3): 315-327. doi: 10.1093/forestry/cpq014.

Pitte JR. 1986. Terres de castanides: Hommes et paysages du châtaignier de l'antiquité à nos jous. Librairie Artthème Fayard, Evreux.

Portela E, Aranha J, Martins A, Pires AL. 1998. Soil factors, farmers' practices and Chestnut Ink Disease: some interactions. Acta Horticulturae 494: 433-441.

Ruíz de la Torre J. 2006. Flora mayor. Ed. MMA, Organismo Autónomo de Parques Nacionales, Madrid. 1756 pp.

Seci A, Seenappa SN, Lushaj BM, Lushaj AB, Lushaj AB, Sina K, Dega E, Myteberi I, Toromani E, Tabaku V, Mine V, Boja A, Brahimi J, Lushaj BS. 2013. Conversion of an old, abandoned chestnut forest into simple coppice and coppice forest into orchards through the wise using of the agroforestry practices and estimated energy potential. Journal of Environmental Science, Computer Science and Engineering & Technology. 2 (2): 249-261.

Serrada R, Montero G, Reque JA. 2008. Compendio de Selvicultura Aplicada en España. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Madrid (España). Ministerio de Educación y Ciencia, Madrid (España).

Sevrin E. 1994. Améliorer les taillis de châtaignier. Fôret Enterprise 97, 4: 13-14.

Solignat G. 1977. Contribution à l'étude du débourrement végétatif chez le châtaignier (*Castanea sp.*), Extrait de la Pomologie française –T XIX, Nº10: 121-126.

Turchetti T, Maresi G. 2000. Effects of diseases on chestnut orchards and forest ecosystems. Ecologia mediterranea 26 (1-2): 113-121.

UNE 56546. 2011. Visual grading for structural sawn timber. Hardwood timber.

Vega A, Arriaga F, Guaita M, Baño V. 2013. Proposal for visual grading criteria of structural timber of sweet chestnut form Spain. European Journal of Wood and Wood Products 71, Issue 4: 529-532. doi: 10.1007/s00107-013-0705-4.

Vogt J, Fonti P, Conedera M, Schröder B. 2006. Temporal and spatial dynamic of stool uprooting in abandoned chestnut coppice forests. Forest Ecology and Management 235: 88-95. doi: 10.1016/foreco.2006.08.008.

Zlatanov T, Velichkov I, Minkov G, Georgieva M, Eggertsson D, Hreidarsson S, Zlatanova M, Georgiev G. 2012. Site index curves for European chestnut (*Castanea sativa* Mill.) in Belasitsa mountain. Izvorni znanstveni članci. Šummarski list 3-4: 153-159.

Zohari D, Hopf H. 1988. Domestication of Plants in the Old World. Clarrendon Press, Oxford.

Objectives

2. Objectives

The overall objective of this thesis was to develop tools for estimating growth and yield of chestnut coppice stands in Northwest Spain to facilitate a suitable management.

The specific objectives were:

- ✓ To model aboveground biomass for the different components (wood, bark, branches and total) at three levels: individual tree, stool and stand.
- ✓ To develop a compatible volume system formed by a taper function, a total volume equation and a merchantable volume equation.
- ✓ To model site quality, stand density, total and merchantable volume and quadratic mean diameter as basic tools in forest management.
- ✓ To develop stand tools, both yield tables for standard silviculture and stand density management diagrams.
- ✓ To analyse site quality through the relations between site index and environmental characteristics, including edaphic, climatic and physiographic.

Results



3.Results

The main results reached in this thesis are as follows:

3.1 Biomass modelling

3.1.1 Individual tree-level biomass system

Two different systems were developed for biomass estimation at this level, considering the following individual tree variables: standing tree variables and stump dimension variables.

In the first system (standing tree variables), it was necessary to combined branches and foliage as a single component in order to improve the fit. Each biomass component was fitted individually and then NSUR methodology was applied in simultaneous fitting in order to ensure the additivity of the tree biomass components. Each biomass component was weighted according to the different weighting factors used in the individual fit. All parameters were found to be significant at $P < 0.05$ and the equations developed explained over 82% of total variability.

In the second system (felled tree variables), it was improved by considering wood and bark as a single component. The presence of heterocedasticity in the crown component again made it necessary to fit this component by weighted regression, the process of individual and simultaneous fitting being carried out in the same way as for the first system. All parameters were found to be significant at $P < 0.05$. The equations developed to estimate stem, crown and total biomass (kg tree^{-1}) from felled tree variables explained over 72% of total variability.

3.1.2 Stool-level biomass system

This system provides information about the distribution of stool biomass in different components (kg stool^{-1}). It was not possible to fit the wood and bark components separately so they were considered together as the stool stem component to provide a better fit. Heterocedasticity was detected in the crown component, and therefore this equation was also fitted by weighted regression. Additivity was ensured by simultaneous fitting of both sets of equations (stem and crown). All parameters were statistically significant with at the 95% confidence level. Three equations were developed to estimate stem, crown and total biomass from stump dimensions, explaining between 84 and 96% of total variability.

3.1.3 Stand-level biomass system

The final system of biomass equations was developed in order to estimate the total biomass (t ha^{-1}) using different stand variables as independent variables. In this level, once again, the presence of heterocedasticity in the different components evaluated involved fitting them by weighted regression. The condition number resulting from the simultaneous fitting (105.31) indicated some problems of multicollinearity. However, the model which was selected had the most restrictive condition number and all parameters in the equation were highly significant, the level of multicollinearity therefore being considered acceptable. Equations developed to estimate wood, bark, crown and total biomass explained between 64 and 73% of total variability.

Validation through the use of an independent data set increased the credibility of the models and reflected the quality of predictions. This was achieved at individual tree and stool level, however, it was not possible at the stand level because it would have been necessary to fell all the trees in some plots to obtain data.

3.2 Compatible volume system

Five taper functions were fitted to estimate diameter at any point along the stem, all of which were significant at the 5% level, except for the Bi (2000) model, where convergence was not achieved. The model of Kozak (2004) was modified to adapt it to local and species conditions.

All models performed well, with mean error below 2.05 cm, each of them explaining more than 95% of total variability. A trend in the residuals depending on the distance and the relative position of the measurements along the stem was detected in the model fitting. Autocorrelation was therefore corrected applying a second-order autoregressive structure, as using a first-order structure proved to be insufficient. Goodness-of-fit statistics showed that the best-fitting models were those of Kozak (2004) and Fang *et al*. (2000). The evolution of bias and mean square root error in diameter estimation by relative classes and in height estimation by diameter class was analysed for the two best fit models.

Taking into account the comparison of the results, and in particular the practical utility of the compatibility between the classic two inputs volume equation and taper equation, the model of Fang *et al.* (2000) was finally selected as the most appropriate.

3.3 Basic equations and other management tools

3.3.1 Site index

Four models were evaluated to develope site index curves for chestnut coppice stands using GADA methodology (Generalized Algebraic Difference Approach). As expected, due to the longitudinal nature of the data, a trend in the residuals as a function of age-lag-residuals within the same tree was detected in all the models. This trend disappeared after correction of autocorrelation using a continuous autorregresive structure to model the error terms.

The GADA formulation derived from the Cieszewski (2002) model, using two parameters to make it site-specific, was finally selected after comparing goodness-of-fit statistics and graphical analysis, and explained over 99% of total variability. The reference age of 22 years was selected as the most suitable in predicting dominant height at other ages.

3.3.2 Stand density

Two equations were developed in this study to estimate stand density with the previous classification of data into two groups (high and low density) and explaining over 65% of total variability in both cases. Comparison of the different equations evaluated showed that age was the most explanatory variable for the behaviour of stand density in chestnut coppice stands, irrespective of whether the stand was, high or low density.

3.3.3 Quadratic mean diameter

The models evaluated to developed quadratic mean diameter equations showed that dominant height, age and stand density were the most explanatory variables.

Two different equations were fitted for direct use or for implementation into yield tables or Stand Density Management Diagrams (SDMDs). Whilst the most accurate model was always sought the constraint was imposed that second management tool (SDMDs) had to include dominant height and stand density. Both for yield tables and SDMDs the equations selected explained more than 80% of total variability.

3.3.4 Total and merchantable volume

The stand volume models analysed revealed that basal area, dominant height and stand density were the most explanatory variables. Two different equations were developed to estimate volume:

- ✓ The first was a merchantable volume equation to be applied in the yield tables. This equation explained more than 95% of total variability and each of its parameters were found to be significant at $P < 0.05$.
- ✓ The second was a total stand volume equation to be applied in the SDMDs. It was not possible to fit a merchantable volume equation which only depended on stand density and dominant height. Total variability explained by this equation was more than 55%.

3.3.5 Stand biomass

As in the last two sections, two sets of equations were developed in relation to stand biomass, the first to be applied in the yield tables and the second one in the SDMDs. In both cases, all parameters were found to be significant at $P < 0.05$.

- ✓ The set of equations developed to be implemented in the yield tables corresponds to the *Stand-level biomass system* presented in Chapter II of this thesis. These equations allow wood, bark, crown and total biomass to be estimated, explaining more than 60% of total variability.

- ✓ Additional equations were tested to be implemented in the SDMDs. These equations only depend on stand density and dominant height as independent variables. This fact meant it was not possible to develop a crown biomass equation, or independent equations for wood and bark, therefore both wood and bark were combined in a single component (stem). Total variability explained by the adjusted equations was more than 65% and 55% for stem and total biomass, respectively.

3.3.6 Yield tables and Stand Density Management Diagrams (SDMDs)

Previously adjusted equations were used to elaborate two management tools: yield tables and stand density management diagrams (SDMDs).

Two yield tables were constructed for each of the site quality indices previously defined (10, 14, 18 and 22 m at a reference age of 22 years), one for each density class (high and low). These allowed the estimation of total volume, merchantable volume with bark up to different top diameters (15, 20 and 40 cm), stem biomass, crown biomass and total stand biomass. This tool shows stand conditions before and after thinnings, quantity of stand removed, mean annual increment and periodic annual increment.

Four SDMDs were developed to estimate total stand volume, stem biomass, crown biomass and total stand biomass. The range of values represented by the axes and the isolines were similar to the range of values included in the data used to construct the diagram. Diagrams to estimate carbon stock have not been included in Chapter IV due to the lack of space, but they are available upon request from the author of this thesis.

3.4 Effects of environmental factors on site index

3.4.1 Regression trees

The relationship between productivity (explained by site index, SI) and soil and environmental factors (physiographic and climatic) was evaluated with two different statistical analyses: the non-parametric CHAID procedure (regression trees) and parametric regression analysis.

With regard to soil parameters, regression trees obtained from the CHAID procedure revealed that sand content is the main soil-related variable that limits height growth of the chestnut coppice stands in NW Spain. The difference between both groups (less sandy soils and sandy soils) was statistically significant and corresponded to 57.34% of sandy soil. The soil regression tree explained 23.97% of total variability.

The analysis of physiographic and climatic conditions showed that summer precipitation is the variable that plays the most important role in the height growth of these stands. Results revealed an important height difference of 3.22 m between both established groups (above/below than 151.00 mm of summer precipitation). At the second level, the most decisive variable in explaining SI was spring precipitation. The physiographic and climatic regression tree explained close to 47.34% of total variability, with a standard error of 1.264 m. No physiographic variable was statistically significant with a 95% level of confidence.

The regression tree including all the different types of environmental factors was identical for the first and second splitter variables since the separate analysis of climate related variables, that is, summer and spring precipitations were the most explanatory variables for SI. The only difference was the inclusion of a third split level defined by the clay percentage, whose critical point is situated in a clay percentage less than or equal to 29.54%. As expected, the highest percentage of variability in SI (50.81%) was explained by this model with a standard error of 1.264 m.

3.4.2 Parametric regression models

As in the regression trees, parametric regression models were fitted separately for each group of variables (edaphic, physiographic and climatic), and for all variables together.

Variables related to soil accounted for a lower percentage of total variability than those related to climate. Summer precipitation and mean annual temperature were the most explanatory variables for the climatic model, explaining over 43% of total variability. The edaphic model explained over 41% of total variability, where clay content, pH and stoniness were the most explanatory independent variables.

The model combining all the different variables explained the highest percentage of variability in SI (52%). This model included summer precipitation and mean annual temperature as independent variables. No soil variables were found to be significant.

3.5 Equations developed

The equations developed in this thesis are summarized by chapters in Table 3.1, Table 3.2, Table 3.3 and Table 3.4.

Table 3.1. Equations for biomass estimation

System	Equation	
Individual tree-level system (standing tree variables)	$w_{wood}=0.01391\cdot\left(d^2\cdot h\right)^{1.006}$	[6.1]
	$w_{bark}=0.004119\cdot h^{1.086}\cdot\left(d^2\right)^{0.7889}$	[6.2]
	$w_{crown}=0.5408\cdot h^{-1.439}\cdot\left(d^2\right)^{1.386}$	[6.3]
	$w_{total}=w_{wood}+w_{bark}+w_{crown}$	[6.4]
Individual tree-level system (felled tree variables)	$w_{stem}=0.2641\cdot d_{stump}{}^{1.800}\cdot h_{stump}{}^{0.1537}$	[6.5]
	$w_{crown}=0.05182\cdot d_{stump}{}^{2.057}$	[6.6]
	$w_{total}=w_{stem}+w_{crown}$	[6.7]
Stool-level system	$w_{stem}=0.2244\cdot n_{tree}{}^{0.9790}\cdot d_{mean}{}^{2.114}$	[6.8]
	$w_{crown}=-9.705\cdot n_{tree}+0.1521\cdot g$	[6.9]
	$w_{total}=w_{stem}+w_{crown}$	[6.10]

Table3.1 (Continuation). Equations for biomass estimation

System	Equation	
Stand-level system	$W_{wood}=0.8582 \cdot d_0^{0.8474} \cdot G^{0.5537}$	[6.11]
	$W_{bark}=0.2449 \cdot H_0^{0.4847} \cdot G^{0.6431}$	[6.12]
	$W_{crown}=14.31 \cdot d_0^{1.221} \cdot H_0^{-1.649} \cdot G^{0.4965}$	[6.13]
	$W_{total}=W_{wood}+W_{bark}+W_{crown}$	[6.14]

Note: w_i dry weight of the *i* biomass component (kg), *d* diameter at breast height (cm), *h* total height (m), d_{stump} diameter of the stump (cm), h_{stump} stump height (cm), d_{mean} mean diameter of all the trees in the stool (cm), n_{tree} number of trees in the stool, *g* basal area of the stool (cm^2), d_0 dominant diameter in the stand (cm), H_0 Dominant height (m), *G* basal area (m^2 ha^{-1}).

Table 3.2. Compatible volume system

$$\mathrm{d}=c_1\sqrt{H^{\left(k-9.869 \cdot 10^{-6}\right)/9.869 \cdot 10^{-6}}(1-q)^{(k-\beta)/\beta}\alpha_1^{I_1+I_2}\alpha_2^{I_2}} \qquad [6.15]$$

$$\mathrm{c}_1=\sqrt{\frac{5.542 \cdot 10^{-5} \cdot D^{5.542 \cdot 10^{-5}}H^{1.914-k/9.869 \cdot 10^{-6}}}{9.869 \cdot 10^{-6}(r_0-r_1)+3.362 \cdot 10^{-5}(r_1-\alpha_1 r_2)+2.667 \cdot 10^{-5}\alpha_1 r_2}}$$

$$r_0=\left(1-h_{stump}/H\right)^{k/9.869 \cdot 10^{-6}}$$

$$r_1=(1-0.07191)^{k/9.869 \cdot 10^{-6}}$$

$$r_2=(1-0.5590)^{k/3.362 \cdot 10^{-5}}$$

$$\beta= \left(9.869 \cdot 10^{-6}\right)^{1-(I_1+I_2)} \cdot \left(3.362 \cdot 10^{-5}\right)^{I_1} \cdot \left(2.667 \cdot 10^{-5}\right)^{I_2}$$

$$\alpha_1=(1-0.07191)^{\frac{\left(3.362 \cdot 10^{-5}-9.869 \cdot 10^{-6}\right)k}{9.869 \cdot 10^{-6} \cdot 3.362 \cdot 10^{-5}}} \qquad \alpha_2=(1-0.5590)^{\frac{\left(2.667 \cdot 10^{-5}-3.362 \cdot 10^{-5}\right)k}{3.362 \cdot 10^{-5} \cdot 2.667 \cdot 10^{-5}}}$$

I_1 = 1 si $p_1 \leq$ q $\leq p_2$, 0 in all other cases.

I_2 = 1 si $p_2 <$ q $\leq$ 1, 0 in all other cases.

Note: *D* over bark diameter at breast height (at 1.30 m above the top of the stool, cm), *d* over bark diameter at height *h* (cm), *H* total tree height (m), *h* height from top of the stool to top diameter *d* (m), h_{stump} stump height (m), *k* is equal to π/40000, *q* is equal to *h/H.*

Table 3.3. Density equations for the low and high density plots

Low density	$Ln\ N=10.61-1.0825\cdot t$	[6.16]
High density	$Ln\ N=11.58-1.172\cdot t$	[6.17]

Note: N stand density (trees ha^{-1}), t age (years).

Table 3.4. Equations for inclusion in the yield tables ([6.11] to [6.14], [6.18], [6.20]) and for inclusion in the SDMDs ([6.19], [6.21], [6.22] and [6.23]), respectively

Model		Equation	
Quadratic mean diameter		$d_g=5.0785\cdot N^{-0.1775}\cdot H_0^{0.6622}\cdot t^{0.1839}$	[6.18]
		$Ln\ d_g=2.143-0.2291\cdot Ln\ N+0.8327\cdot Ln\ H_0$	[6.19]
Merchantable volume		$V_{mi}=0.7901\cdot G^{1.0106}\cdot H_0^{0.7729}\cdot e^{-0.9259\cdot\left(\frac{d_i}{d_g}\right)^{3.360}}$	[6.20]
Total stand volume		$Ln\ V_m=-5.285+0.5220\cdot Ln\ N+2.455\cdot Ln\ H_0$	[6.21]
Stand biomass	Wood	$W_{wood}=0.8582\cdot d_0^{0.8474}\cdot G^{0.5537}$	[6.11]
	Bark	$W_{bark}=0.2449\cdot H_0^{0.4847}\cdot G^{0.6431}$	[6.12]
	Crown	$W_{crown}=14.31\cdot d_0^{1.221}\cdot H_0^{-1.649}\cdot G^{0.4965}$	[6.13]
	Total	$w_{total}=w_{wood}+w_{bark}+w_{crown}$	[6.14]
	Stem	$Ln\ W_{stem}=-6.735+2.616\cdot Ln\ H_0+0.5386\cdot Ln\ N$	[6.22]
	Total	$Ln\ W_{total}=-5.1861+2.229\cdot Ln\ H_0+0.5231\cdot Ln\ N$	[6.23]

Note: V_{mi} merchantable stand volume ($m^3\ ha^{-1}$), V_m total stand volume ($m^3\ ha^{-1}$), G basal area ($m^2\ ha^{-1}$), H_0 dominant height (m), d_i limit diameter (cm), d_g quadratic mean diameter (cm^2), N stand density (trees ha^{-1}), W_i dry weight of the i biomass component (kg), d_0 dominant diameter (cm).

Table 3.5. Equations for SI depending on environmental factors

Model	Equation	
Climatic	$SI=68.518-0.189\cdot SuP-2.204\cdot MAT$	[6.24]
Edaphic	$SI=3.201\cdot Clay-0.240\cdot pH-0.079\cdot Sto$	[6.25]
All variables available	$SI=74.211-0.211\cdot SuP-2.402\cdot MAT$	[6.26]
	$SI=-7.034+0.065\cdot WP$	[6.27]
	$SI=8.769+0.085\cdot Sand$	[6.28]

Note: SI site index (m at 22 years), *SuP* summer precipitation (mm), *MAT* mean annual temperature (°C), *Clay* clay content (%), *Sto* stoniness (%), *WP* winter precipitation (mm), *Sand* sand content (%).

3.6 References

Bi H 2000. Trigonometric variable-form taper equations for australian eucalypts. Forest Science 46 (3): 397-409.

Cieszewski CJ. 2002. Comparing fixed-and variable-base-age site equations having single versus multiple asymptotes. Forest Science 48: 7–23.

Fang Z, Borders BE, Bailey RL. 2000. Compatible volume-taper models for loblolly and slash pine based on a system with segmented-stem form factors. Forest Science 46: 1-12.

Kozak A. 2004. My last words on taper equations. The Forestry Chronicle 80, №4: 507-515. doi: 10.5558/tfc80507-4.

Conclusions

4. Conclusions

The main conclusions reached in this thesis are as follows:

4.1 Biomass modelling

- ✓ An accurate tool for biomass estimation dependent on the degree of detail of data – individual tree, stool and stand – was provided for chestnut coppice stands in Northwest Spain.
- ✓ The first level allows calculation of individual tree biomass for different components of standing or felled trees. The second and third levels enable the estimation of stool and stand biomass components, respectively.
- ✓ The different biomass levels considered accounted for between 60% and 90% of the total variability, depending on the level and component evaluated.
- ✓ The use of an independent data set in the validation process reflected the quality of predictions and confirmed the credibility of the models.
- ✓ Knowledge of biomass availability in this type of stands can be applied to studies of carbon sequestering, amount of fuel available, fire propagation conditions, etc.

4.2 Compatible volume system

- ✓ The five taper models analysed presented good performance in estimating diameter along the stem and appropriately described the stem profile for chestnut coppice stands in Northwest Spain, except for the variable exponent function proposed by Bi (2000) where convergence was not achieved.
- ✓ Goodness-of-fit statistics and prediction ability for diameter and height along the stem revealed that the compatible volume system proposed by

Fang *et al*. (2000) best explains the profile of chestnut coppice (98% of total variability and mean error of 1.19 cm).

- ✓ The system selected has the advantage of being a compatible system formed by a taper function, a total volume equation and a merchantable volume equation.
- ✓ Validation using an independent data set reflected the quality of predictions and confirmed the ability of the selected taper function to describe stem profile in chestnut coppice stands in Northwest Spain.
- ✓ The lack of taper functions to describe stem profile in chestnut coppice stands in the rest of Spain or elsewhere, points to the value of using the system developed here in the first instance, until new taper functions are developed to ensure the most accurate estimations possible for each specific area.

4.3 Basic equations and other management tools

- ✓ The basic tools developed in this chapter compensate for the practically non-existent studies of chestnut coppice stands growth and yield.
- ✓ The dynamic site index equation proposed by Cieszewski (2002) proved the most accurate in explaining site index and height-growth estimates. The reference age selected as the most suitable for predicting height at other ages was 22 years.
- ✓ Stand density evolution in coppice stands is one of the most difficult and important variables to estimate, as a consequence of many shoots growing fom the same stool. This fact, combined with the absence of management and the heterogeneity of chestnut coppice stands in northwestern Spain rendered the development of a unique equation to explain the evolution of these variables impossible. This was solved by classifying the data into two groups: high and low density.
- ✓ Knowledge of the state and behaviour of chestnut coppice stands was completed with equations to predict quadratic mean diameter, total and merchantable volume and several biomass components. These tools can

be used directly or incorporated into yield tables or stand density management diagrams.

- ✓ Two different management tools to design and evaluate future management options were developed: the classic traditional yield tables, and the more visual stand density management diagrams. Both tools enable total or merchantable volume, stem biomass, crown biomass, total stand biomass or carbon stocks to be estimated.
- ✓ Two yield tables, one for each density class (high and low), were developed for each of the previously established site quality curves (10, 14, 18 and 22 m at a reference age of 22 years).
- ✓ These accurate management tools are applicable to any type of management scenario dependent on the stand characteristics and provide the starting point for more detailed yield analysis such as dynamic growth models, when the relevant additional information becomes available.

4.4 Effects of environmental factors on site index

- ✓ The analysis carried out reflected the importance of climatic characteristics in explaining the productivity of chestnut coppice stands in Northwest Spain.
- ✓ Results obtained in this chapter indicate that the best site qualities were observed in plots with lower summer precipitations and lower mean annual temperatures.
- ✓ Dasometric variables are often more difficult and slower to obtain than climatic ones. In addition climatic characteristics are sometimes already known for certain geographic locations. All of which make the regression models developed here even more useful and important in real forestry scenarios.
- ✓ In a future scenario of unpredictable climatic changes the importance of the effects of edaphic and climatic variables on site productivity is fundamental for planning both investment and work in order to obtain the best performance according to different site qualities.

Publications

A three level system for estimating the biomass of *Castanea sativa* Mill. coppice stands in north-west Spain

Forest Ecology and Management 291 (2013) 417–426

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

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

A three level system for estimating the biomass of *Castanea sativa* Mill. coppice stands in north-west Spain

María Menéndez-Miguélez [a,*], Elena Canga [a,1], Marcos Barrio-Anta [b], Juan Majada [a,b,1], Pedro Álvarez-Álvarez [b]

[a] Forest and Wood Technology Research Centre (CETEMAS)/Finca Experimental "La Mata" s/n, Grado, Asturias, Spain
[b] Research Group in Atlantic Forests (GIS-Forest), Department of Organisms and Systems Biology, University of Oviedo, Escuela Politécnica de Mieres (E.P.M.), Campus Universitario de Mieres, C/Gonzalo Gutiérrez Quirós, 33600 Mieres, Spain

ARTICLE INFO

Article history:
Received 27 June 2012
Received in revised form 23 November 2012
Accepted 25 November 2012

Keywords:
Chestnut coppice
Biomass
Individual tree
Stool
Stand

ABSTRACT

Aboveground biomass was studied in *Castanea sativa* Mill. coppice stands in north-west Spain, and biomass equations were fitted at three levels (individual tree, stool and stand). Four systems of biomass estimation were developed. In two of the systems, the following individual tree variables were taken into account: standing tree variables and stump dimension variables. In the other two systems, biomass was estimated at stool and stand level, respectively.

In order to represent the existing range of ages, stand densities and sites in the study area, samples of 120 trees (for the individual tree level), 45 stools (for the stool level) and 70 plots (for the stand level) were chosen for study. The trees were felled and destructively sampled to separate biomass into the following components: wood, bark, thick branches, medium branches, thin branches and leaves. Several equations for quantifying the biomass of the different biomass components were evaluated. Heterocedasticity was corrected for by weighted fitting. To guarantee the additivity of the different biomass components, the equations were fitted simultaneously by nonlinear seemingly unrelated regressions (NSURs).

The different biomass levels considered accounted for between 60% and 90% of the total variability, depending on the level and component evaluated. Most of the equations developed in this study were evaluated with an independent dataset, which confirmed the good performance of the biomass equations for prediction purposes.

1. Introduction

The edaphic, climatic and ecological conditions in northern Spain are ideal for optimal growth of sweet chestnut (*Castanea sativa* Mill.) (Gandullo et al., 2004).

In Spain, chestnut stands are distributed over an area of 272,400 ha (Fig. 1), of which 154,500 ha are covered by pure chestnut stands, i.e. in which chestnut is the dominant tree species (chestnut tree cover rate, CTR ⩾ 60%). The existing types of chestnut woodland differ widely in terms of stand structure (coppice stands and high forest) and the main productive aim (nut and wood production). In north-west Spain, coppice stands devoted to nut production have been almost totally abandoned, and most stands are now devoted to production of high quality timber and biomass.

Sweet chestnut forest covers a total area of 123,549 ha in Asturias, mainly as coppice stands (approximately 70,000 ha are pure coppice stands) (DGCONA, 2003). The average total volume (with bark) of sweet chestnut stands harvested in Asturias in 2008 was 21,737 m^3 (the mean value for the period 2002–2008 was 40,000 m^3) (SADEI, 2008), which represents 19.9% of the total volume of this species harvested during 2008 in Spain (109,285 m^3) (MARM, 2008).

The chestnut coppice stands currently existing north-western Spain (Fig. 1) were established as a result of the economic and cultural changes that occurred after the 18th century. However, during the last 30–60 years, many traditional coppices have been abandoned or the rotation time has been greatly lengthened, resulting in unstable and degraded stands. The Government of Asturias is currently working to establish a regional strategy for sustainable harvesting of forest biomass, particularly aimed at the exploitation of chestnut coppice. Several biomass management plans have been proposed for this purpose (Álvarez-Vergel et al., 2011).

---

[*] Corresponding author. Present address: CETEMAS/Forest and Wood Technology Research Centre/Finca Experimental "La Mata" s/n, Grado, Asturias, Spain. Tel.: +34 985 75 47 25.
E-mail address: mmenendez@cetemas.es (M. Menéndez-Miguélez).
URL: http://www.cetemas.es (M. Menéndez-Miguélez).
[1] Tel.: +34 985 75 47 25.

0378-1127/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2012.11.040

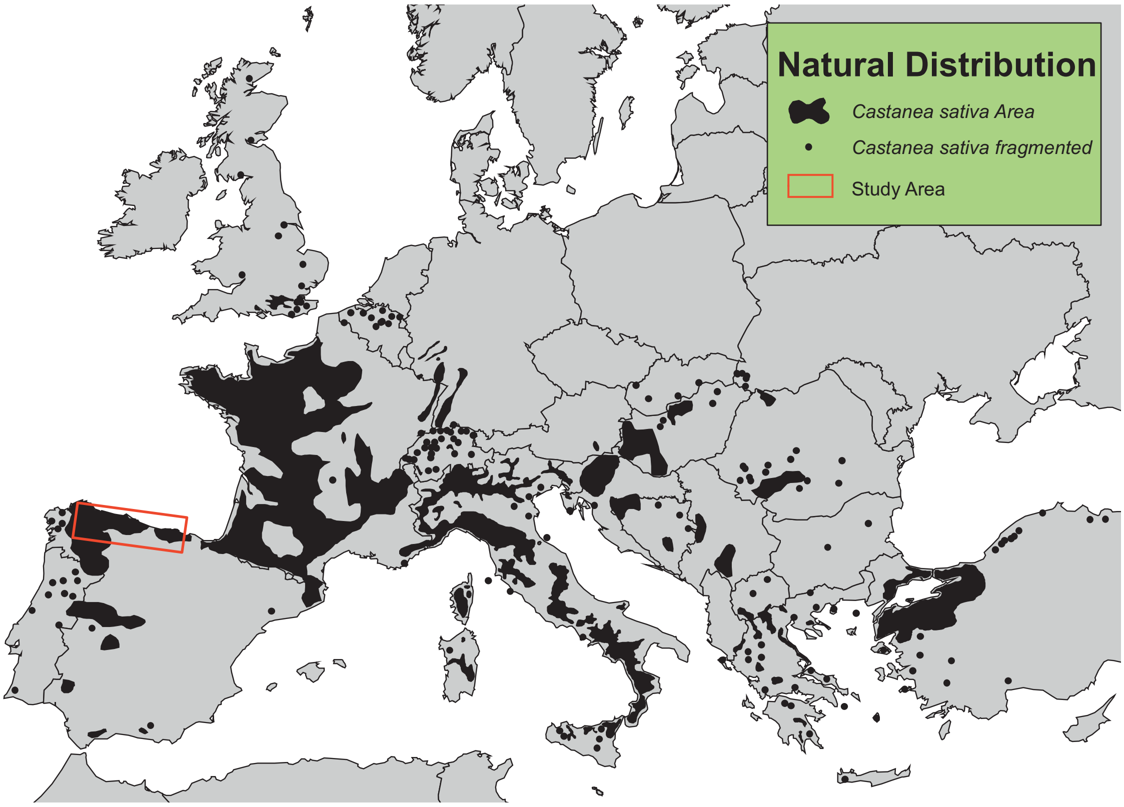


Fig. 1. Distribution of chestnut trees in Europe and location of the study area.

Different management options can be applied to chestnut timber production because of the great facility for stool sprouting (Bourgeois et al., 2004). For this reason, and in accordance with the area covered by the species in Asturias, it is essential to estimate the weight of the biomass components, in order to provide suitable management tools for use by forest managers and researchers (carbon cycle studies, nutritional balances of the forest system, etc.) at different levels (e.g. individual tree or stand level).

Tree biomass quantification is also essential for determining amounts of forest resources, and the data is also useful for helping us to understand changes in forest structure resulting from succession and to distinguish between forest types. Information on ecosystem dynamics and functionality is also essential from an environmental point of view, and as a result, considerable research effort has been made in recent decades to estimate individual tree biomass and to relate this to tree characteristics (Cunia, 1986, 1988; Ter-Mikaelian and Korzukhin, 1997; Waring and Running, 1998; Patricio and Monteiro, 2005). Furthermore, particular interest has been directed towards determining carbon stocks in forests, which are the main terrestrial sinks for carbon (Kirschbaum, 1996), although the extent to which they act as C sinks will depend on the management regime applied.

Biomass of individual trees, aboveground stand biomass and their yearly increments and nutrient contents have been studied in coppices in Spain, Italy and France (Bédéneau, 1988; Leonardi et al., 1996; Cutini, 2000; Santa Regina, 2000; Salazar et al., 2010) and also in high forest in Portugal (Patricio and Monteiro, 2005). Some studies have also related biomass estimation in *C. sativa* to carbon accumulation and nutrient budgets (Ranger et al., 1990; Santa Regina, 2000; Montero et al., 2005; Pires and Portela, 2005) and to the effect of thinning intensity on the growth and final biomass, or the ground vegetation production in relation to tree cover (Gallardo et al., 1998).

The aim of the present study was to develop biomass equations for different levels (individual tree, stool and stand) to enable evaluation of the carbon sequestration potential of each and development of an efficient management approach for chestnut coppice stands in north-western Spain.

2. Materials and methods

2.1. Data collection

The data used in this study were collected from a network of 70 circular permanent plots established in chestnut coppice stands located throughout the area of distribution of the species in Asturias. The plots were subjectively selected to represent the existing range of ages, stand densities and sites. The plot size (15 m radius) ensured a minimum of 30 tally trees (diameter at breast height greater than 5 cm) per plot. All the trees included in the plot were labelled with a number, and the diameter at breast height (DBH) (diameter at 1.3 m above the top of the stool, in cm) was measured with a tree caliper, to the nearest 0.1 cm. Total height and height to the base of live crown (which was considered as the lower insertion point of at least three consecutive live branches in a tree) were measured with a digital hypsometer, to the nearest 0.1 m, in all trees. Information such as the respective stool for each tree, if trees were alive or dead, and healthy or damaged was also recorded.

The following stool variables were recorded or calculated for each plot: the largest stem diameter per stool (d_{max}, cm) and the corresponding height (h_{max}, m), the arithmetic and quadratic stool diameter (d_{mean} and d_g, cm), the stool basal area (g, cm^2) and the number of stems per stool (n_{tree}).

At stand level, the following variables were computed: dominant diameter (d_0, cm) as the average diameter of the 100 thickest trees per hectare, dominant height or average height of the 100 thickest trees per hectare (H_0, m), basal area (G, m^2) and number of stems per hectare (N).

At 49 locations, one complete stool was felled and the height and the arithmetic mean of two perpendicular diameters of the remaining stumps of each stem were recorded. After felling, trees were destructively sampled to separate aerial biomass into branches of diameter larger than 7 cm, thick branches (diameter 2–7 cm), branches of diameter less than 2 cm, and wood (logs with bark with a thin-end diameter of 7 cm). The total fresh weight of each fraction was measured in the field with a portable balance. Three disks of wood including bark were cut in each stem (from the bottom, middle and the top). The disks, together with representative composite samples of each tree component, were sampled at the same time as bulk weighing was carried out, and they were transported to laboratory and weighed on a digital balance. The sample of branches less than 2 cm was later subdivided into twigs (diameter less than 0.5 cm), thin branches (diameter 0.5–2 cm) and leaves. Finally, the samples were oven-dried to constant weight at 65 ± 2 °C for determination of the proportion of dry matter (biomass) in each component. The dried disks were also used to calculate the dry weight ratios of wood to bark. The stool biomass (kg $stool^{-1}$) and the stand biomass (kg $hectare^{-1}$) fractions were aggregated from the corresponding tree values for each stool and plot, respectively; this enabled analysis of the data at three different levels according to the degree of detail: individual tree, stool and stand.

An independent network of 30 plots (established by the University of Oviedo several years before the principal sample) was used for validation purposes. Plot installation and data collection were carried out following the same methodology used for the fitting dataset, except that branches less than 2 cm were not subdivided into three components. In each plot, a representative stool was felled and 70 trees were destructively sampled for biomass estimation. The height-diameter distribution for the fitting and validation samples are very similar (Fig. 2), so that robust conclusions can be reached from the validation analysis.

Scatter plots of biomass weight data, by fractions, against DBH or total height and box plots of biomass weight data against diameter classes were visually examined to detect anomalous values. Only 12.5 % of the fitting data were identified as outliers. Some of these anomalous values were found to correspond to mistakes in measuring diameters or in transcribing field notes, although most of the extreme data points corresponded to stem sections that were deformed by canker and other types of physical damage. As a consequence, 15 trees were removed from the fitting data set. No anomalous values were found in the validation database. Table 1 shows the summary statistics including mean, minimum, maximum and standard deviation of the main tree, stool and stand related-variables measured in the plots and in the trees that were destructively sampled to measure biomass for both model fitting and model validation.

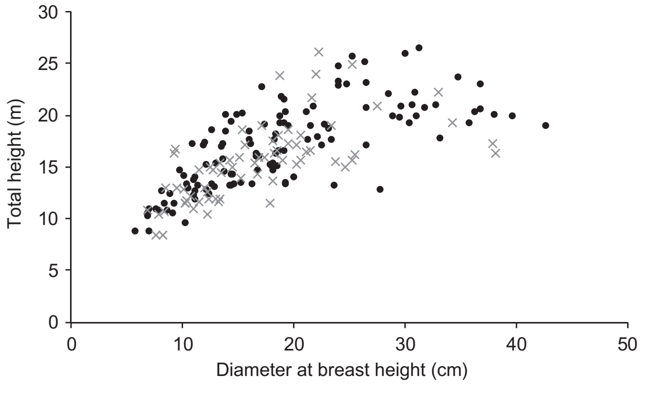


Fig. 2. Plot of diameter at breast height against total height of sampled trees (●) and validation sample (x).

2.2. Biomass systems, models and variables considered

Four different systems were developed for biomass estimation. In two of the systems, the following individual tree variables were considered: standing tree variables and stump dimension variables. In the other two systems, biomass was estimated at stool and stand level, respectively.

Linear and nonlinear allometric models have been widely used in forest biomass estimation (Cunia and Briggs, 1984; Reed and Green, 1985; Reed et al., 1996) and will be considered in this study. The general mathematical formulations of these models are as follows:

Linear (additive error):

$$Y = \beta_0 \cdot X_1 + \ldots + \beta_j X_j + \varepsilon \tag{1}$$

Nonlinear (additive error):

$$Y = \beta_0 \cdot X_1^{\beta_1} \cdot X_2^{\beta_2} \ldots X_j^{\beta_j} + \varepsilon \tag{2}$$

where Y = total biomass or biomass of the different components at each level of analysis, X_j = independent variable at each level, β_j = parameter of the model and ε = error.

Considering standing tree variables, diameter at breast height (d) is the most common explanatory variable since it is most closely correlated with biomass. However, the accuracy of the biomass estimates is usually increased by inclusion of tree height (h) as the second predictor and development of combined d–h equations (Wang, 2006). Live crown variables such as length or the diameter at the base of the crown have improved estimates of branch biomass or total crown biomass (Satoo and Madgwick, 1982; Clark, 1982). Some authors have also considered stand variables (such as age, basal area, site index or dominant or mean height) in estimating biomass at tree level, thus improving the accuracy of the estimations (Satoo and Madgwick, 1982; Bond-Lamberty et al., 2002; Porté et al., 2002; Balboa-Murias et al., 2006). On the other hand, in order to predict tree biomass from stump dimensions, only stump diameter with or without bark and stump height are considered as explanatory variables in this study.

Stool level analysis was carried out in an attempt to estimate biomass quickly by measuring only some stems in a stool. It seems reasonable to estimate biomass at this level as the product of the biomass of a representative tree of the stool (given by mean diameter and/or height) and the number of stems per stool. The following variables were considered at this level: diameter of the thickest tree and its height, number of stems per stool, arithmetic mean stool diameter, quadratic mean stool diameter and stool basal area.

With the systems of equations including stand variables, explicit equations including some of the following variables could be used to predict the current yield (as volume or biomass): mean stand height, an indicator of stand density, basal area, and site index (Clutter et al., 1983). The following explanatory variables were considered at this level: arithmetic mean diameter, quadratic mean diameter, dominant diameter, basal area, arithmetic mean height and dominant height.

2.3. Model fitting and evaluation

Model fitting was carried out in two stages for each level. First, each biomass fraction was fitted individually by use the REG or the NLIN procedure of SAS/STAT® (SAS Institute Inc., 2004). Initial parameters for running the iteration process when fitting allome-

Table 1
Descriptive statistics of main variables used in the three levels of analysis for both fitting and validation.

	Fitting					Validation				
	n	Min	Max	Mean	Sd	n	Min	Max	Mean	Sd
Individual tree level										
d	105	7.10	42.75	19.76	7.91	70	6.90	49.15	17.44	7.91
h	105	10.37	26.35	17.29	3.83	70	8.35	26.07	15.46	3.72
d_{stump}	104	9.50	63.50	24.03	9.93	70	10.00	69.75	24.36	10.56
h_{stump}	104	0.40	60.00	15.59	11.83	70	2.00	68.00	12.70	12.48
w_{wood}	105	2.45	580.63	127.23	116.66	70	2.77	660.38	93.45	109.11
w_{bark}	105	0.34	40.35	11.82	9.70	70	0.43	61.08	7.59	9.54
w_{b7}	33	1.27	237.90	24.89	43.03	70	0	186.94	6.29	31.15
w_{b27}	105	2.32	99.86	21.81	19.45	70	0.16	190.99	20.16	29.99
w_{b052}	105	0.57	41.53	9.16	8.58	–	–	–	–	–
w_{b05}	105	0.053	12.98	1.59	2.02	–	–	–	–	–
w_{foliage}	105	0.0043	29.01	3.92	4.24	–	–	–	–	–
w_{crown}	105	6.24	351.10	44.31	53.06	70	5.28	561.89	43.37	86.45
w_{total}	105	13.77	936.50	183.40	172.80	70	11.43	1283.36	144.41	196.42
$w_{\mathrm{wood\_stump}}$	104	1.15	580.63	118.11	118.68	–	–	–	–	–
$w_{\mathrm{bark\_stump}}$	104	0.11	40.35	10.82	9.83	–	–	–	–	–
$w_{\mathrm{stem\_stump}}$	104	1.27	605.54	128.93	127.98	70	3.19	721.46	101.04	118.42
$w_{\mathrm{crown\_stump}}$	104	6.24	351.15	40.88	52.64	70	5.28	561.89	43.37	86.45
$w_{\mathrm{total\_stump}}$	104	10.78	936.51	169.82	174.94	70	11.43	1283.36	144.41	196.42
Stool level										
d_{max}	45	13.65	42.75	25.12	7.074	30	9.40	49.15	21.41	9.42
h_{max}	45	12.66	26.35	19.38	3.18	30	10.44	26.07	16.83	3.81
n_{tree}	45	1	8	1.87	1.39	30	1	7	2.43	1.33
d_{mean}	45	12.89	42.75	23.83	7.61	30	9.11	49.15	18.99	9.01
d_g	45	12.97	42.75	23.95	7.53	30	9.14	49.15	19.31	9.01
g	45	177.80	3833.44	773.67	602.09	30	113.09	1897.30	672.33	446.29
$W_{\mathrm{wood\_stool}}$	45	59.71	1198.81	283.50	215.70	–	–	–	–	–
$W_{\mathrm{bark\_stool}}$	45	5.36	134.40	26.22	21.44	–	–	–	–	–
$W_{\mathrm{stem\_stool}}$	45	66.42	1333.75	309.73	236.10	30	26.75	721.46	235.76	185.25
$W_{\mathrm{crown\_stool}}$	45	14.69	501.54	96.08	100.92	30	10.93	561.89	101.79	123.32
$W_{\mathrm{total\_stool}}$	45	81.12	1835.30	405.82	329.07	30	37.68	1283.36	337.56	285.69
Stand level										
d_0	70	14.01	44.30	29.91	7.17	30	15.13	50.97	29.96	9.01
H_0	70	12.16	28.17	19.83	3.40	30	10.75	23.37	16.52	3.27
d_g	70	8.44	45.75	20.41	6.52	30	6.31	28.97	18.51	6.27
G	70	16.33	104.20	43.17	15.63	30	3.41	35.40	10.29	6.79
N	70	410.26	4753.40	1596.80	979.10	30	222.82	8244.23	2025.51	1762.97
$W_{\mathrm{wood\_stand}}$	70	36.36	233.38	123.60	47.31	30	30.49	452.61	127.34	106.34
$W_{\mathrm{bark\_stand}}$	70	4.76	20.35	11.86	3.82	30	2.52	41.15	11.39	8.56
$W_{\mathrm{crown\_stand}}$	70	16.91	78.67	42.49	12.07	30	23.71	203.49	64.43	42.26
$W_{\mathrm{total\_stand}}$	70	58.23	299.81	177.95	59.93	30	58.11	697.26	203.16	152.63

Note: d, diameter at breast height (cm), h, height (m), d_{stump}, stump diameter (cm), h_{stump}, stump height (cm), d_{max}, maximum diameter of all the trees of the stool (cm), h_{max}, maximum height of all the trees of the stool (m), n_{tree}, number of trees in the stool, d_{mean}, mean diameter of all the trees in the stool (cm), d_g quadratic mean diameter of all the trees in the stool (cm), g, basal area of the stool (cm^2), d_0, dominant diameter in the stand (cm), H_0, average height of the 100 thickest trees per hectare (m), d_g, quadratic mean diameter of the stand (cm), G, basal area (m^2 ha^{-1}), N, number of stems per hectare (stems ha^{-1}). w_i, (kg), the individual tree biomass of the different components evaluated, W_i (t ha^{-1}) the stool or stand biomass of the different components evaluated.

tric models were obtained from the linearized form of a previous linear fit.

In order to select the best equations for each biomass fraction, two goodness-of-fit statistics were examined: the coefficient of determination (R^2) (Eq. (3)) and the root mean square error (RMSE) (Eq. (4)). The coefficient of determination (R^2) indicates the proportion of the total variance that is explained by the model; the RMSE analyses the accuracy of the estimates and is expressed in the same units as the dependent variable. Although there are several shortcomings associated with use of the R^2 in nonlinear regression, the general usefulness of some global measure of model adequacy appears to override some of those limitations (Ryan, 1997). The expressions of these statistics are summarized as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{i=n}(Y_i - \widehat{Y}_i)^2}{\sum_{i=1}^{i=n}(Y_i - \overline{Y})^2} \tag{3}$$

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

where Y_i, $\widehat{Y}_i$ and $\overline{Y}$ are the observed, predicted and average values of the dependent variable, respectively; n is the total number of observations used to fit the model; p is the number of model parameters.

Single indices of overall prediction (R^2 and RMSE) are good indicators of the effectiveness of each biomass system when complemented with the analysis of the scatter plots of residuals.

In the second step, the best equations for each biomass component of each of the four systems were fitted simultaneously by nonlinear seemingly unrelated regression (NSUR), by use of the MODEL procedure of SAS/ETS® (SAS Institute Inc., 2004). This method fits an apparently nonrelated equation system formed by the equations of the biomass fractions considered and the total biomass equation. The NSUR method takes into account that equation errors are correlated (Borders, 1989; Parresol, 1999, 2001), and it presents the best fitting solution that minimizes the global errors associated with these equations, although the solution for each biomass fraction is not necessary the best. This approach was also found to be the best method for forcing additivity among individual fractions of biomass in a comparison of three different procedures (Parresol, 1999). This important feature of biomass systems refers to the fact that estimates of total biomass equation must be equal to the sum of the estimates of the equations of each biomass fraction. To ensure the additivity of the system using the NSUR procedure, the total biomass equation must be expressed as the sum of the equations for each biomass fraction.

Two common problems of biomass equations were evaluated: heterocedasticity and multicollinearity. Although the least squares estimates of regression coefficients remain unbiased and consistent under the presence of multicollinearity and heteroscedasticity, they are not necessarily the most efficient (Myers, 1990). Multicollinearity refers to the existence of strong intercorrelations among the independent variables, mainly due to the use of complicated models with several polynomial terms (Kozak, 1997). In this study, the presence of multicollinearity was evaluated by the condition number (CN), which is defined as the square root of the ratio of the largest ($\lambda_{\max}$) to the smallest eigenvalue ($\lambda_{\min}$). According to Belsey (1991), if the condition number ranges from 5 to 10, collinearity is not a major problem, if it is the range of 30–100, then there are problems associated with collinearity, and if it is in the range of 1000–3000 there are severe problems associated with collinearity.

Heterocedasticity often occurs in biomass data, that is, the error variance is not constant over all observations (Parresol, 1999). In the present study, heterocedasticity was detected by plotting the studentized residuals against predicted values. The lack of homogeneity in the error variance was corrected by weighting each observation during the fitting process by the inverse of its variance (σ_i^2). Although the variance is unknown, it is often assumed that the variance of the error of the i_{th} individual can be modelled as a power equation of the independent variables X_{i} (Furnival, 1961), i.e., $\sigma_i^2 = (X_i)^k$. The most reasonable value of the exponential term k is obtained by the optimizing method proposed by Harvey (1976), which consists of using the estimated errors of the unweighted equation ($\hat{e}_i$) as the dependent variable in the error variance model (Eq. (5)), or taking the natural logarithm of the equation (Eq. (6)).

$$\hat{e}_i^2 = \gamma \cdot (X_i)^k \tag{5}$$

$$In\,\hat{e}_i^2 = In\;\gamma + k \cdot In(X_i) \tag{6}$$

where the k parameter of Eq. (6) was estimated for each biomass equation by linear regression. The k values were subsequently included in the different weighting factors tested according to the independent variables used in the equations (i.e. d^{-k}, $(d^2)^{-k}$, h^{-k}, $(d^2h)^{-k}$). These weighting equations, which were selected individually for the biomass equations, were later used in the simultaneous fitting.

2.4. Model validation

Because the quality of fit does not necessarily reflect the quality of future prediction, validation is necessary to evaluate the predictive quality of the different biomass models (Myers, 1990). Model validation ensures that model predictions represent the most likely real outcome and increases the credibility of the model (Huang, 2002). According to several authors, the only method that can be regarded as "true" validation involves the use of a new independent dataset (Vanclay and Skovsgaard, 1997; Kozak and Kozak, 2003; Yang et al., 2004). In this study, an independent data set of 30 stools and 70 trees from 30 plots was used. Two validation statistics were calculated to assess the overall prediction performance of the fitted equations on this validation data set: (i) an estimate of average prediction error (APE) (Eq. (7)) (Weisberg, 1985); and (ii) mean bias (Eq. (8)) estimated as an overall average and summarized by diameter class similar to that used by Zhang (1997). Both statistics presented the errors in the same units as the biomass component evaluated. The APE statistic in the validation process is similar to the RMSE in the fit.

$$\text{APE} = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \widehat{Y}_i)^2}{n}} \tag{7}$$

$$\overline{Bias} = \frac{\sum_{i=1}^{n}(Y_i - \overline{Y}_i)}{n} \tag{8}$$

where Y_{i} is the observed or real value, $\widehat{Y}_i$ is the estimated value with the model, and n is the sample size of the validation data.

To examine the performance of the models in greater detail, the values of $\overline{Bias}$ were plotted against the independent variable classes. These graphs are of interest since they illustrate areas across systems of a grouping variable to which the biomass systems provide particularly poor or good predictions.

Validation of stand-level models would require felling and weighing all trees included in the inventory plots. As this task is very costly and often impossible to carry out, the stand-level equations were not validated.

3. Results

3.1. Individual tree-level biomass systems

3.1.1. Standing tree variables

The first system of biomass equations was fitted in order to estimate individual tree biomass (kg tree^{-1}) from standing tree variables. At this level, the different sizes of branches and foliage were combined in a single component (crown) in order to improve the fit.

Once each biomass component was fitted individually, simultaneous fitting was carried out by NSUR in order to guarantee the additivity of the tree biomass components. All of the independent variables included in the different biomass component equations (wood, bark and crown) were also included in the total biomass equation; additivity was guaranteed by setting restrictions to the parameters. Each biomass component equation was weighted according to the different weighting factors used in the individual fit. The weighting factors, the predicted values of the parameters, the condition number and goodness-of-fit statistics obtained by simultaneous fitting in the set of three biomass equations are shown in Table 2. All the parameter estimates were found to be significant at $P < 0.05$. The best fits were obtained in wood and total biomass component. The condition numbers obtained in the fits (Table 2) did not indicate severe problems of multicollinearity in the models.

Plots of the values predicted from the different biomass equations against the observed values are shown in Fig. 3.

3.1.2. Felled tree variables

The second system enables estimation of individual tree biomass (kg tree^{-1}) from felled tree variables. Initially, wood, bark and crown were considered as the different biomass components. However, we finally decided to combine wood and bark in a single component (stem) for an improved fit.

Graphical analysis revealed the existence of heterocedasticity in the crown biomass component; as a consequence, this component was fitted again by weighted regression. The system of equations was fitted simultaneously to ensure additivity. The weighting factor, the parameter estimates and the goodness-of fit statistics of the simultaneous fitting are shown in Table 3. All the parameter estimates were found to be significant at $P < 0.05$. The condition number resulting from the fits did not indicate multicollinearity.

Table 2
Weighting factors, parameter estimates, associated approximate standard errors and goodness of fit measures for the simultaneous fitting of standing tree equations.

Equation	W. factor	b_{ij}	Estimate	Std. error	$Pr > \|t\|$	RMSE	R^2	CN
$w_{\mathrm{wood}} = b_{01} \cdot (d^2 \cdot h)^{b_{11}}$	$(d^2 \cdot h)^{1.276}$	b_{01}	0.01391	0.0022	<0.0001	27.21	0.9456	21.99
		b_{11}	1.006	0.0167	<0.0001			
$w_{\mathrm{bark}} = b_{02} \cdot h^{b_{12}} \cdot (d^2)^{b_{22}}$	$(h)^{3.049}$	b_{02}	0.004119	0.0012	0.0014	2.720	0.9216	42.35
		b_{12}	1.086	0.1188	<0.0001			
		b_{22}	0.7889	0.0311	<0.0001			
$w_{\mathrm{crown}} = b_{03} \cdot h^{b_{13}} (d^2)^{b_{23}}$	$(d^2)^{1.357}$	b_{03}	0.5408	0.2203	0.0158	22.50	0.8211	38.61
		b_{13}	-1.439	0.2016	<0.0001			
		b_{23}	1.386	0.0519	<0.0001			
$w_{\mathrm{total}} = w_{\mathrm{wood}} + w_{\mathrm{bark}} + w_{\mathrm{crown}}$	–	–	–	–	–	42.21	0.9420	45.07

Note: w_i the dry weight of the i biomass component (kg), d is the diameter at breast height (cm), h is the total height (m), b_{ij} fitting parameters, RMSE root mean square error, R^2 coefficient of determination, CN the condition number.

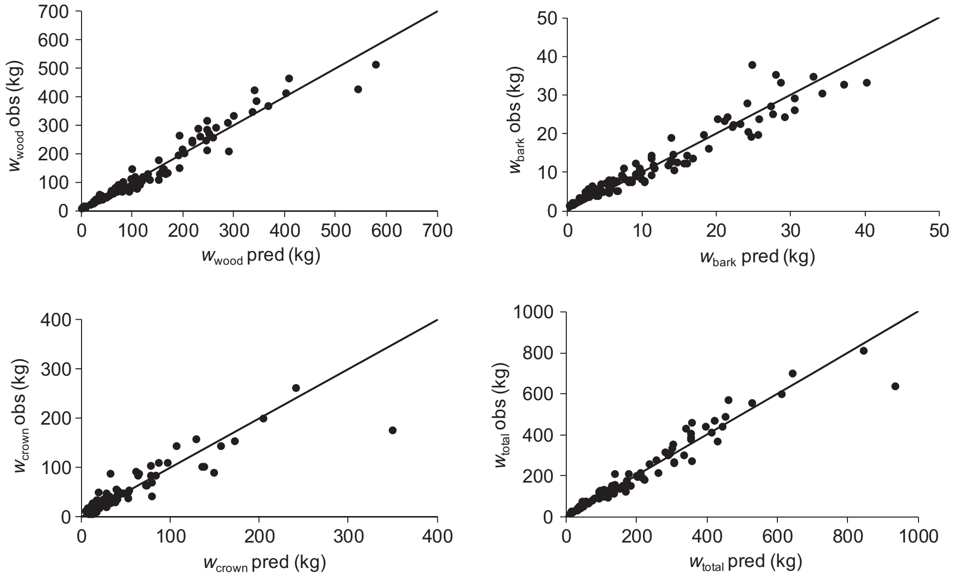


Fig. 3. Plot of predicted values against observed values for the different biomass components and for the total biomass of the standing tree variables at the individual tree level.

Table 3
Weighting factors, parameter estimates, associated approximate standard errors and goodness of fit measures for the simultaneous fitting of felled tree equations.

Equation	W. factor	b_{ij}	Estimate	Std. error	$Pr > \|t\|$	RMSE	R^2	CN
$w_{\mathrm{stem}} = b_{01} \cdot d_{\mathrm{stump}}^{b_{11}} \cdot h_{\mathrm{stump}}^{b_{21}}$	–	b_{01}	0.2641	0.0691	0.0002	45.49	0.8743	25.65
		b_{11}	1.800	0.0691	<0.0001			
		b_{21}	0.1537	0.0320	<0.0001			
$w_{\mathrm{crown}} = b_{02} \cdot d_{\mathrm{stump}}^{b_{12}}$	$(d_{\mathrm{stump}})^{4.525}$	b_{02}	0.05182	0.00910	<0.0001	27.90	0.7191	15.31
		b_{12}	2.057	0.0537	<0.0001			
$w_{\mathrm{total}} = w_{\mathrm{stem}} + w_{\mathrm{crown}}$	–	–	–	–	–	62.13	0.8757	26.99

Note: w_i is the dry weight of the i biomass component (kg), d_{stump} is the diameter of the stump (cm), h_{stump} is the stump height (cm), b_{ij} fitting parameters, RMSE root mean square error, R^2 coefficient of determination, CN the condition number.

3.2. Stool-level biomass system

The third system of biomass equations provides information about the stool biomass in different components (kg stool^{-1}). In the fit, the stool wood and the stool bark component were considered together as the stool stem component because they provide a better fit in this form.

Heterocedasticity was detected in the crown biomass component, and therefore this equation was fitted again by weighted regression. The NSUR method was applied for the simultaneous fitting of both sets of equations (stem and crown). The weighting factor, the estimation of the parameters and statistics for the simultaneous fitting are shown in Table 4. The condition numbers did not indicate severe multicollinearity.

3.3. Stand-level biomass system

The final system of biomass equations was calculated in order to estimate the total stand biomass (t ha^{-1}) by use of different stand variables as independent variables. In this case, heterocedasticity was detected in the different components evaluated (wood, bark and crown), so they were fitted again by weighted regression.

Table 4
Weighting factors, parameter estimates, associated approximate standard errors and goodness of fit measures for the simultaneous fitting of stool equations.

Equation	W. factor	b_{ij}	Estimate	Std. error	$Pr > \|t\|$	RMSE	R^2	CN
$W_{stem} = b_{01} \cdot n_{tree}^{b_{11}} \cdot d_{mean}^{b_{21}}$	–	b_{01}	0.2244	0.07350	0.0039	58.83	0.9407	33.84
		b_{11}	0.9790	0.03100	<0.0001			
		b_{21}	2.114	0.09380	<0.0001			
$W_{crown} = b_{02} \cdot n_{tree} + b_{12} \cdot g$	$(n_{tree})^{0.1671}$	b_{02}	-9.705	3.084	0.0030	40.23	0.8447	47.47
		b_{12}	0.1521	0.007020	<0.0001			
$W_{total} = W_{stem} + W_{crown}$	–	–	–	–	–	66.68	0.9627	34.64

Note: W_i is the dry weight of the i biomass component (kg), d_{mean} is the mean diameter of all the trees in the stool (cm), n_{tree} is the number of trees in the stool, g is the basal area of the stool (cm^2) b_{ij} are fitting parameters, RMSE is the root mean square error, R^2 is the coefficient of determination, CN is the condition number.

Table 5
Weighting factors, parameter estimates, associated approximate standard errors and goodness of fit measures for the simultaneous fitting of stand equations.

Equation	W. factor	b_{ij}	Estimate	Std. error	$Pr > \|t\|$	RMSE	R^2	CN
$W_{wood} = b_{01} \cdot d_0^{b_{11}} \cdot G^{b_{21}}$	$(d_0)^{3.203}$	b_{01}	0.8582	0.1946	<0.0001	27.72	0.7289	35.83
		b_{11}	0.8474	0.08490	<0.0001			
		b_{21}	0.5537	0.06340	<0.0001			
$W_{bark} = b_{02} \cdot H_0^{b_{12}} \cdot G^{b_{22}}$	$(H_0)^{2.836}$	b_{02}	0.2449	0.09660	0.0136	2.150	0.6869	47.34
		b_{12}	0.4847	0.1723	0.0064			
		b_{22}	0.6431	0.08690	<0.0001			
$W_{crown} = b_{03} \cdot d_0^{b_{13}} \cdot H_0^{b_{23}} \cdot G^{b_{33}}$	$(d_0)^{1.393}$	b_{03}	14.31	2.943	<0.0001	7.290	0.6399	76.99
		b_{13}	1.221	0.09180	<0.0001			
		b_{23}	−1.649	0.1108	<0.0001			
		b_{33}	0.4965	0.05930	<0.0001			
$W_{total} = W_{wood} + W_{bark} + W_{crown}$	–	–	–	–	–	33.56	0.7045	105.3

Note: W_i is the dry weight of the i biomass component (kg), d_0 is the dominant diameter in the stand (cm), H_0 is the average height of the 100 thickest trees per hectare (m), G is the basal area (m^2 ha^{-1}), b_{ij} are fitting parameters, RMSE is the root mean square error, R^2 is the coefficient of determination.

The weighting factors, parameter estimates and statistics of the simultaneous fitting are shown in Table 5. The condition number resulting from the simultaneous fitting was 105.31, which indicates that some problems of multicollinearity may arise (Belsey, 1991). However, the model selected had the most restrictive condition number and the level of multicollinearity was considered acceptable. All of the parameters in the equation were highly significant, so that the multicollinearity problems were not considered important because they would only affect the confidence intervals for the regression coefficients. Nonetheless, it is recommended that models with less severe multicollinearity should be used whenever possible (Kozak, 1997).

3.4. Model validation

The statistics used in model validation are shown in Table 6. The APE generally increased in the following order: standing tree equations (25.77 kg tree^{-1}), felled tree equations (46.76 kg tree^{-1}), stool equations (53.76 kg stool^{-1}), for the total biomass components evaluated; the same applies to the other biomass components. All of the $\overline{Bias}$ values obtained for the standing tree variables were similar (close to zero), which indicates that the equations provide accurate predictions. However, the values obtained for this statistic in the other systems (felled tree and stool) were far from zero. Despite this, the felled tree and the fitted stool tree biomass equations are useful when the only data available are the stool or stump dimensions. Although the $\overline{Bias}$ values indicate that the woody part of the tree was always overestimated (negative values) in the biomass equations, the crown component equations underestimated (positive values) the biomass in all the different systems fitted. The total biomass was more variable as it was underestimated in the standing and felled tree equations and overestimated in the stool level equations.

The graphs of the mean prediction bias are shown in Fig. 4; the $\overline{Bias}$ variation interval increased in the following order: standing tree (±20 kg tree^{-1}), felled tree (±40 kg tree^{-1}) and stool equations (±80 kg stool^{-1}). There was little difference in $\overline{Bias}$ up to a DBH of approximately 25 cm, with trends of increasing bias for larger trees across all components (Fig. 4a and b). The crown and total biomass component presented an increasing tendency to underestimate the biomass of trees of DBH > 25 cm for the standing and the felled tree system, and the biomass of stools of surface > 1000 cm^2.

Table 6
APE and $\overline{Bias}$ statistics generated from the assessment of prediction errors for the three systems fitted in the validation process.

	APE (mean ± std error)	$\overline{Bias}$ (mean ± std error)
Standing tree		
Wood	15.55 ± 23.74	0.52 ± 28.43
Bark	2.38 ± 2.05	−1.52 ± 2.76
Crown	13.23 ± 31.42	1.65 ± 34.08
Total	25.77 ± 46.39	0.65 ± 53.15
Felled tree		
Stem	37.62 ± 26.43	−29.48 ± 35.40
Crown	15.81 ± 31.95	−4.47 ± 35.43
Total	46.76 ± 40.12	−33.95 ± 51.55
Stool		
Stem	51.53 ± 37.52	−34.96 ± 53.78
Crown	39.49 ± 57.43	14.18 ± 68.59
Total	53.76 ± 55.16	−4.55 ± 77.56

Note: APE is the average prediction error; $\overline{Bias}$ is the mean bias.

4. Discussion

Traditional coppice stands of sweet chestnut *C. sativa* Mill. in northern Spain are of great interest in terms of sustainable forestry, and therefore the productive capacity of these stands is also of great interest. This study aimed to develop the tools required to estimate biomass at different levels or according to the informa-

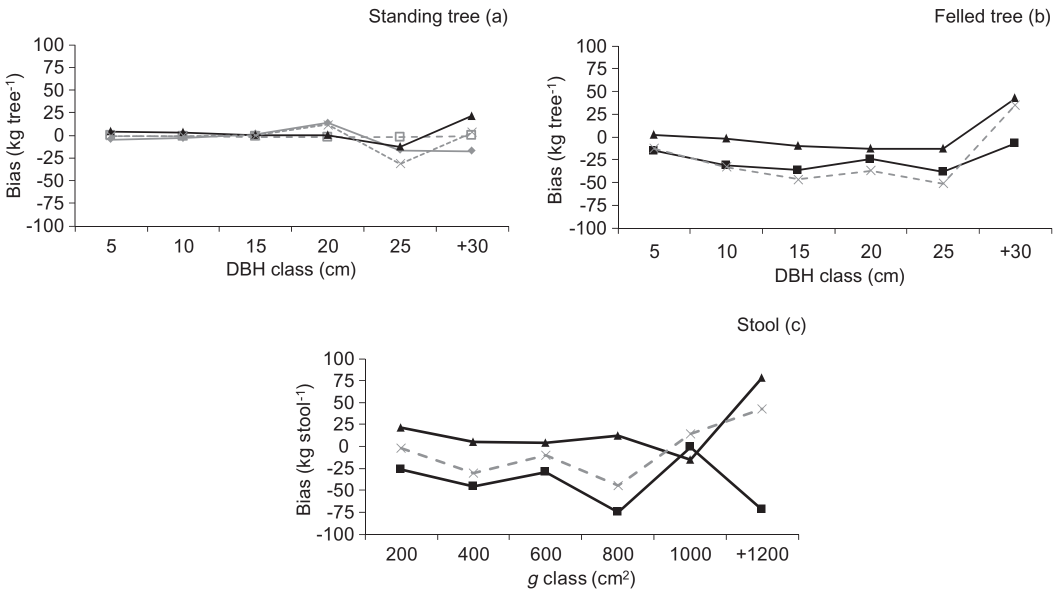


Fig. 4. Plot of DBH classes by components against mean prediction bias, for wood (-●-), bark (-□-), stem (-■-), crown (-▲-) and total (-x-) biomass for different systems: (a) standing tree, (b) felled tree and (c) stool biomass equations.

tion available. Such tools can be applied directly in forest management, forest assessment or in different research studies that require this type of information as a starting point.

In this study, different equations for estimating biomass at three levels (individual tree, stool and stand) were developed. For all models, the RMSE was low, the R^2 was high and multicollinearity was weak. Adequate estimates of the biomass of chestnut coppice stands in the north-west Spain were obtained, and a high percentage of total variability was explained, as in other studies (Leonardi et al., 1996; Cutini, 2000). Problems of heterocedasticity were resolved by weighted regression. Simultaneous fitting was carried out to ensure additivity. All the parameter estimates were found to be significant at $P > 0.05$. Because the NSUR method takes into account the contemporaneous correlations, it yields lower variance (Parresol, 2001) and parameters with lower standard errors than other types of analysis.

For the individual tree level system using standing tree variables, diameter at breast height and height were selected as predictive variables for all biomass components. Although it is known that diameter, height and biomass are closely related (Satoo and Madgwick, 1982), height is not always included in biomass equations together with diameter because both are highly correlated and the increased accuracy resulting from inclusion of height is negligible (Jokela et al., 1986; Ter-Mikaelian and Korzukhin, 1997; Johansson, 1999; Porté et al., 2002; Jenkins et al., 2003). In the present study, the use of height as a second independent variable for the standing tree equations was required in order to improve the predictive ability of the biomass component equations, which finally accounted more than 80% of the total variability, as also reported by other authors (Leonardi et al., 1996; Reed and Tomé, 1998; Cutini, 2000; Santa Regina, 2000; Montero et al., 2005). Some crown variables have been found to work well in predicting crown fractions (Clark, 1982; Satoo and Madgwick, 1982; Carvalho and Parresol, 2003). In this case, inclusion of crown variables did not explain higher levels of variability for the different models evaluated, and therefore these variables were not finally included. Some studies included age as an independent variable, along with diameter and height, in biomass models (Bédéneau, 1988; Porté et al., 2002; Saint-André et al., 2005), but in this study, age was not considerate as an explanatory variable.

For the individual tree level system that used felled tree variables, the diameter and height of stump were included as independent variables. Inclusion of these variables increased the accuracy of the system by more than 70%. These types of equations are very useful for estimating biomass when the only information available is the stump dimensions (e.g. after felling, thinning, strong winds, etc.). Several equations have been used to estimate diameter at breast height or individual tree volume from the stump dimensions. However, equations have not been used to estimate biomass from stump variables.

The main purpose of the stool biomass level equations was to simplify the inventory to quantity the biomass per stool by measurement of only one or two trees per stool (e.g. one or two trees of maximum diameters and the corresponding heights). These variables explained only 50% of the total sample variability, which was therefore estimated from variables that were more difficult to measure than the others (number of trees, mean diameter of all the trees, basal area of the stool). Finally, the system of equations accounted for more than 80% of the total variability.

For the stand level, the inventory would have been simplified by inclusion of a single variable such as dominant diameter, but this variable showed a low degree of accuracy in the estimation (relative to the 60–70% of the total variability accounted in this study). Similar results were obtained by Vega-Alonso et al. (1993), Barrio-Anta et al. (2006) and Castedo-Dorado et al. (2009). As a consequence, dominant diameter, basal area and dominant height were finally selected as significant variables for predicting biomass of the different components. These variables by themselves explained more than 63% of the variability and provided accurate estimates of stand biomass by measuring only height of a few dominant trees. On the contrary, stand density did not provide a significant improvement over the different components evaluated. Both stand basal area and dominant height have been widely used by researchers to predict volume yield (i.e. Brooks and Wiant, 2004), which is closely related to stem wood biomass. Other variables such as stand density and dominant diameter are included in some biomass component equations (especially leaves/needles and branches), to take into account the stage of stand development and the level of competition within the stand (Bi et al., 2010).

Validation with an independent data for the first two levels (individual tree and stool) confirmed the applicability of the different biomass equations estimated for chestnut coppices systems in north-western Spain. Both validation statistics, APE and $\overline{Bias}$, increased in the following order: standing tree, felled tree and stool equations. Similar results were obtained by Case and Hall (2008). Despite the less accurate predictions of the stool and felled tree equations, both of these systems are useful if the only available data are the stool or stump dimensions. The magnitude of $\overline{Bias}$ did not vary greatly in relation to tree size and only varied notably for the largest classes. This can be partly attributed to the relatively small number of trees and stools sampled in the larger classes (based on diameter or basal area, respectively).

5. Conclusions

A three level system for biomass estimation in chestnut coppice stands in north-western Spain was developed according to the degree of detail of data: individual tree, stool or stand. The first level enabled calculation of individual tree biomass for different components of standing or felled trees: wood, bark, crown and total biomass for the former, and stem, crown and total biomass for the latter. The second level was fitted for three stool biomass components: stem, crown and total biomass. The last level was fitted in order to calculate stand biomass for four different components: wood, bark, crown and total biomass.

As expected, the accuracy of the different biomass component equations differed for each level studied, although the coefficients of determination were high for all: more than 80% for the standing tree variables and the stump equations, more than 70% for the felled tree variables and more than 60% for the stand equations. Different ranges of RMSE values were obtained for the biomass components evaluated; the root mean square error varied between 24 and 58 kg for the stem component, between 7 and 40 kg for the crown component, and between 33 and 66 kg for the total component, for the different levels evaluated. The relatively lower accuracy of crown component models may be due to different factors: (i) the sensitivity of the components to sampling opportunity, and (ii) differences in the distribution of dry matter between crown and stem depending on stand age and stocking density.

Validation by use of an independent data set reflected the quality of predictions and increased the credibility of the models. For the stand level, it is advisable to fell all of the trees in some plots to obtain data to complete the validation process for all levels studied.

The advantage of the equations presented is that they are simple, practical and easy to use, and they provide rapid and inexpensive biomass estimates with low data requirements. The information obtained with these biomass equations, which is applicable to data on individual trees (standing or felled trees), stools or stands, can be applied to forest inventories and to a great variety of types of studies (e.g. amount of fuel and the fire propagation conditions, carbon sequestering, site sustainability, etc.)

Acknowledgments

The authors are grateful to the Ministry of Science and Innovation of Spain (MICIN) and the Plan for Science, Technology and Innovation of the Principality of Asturias (PCTI) for funding the research project "Forest and industrial evaluation of Spanish chestnut" (VALOCAS). These authors also thank The Asturian Energy Foundation (FAEN) for funding the research project "Characterization, quantification and zonification of chestnut residues as a biomass resource" (EM-172-09) for the validation data.

References

Álvarez-Vergel, R., Blanco-González, J., Colina-Vuelta, A., Fernández-Bustamante, C., Fernández-Martínez, M., García-de la Fuente, L., García-Fernández, R., González-Álvarez, J., Roces-Díaz, J.V., García-Rubio, U., 2011. Estrategia regional de aprovechamiento sostenible de la biomasa forestal del Principado de Asturias. Diseño de Programas y Medidas. Gobierno del Principado de Asturias. Consejería de Medio Rural y Pesca; Consejería de Industria y Empleo. 96 pp.

Balboa-Murias, M.A., Rodríguez-Soalleiro, R., Merino, A., Álvarez-González, J.G., 2006. Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives. Forest Ecology and Management 237, 29–38.

Barrio-Anta, M., Balboa-Murias, M.A., Castedo-Dorado, F., Diéguez-Aranda, U., Álvarez-González, J.G., 2006. An ecoregional model for estimating volume, biomass and carbon pools in maritime pine stands in Galicia (northwestern Spain). Forest Ecology and Management 223, 24–34.

Bédéneau, M., 1988. Croissance du taillis de châtaignier en France. premiers résultats. Annales des Sciences Forestieres 45 (3), 265–274.

Belsey, D.A., 1991. Conditioning Diagnostics, Collinearity and Weak Data in Regression. Wiley, New York.

Bi, H., Long, Y., Turner, J., Lei, Y., Snowdon, P., Li, Y., Harper, R., Zerihum, A., Ximenes, F., 2010. Additive prediction of aboveground biomass for *P. radiate* (D. Don) plantations. Forest Ecology and Management 12, 2301–2314.

Bond-Lamberty, B., Wang, C., Gower, S.T., 2002. Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere 32, 1441–1450.

Borders, B.E., 1989. System of equations in forest stand modeling. Forest Science 35, 548–556.

Bourgeois, C., Sevrin, É., Lemaire, J., 2004. Les guides du sylviculteur. Le châtaignier un arbre, un bois. Deuxième édition. Institut pour le Développement Forestier.

Brooks, J.R., Wiant, H.V., 2004. A simple technique for estimating cubic volume yields. Forest Ecology and Management 203, 373–380.

Carvalho, J.P., Parresol, B.R., 2003. Additivity in tree biomass components of Pyrenean oak (*Quercus pyrenaica* Willd.). Forest Ecology and Management 179, 269–276.

Case, B.S., Hall, R.J., 2008. Assessing prediction errors of generalized tree biomass and volume equations for the boreal forest region of west-central Canada. Canadian Journal of Forest Research 38, 878–889.

Castedo-Dorado, F., Crecente-Campo, F., Álvarez-González, J.G., Barrio-Anta, M., 2009. Development of a stand density management diagram for radiate pine stands including assessment of stand stability. Forestry 82, 1–16.

Clark, A., 1982. Predicting biomass production in the South. In: Hotvedt, J.E., Jackson, B.D. (Eds.). Predicting Growth and Yield in the Mid-South. 1st Annual For. Symp. Louisiana State University, Baton Rouge, L.A. pp. 119–139

Clutter, J.L., Forston, J.C., Pienaar, L.V., Brister, G.H., Bailey, R.L., 1983. Timber Management: A Quantitative Approach. Wiley, New York.

Cunia, T., 1986. Construction of tree biomass tables by linear regression techniques. In: Estimating Tree Biomass Regressions and their Error. Proceedings of the Workshop on tree Biomass Regression Functions and their Contribution to the Error of Forest Inventory Estimates. 26–30 May. Syracuse, New York. pp. 27–37.

Cunia, T., 1988. On the error of biomass regressions and the corresponding inventory estimates. In: Daniels, R.A., Watson, W.F., Savelle, I.W. (Eds.). Proc. of the 9th Annual Southern Forest Biomass Workshop. Mississippi State University, Mississippi State. pp. 93–109.

Cunia, T., Briggs, R.D., 1984. Forcing additivity of biomass tables: some empirical results. Canadian Journal of Forest Research 14, 376–384.

Cutini, A., 2000. Biomass, litterfall and productivity in chestnut coppices of various age at Monte Amiata (Central Italy). Ecologia Mediterranea 26 (1–2), 33–41.

DGCONA, 2003. Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España.

Furnival, G.M., 1961. An index for comparing equations used on constructing volume tables. Forest Science 7, 337–341.

Gallardo, J.F., Martin, A., Moreno, G., Santa Regina, I., 1998. Nutrient cycling in deciduous forest ecosystems of the Sierra de Gata mountains: nutrient supplies to the soil through both litter and throughfall. Annales des Sciences Forestieres 55, 771–784.

Gandullo, J.M., Blanco, A., Sánchez, O., Rubio, A., Elena, R., Gómez, V., 2004. Las estaciones ecológicas de los castañares españoles. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria. Ministerio de Educación y Ciencia.

Harvey, A.C., 1976. Estimating regression models with multiplicative heterocedasticity. Econometrica 44, 461–465.

Huang, S., 2002. Validating and localizing growth and yield models: procedures, problems and prospects. In: Proceedings of IUFRO Workshop on Reality, Models and Parameter Estimation: The Forestry Scenario. Sesimbra.

Jenkins, J.C., Chojnachky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. Forest Science 49, 12–35.

Johansson, T., 1999. Biomass equations for determining fractions of pendula and pubescens birches growing on abandoned farmland and some practical implications. Biomass Bioenergy 16, 223–238.

Jokela, E.J., Van Grup, K.P., Briggs, R.D., White, E.H., 1986. Biomass estimation equations for Norway spruce in New York. Canadian Journal of Forest Research 16, 413–415.

Kirschbaum, M.U.F., 1996. The carbon sequestration potential of tree plantations in Australia. In: Eldridge, K.G., Crowe, M.P., Old, K.M. (Eds.), Environmental Management: The Role of Eucalyptus and Other Fast Growing Species. CSIRO Forestry and Forest Products.

Kozak, A., 1997. Effects of multicollinearity and autocorrelation on the variable-exponent taper functions. Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestière 27, 619–629.

Kozak, A., Kozak, R., 2003. Does cross validation provide additional information in the evaluation of regression models? Canadian Journal of Forest Research 33, 976–987.

Leonardi, S., Regina, I.S., Rapp, M., Gallego, H.A., Rico, M., 1996. Biomass, litterfall and nutrient content in *Castanea sativa* coppice stands of southern Europe. Annales des Sciences Forestières 53, 1071–1081.

MARM, 2008. Anuario de Estadística Forestal, Área de Medio Ambiente, Madrid, España. p. 104.

Montero, G., Ruiz-Peinado, R., Muñoz, M., 2005. Producción de biomasa y fijación de CO_2 por los bosques españoles. Monografías INIA: Serie Forestal no 13.

Myers, R.H., 1990. Classical and Modern Regression with Applications, Second ed. Duxbury Press, Belmont. CA.

Parresol, B.R., 1999. Assessing tree and stand biomass: a review with examples and critical comparison. Forest Science 45 (4), 573–593.

Parresol, B.R., 2001. Additivity of nonlinear biomass equations. Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestière 31, 865–878.

Patricio, M.S., Monteiro, M.L., 2005. Biomass equations for Castanea sativa High Forest in the Northwest of Portugal. In: Abreu, C.G., Rosa, E., Monteiro, A.A. (Eds.), Proc. Third Intl. Chestnut Congress, Acta Hort. 693. pp. 727–732.

Pires, A.L., Portela, E., 2005. Impact of management practices on chestnut grove nutrient budgets. In: Proceedings of the Third International Chestnut Congress. pp. 677–684.

Porté, A., Trichet, P., Bert, D., Loustau, D., 2002. Allometric relationships for branch and tree woody biomass of Maritime pine (*Pinus pinaster* Ait.). Forest Ecology and Management 158, 71–83.

Ranger, J., Félix, C., Bouchon, J., Nys, C., Ravart, M., 1990. Dynamique d'incorporation du carbone et des éléments nutritifs dans un taillis simple de châtaignier (*Castanea sativa* Miller). Annales des Sciences Forestières 47, 413–433.

Reed, D.D., Green, E.J., 1985. A method of forcing additivity of biomass tables when using nonlinear models. Canadian Journal of Forest Research 15, 1184–1187.

Reed, D., Tomé, M., 1998. Total aboveground biomass and net dry matter accumulation by plant component in young *Eucalyptus globulus* in response to irrigation. Forest Ecology and Management 103, 21–32.

Reed, D.D., Liechty, H.O., Jones, W.A., Zhang, Y., 1996. Above and belowground dry matter accumulation pattern derived from dimensional biomass relationships. Forest Science 42, 236–241.

Ryan, T.P., 1997. Modern Regression Methods. John Wiley & Sons, New York.

SADEI, 2008. Anuario estadístico de Asturias. Instituto Asturiano de Estadística. Gobierno del Principado de Asturias, Oviedo, Spain.

Saint-André, L., M'Bou, A.T., Mabiala, A., Mouvondy, W., Jourdan, C., Roupsard, O., Deleporte, P., Hamel, O., Nouvellon, Y., 2005. Age-related equations for above- and below-ground biomass of a Eucalyptus hybrid in Congo. Forest Ecology and Management 205, 199–214.

Salazar, S., Sánchez, L.E., Galindo, P., Santa Regina, I., 2010. Above-ground tree biomass equations and nutrient pools for a paraclimax chestnut stand and for a climax oak stand in the Sierra de Francia Mountains, Salamanca, Spain. Scientific Research and Essays 5 (11), 1294–1301.

Santa Regina, I., 2000. Organic matter distribution and nutrient fluxes within a sweet chestnut (*Castanea sativa* Mill.) stand of the Sierra de Gata, Spain. Annals of Forest Science 57, 691–700.

SAS Institute Inc., 2004. SAS/STAT®. 9.1. User's Guide. SAS Institute Inc., Cary, NC.

Satoo, T., Madgwick, H.A.I., 1982. Forest Biomass. Forestry Science. Kluwer Academic Publishers Group, Holanda.

Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass equations for sixty-five North American tree species. Forest Ecology and Management 97, 1–24.

Vanclay, J.K., Skovsgaard, J.P., 1997. Evaluating forest growth models. Ecological Modeling 98, 1–12.

Vega-Alonso, P., Vega-Alonso, G., González-Rosales, M., Rodríguez San José, A., 1993. Mejora del Pinus pinaster Ait. en Galicia. I Congreso Forestal Español, 14–18 de junio de 1993, Lourizán, Pontevedra. Tomo II. pp 129–134.

Wang, C., 2006. Biomass allometric equations for 10 co-occurring tree species in Chinese temperate forests. Forest Ecology and Management. 222, 9–16.

Waring, R.H., Running, S.W., 1998. Forest Ecosystems: Analysis at Multiple Scales, Second ed. Academic Press, San Diego, CA.

Weisberg, S., 1985. Applied Linear Regression, Second ed. John Wiley and Sons, Inc.

Yang, Y., Monserud, R.A., Huang, S., 2004. Evaluation of diagnostic tests and their validating forest biometric models. Canadian Journal of Forest Research 34, 619–629.

Zhang, D., 1997. Cross-validation of non-linear growth functions for modeling tree height-diameter relationships. Annals of Botany 79, 251–257.

Stem taper functions for sweet chestnut (*Castanea sativa* Mill.) coppice stands in northwest Spain

Annals of Forest Science (2014) 71:761–770
DOI 10.1007/s13595-014-0372-6

ORIGINAL PAPER

Stem taper function for sweet chestnut (*Castanea sativa* Mill.) coppice stands in northwest Spain

**María Menéndez-Miguélez · Elena Canga ·
Pedro Álvarez-Álvarez · Juan Majada**

Received: 27 January 2014 / Accepted: 19 March 2014 / Published online: 8 April 2014

Abstract
• *Context* Despite the economic importance of *Castanea sativa* Mill. in northwest Spain, studies of its growth and yield are practically non-existent.
• *Aims* A compatible system formed by a taper function, a total volume equation, and a merchantable volume equation was developed for chestnut (*C. sativa* Mill.) coppice stands in northwest Spain.
• *Methods* Data from 203 destructively sampled trees were used for the adjustment. Outliers were removed with a non-parametric local adjustment, providing a final data set of measurements taken from 3,188 sections which was used to test five taper models (compatible and non-compatible). A second-order continuous autoregressive error structure was used to model the error term and account for autocorrelation. Presence of multicollinearity was evaluated with the condition number. Comparison of the models was carried out using overall goodness-of-fit statistics and graphical analysis.
• *Results* Results show that the models developed by Fang et al. in For Sci 46: 1–12, 2000 and Kozak in For Chron 80, N 4: 507–515, 2004 were superior to other equations in predicting diameter for chestnut coppice stands.
• *Conclusion* The compatible volume system developed by Fang et al. in For Sci 46: 1–12, 2000 was finally selected as it provided the best compromise between describing stem profile and also estimating merchantable height, merchantable volume, and total volume and therefore provides the first specific tool for more effective management of chestnut coppice stands.

Keywords Chestnut coppice · Volume system · Segmented model · Compatible equations

1 Introduction

Sweet chestnut (*Castanea sativa* Mill.) covers more than 2.5 million hectares in Europe, with a distribution reaching from the Southern Mediterranean to central, Atlantic, and Eastern Europe (Conedera et al. 2004). Chestnut forests have been recognized as habitats of interest in the European Natura 2000 network and are considered characteristic cultural landscapes of the Mediterranean and Atlantic regions (Díaz Varela et al. 2009). In northwest Spain, chestnut is the most important forest species, covering over 100,000 ha, mainly as coppice stands (DGCONA 2013). This area accounts for over 95 % of the potential area for chestnut coppice stands in Spain.

Although chestnut fruit production has traditionally driven management in the region, changes in markets and local economies have resulted in timber production becoming the main objective in most exploitation nowadays (Álvarez et al. 2000). The vitality of the chestnut root system, with stools capable of sustainably producing an abundance of shoots, and high productivity (8–16 m^3 ha^{-1} $year^{-1}$ depending on site conditions) facilitate management under a coppice system (Giudici et al. 2000). Chestnut coppice produces valuable

Handling Editor: Aaron R Weiskittel

Contribution of the co-authors María Menéndez-Miguélez supervised field work, analyzed data and wrote the paper. Elena Canga designed data collection, analyzed data, and reviewed the paper. Pedro Álvarez-Álvarez contributed to the discussion of the results and reviewed the paper. Juan Majada coordinated the research project.

M. Menéndez-Miguélez (✉) · E. Canga · J. Majada
Forest and Wood Technology Research Centre (CETEMAS), Finca Experimental "La Mata" s/n, Grado, Asturias, Spain
e-mail: mmenendez@cetemas.es
URL: http://www.cetemas.es

P. Álvarez-Álvarez
Research Group in Atlantic Forests (GIS-Forest), Department of Organisms and Systems Biology, Escuela Politécnica de Mieres (EPM), University of Oviedo, Campus Universitario de Mieres, C/Gonzalo Gutiérrez Quirós, 33600 Mieres, Spain

timber in relatively short rotations (20–40 years) compared to other hardwoods (Gallardo et al. 2000; Kerr and Evans 1993). The total volume (with bark) of sweet chestnut stands (high forest and coppice stands together) harvested in Spain during 2011 was 58,090 m^3 (MARM 2011), with more than 42.46 % of this total volume being formed by trees from coppice stands in northwest Spain.

Estimating timber volume stocks as accurately as possible is essential in forest management. It is therefore necessary to develop tools that allow the reliable estimation of tree volume using variables which are easy to measure in the field, such as diameter at breast height (D) and total height (H). One such tool is individual tree volume equations. However, these equations have the disadvantage of not being able to predict tree volume for wood products which are classified by merchantable size depending on log dimensions.

There are a number of ways to address this issue, the two most important of which are developing volume-ratio equations that predict merchantable volume as a percentage of total volume (Burkhart 1977; Clutter 1980; Reed and Green 1984) or using taper functions.

Taper functions describe stem taper (Brink and Gadow 1986; Kozak 1988; Riemer et al. 1995) and provide forest managers with estimates of (a) diameter at any point along the stem, (b) total stem volume, (c) merchantable volume and merchantable height to any top diameter and from any stump height, and (d) individual volumes for logs of any length at any height above the ground (Kozak 2004). Such functions can be implemented in different computer software specially developed for this type of calculation, such as GesMO (Diéguez-Aranda et al. 2009) or CubiFOR (Rodríguez et al. 2008). To develop this type of function, it is necessary to have a longitudinal data structure, that is, multiple measurements for each individual (Lindstrom and Bates 1990).

Ideally, a taper equation should be compatible, meaning that the volume computed by integration of the taper function should be equal to that calculated by a total volume equation (Clutter 1980; Demaerschalk 1972; Fang et al. 2000). Examples of compatible volume-estimating systems are the works carried out by Demaerschalk (1972), Goulding and Murray (1976), and Fang et al. (2000).

Prediction tools are essential to understand the development of forest stands and subsequently decide on the best management strategy. In Spain, many taper functions have been developed for different forest species (Barrio-Anta et al. 2007; Crecente-Campo et al. 2009; Diéguez-Aranda et al. 2006); however, there is currently no taper function available for chestnut coppice, either in Spain or elsewhere in the world. This work is a result of looking to remedy this gap in provision, and its main objective is to develop a taper function able to correctly describe the profile of and ensure appropriate estimates of stem volume using chestnut coppice stands in northwest Spain as a baseline. Specifically, we wish to focus on two questions: (a) Is it possible to correctly describe the huge variability of stem profiles in chestnut coppice stands given the high number of stems which may grow from a single stool, and (b) which model best describes this type of profile and its variability?

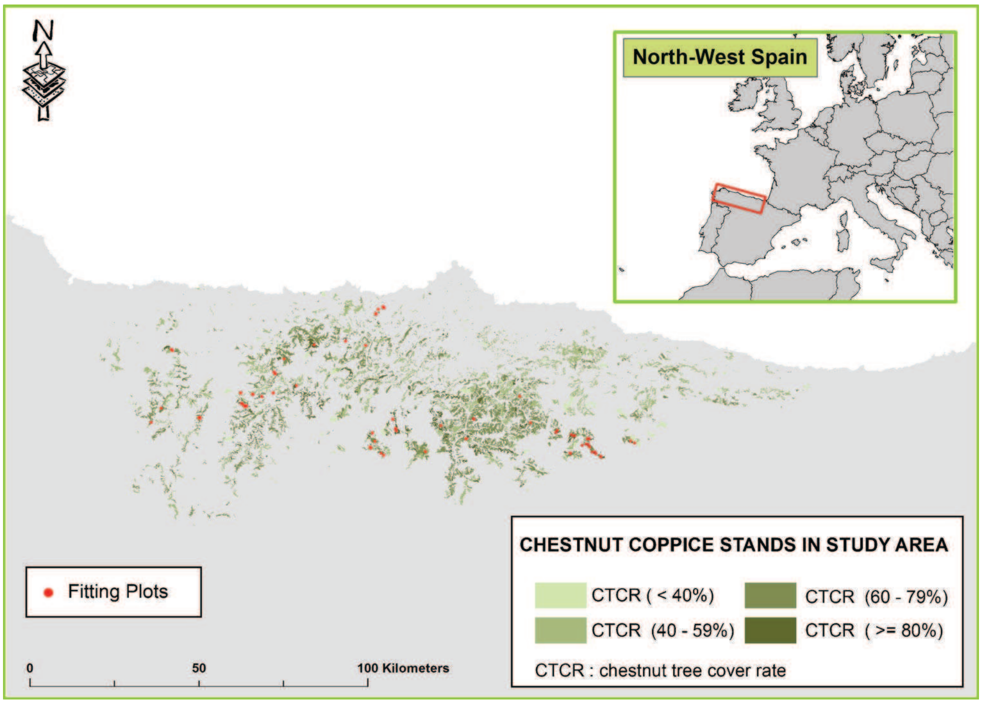


Fig. 1 Map showing cover rates for chestnut coppice stands in the study area. Fitting plots are indicated by *red dots*

Table 1 Descriptive statistics of tree and stand data sets used in the analysis for fitting and validation

	Fitting					Validation				
	n	Mean	Min	Max	Std. dev.	*n*	Mean	Min	Max	Std. dev.
Individual tree										
Nº logs	3,188	16.30	6	25	3.89	719	11.83	3	20	4.07
D	3,188	25.69	10.20	44.50	7.94	719	19.65	6.90	49.15	8.12
H	3,188	19.26	9.54	31.02	3.37	719	16.68	8.35	26.08	3.84
$n_{\text{tree\_a}}$	3,188	1.87	1	8	1.39	719	2.43	1	7	1.33
h_{stump}	3,188	0.12	0	0.60	0.10	719	0.14	0.020	0.68	0.14
V	3,188	0.35	0.011	1.85	0.30	719	0.19	0.020	1.01	0.19
Stand										
$n_{\text{ree\_b}}$	63	2.19	1	26	2.25	30	2.73	1	24	2.42
N	63	1,692.52	410.26	4,753.42	942.07	30	2,025.51	222.82	8,244.23	1,762.97
G	63	40.01	16.33	65.33	11.30	30	10.29	3.41	35.40	6.79
H_{m}	63	16.93	10.63	24.16	3.09	30	–	–	–	–
H_0	63	19.91	12.15	28.17	3.09	30	16.52	10.75	23.37	3.27

D diameter at breast height (cm), H height (m), n_{tree_a} number of stems from the stool where the sampled tree was cut, h_{stump} stump height (m), V total over bark stem volume (m^3), n_{tree_b} number of stems in the stool, N number of stems per hectare (stems ha^{-1}), G basal area (m^2 ha^{-1}), H_m mean height (m), H_0 average height of the 100 thickest trees per hectare (m)

2 Material and methods

2.1 Data

The data used in this study were collected in 70 coppice stands covering the existing range of ages, stand densities, and sites of this species in the region. Figure 1 shows the map with the locations of the stands used for the fitting data.

A total of 203 trees were felled and destructively sampled. Trees had to be healthy and of a standard shape (i.e., not forked nor excessively branched) and were selected in order to ensure a representative distribution of diameter and height classes (Table 1).

Before felling, diameter at breast height D (diameter at 1.3 m above the top of the stool, in cm) was measured to the nearest 0.1 cm for each tree. The trees were then felled and total bole length, that is, total height H, (in m) measured to the nearest 0.1 m. The trees were cut into 1-m logs, up to a top diameter of 7 cm, and measured to the nearest centimeter. Two perpendicular over bark diameters (d, cm) and two perpendicular bark thicknesses were measured to the nearest 0.1 cm in each cross section (at height h, in m, above the top of the stool). Over bark log volumes were calculated in cubic meters using Smalian's formula, and the top section was treated as a cone. Over bark total stem volume was obtained by summing the over bark log volumes and the volume of the top section. Finally, 3,282 pairs of diameter (d) at a certain height (h) measurements were used for the original fitting data set.

Data from an independent network of plots (established by the Atlantic Forest Systems Research Group (GIS-Forest), Department of Organisms and Systems Biology, University of Oviedo) was used for validation purposes. The height-diameter distributions for the fitting and validation samples are very similar (Fig. 2), indicating that robust conclusions can be reached from the validation analysis.

The scatterplot of relative diameter (d/D) against relative height (h/H) was examined visually to detect possible anomalies in the data. This first analysis detected a number of outliers (many of them corresponded to trees with abnormalities) which were removed. A second analysis was carried out with the systematic procedure proposed by Bi (2000) to detect and remove other possible outliers, whereby local adjustment

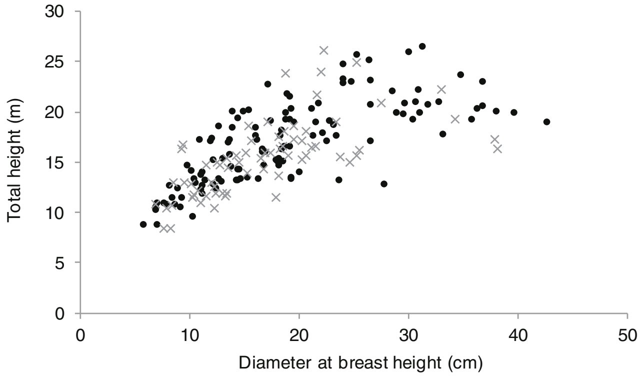


Fig. 2 Plot of diameter at breast height against total height of sampled trees (*black dot*) and validation sample (*multiplication sign*)

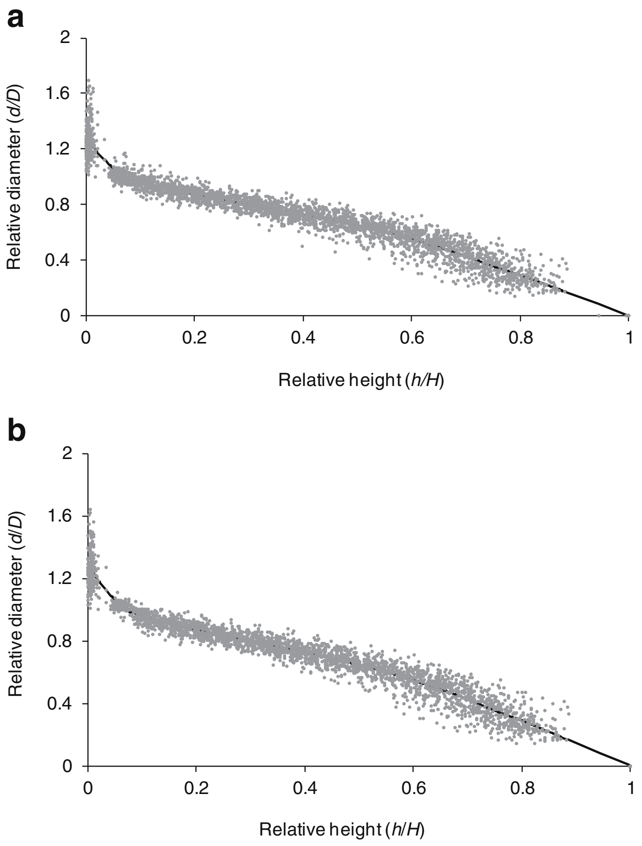


Fig. 3 Data points of relative diameter and relative height plotted with a local regression LOESS smoothing curve (smoothing factor=0.25) for all data (**a**) and after the elimination of outliers (**b**)

was performed by the LOESS procedure of SAS/STAT® (SAS Institute Inc. 2004a) with a smoothing factor of 0.25. Using this approach, the number of extreme values accounted for 2.83 % of total taper measurements. A small percentage of the extreme data points were the result of errors in measuring bole sections or in the transcription of field notes, but most were the result of measurements in sections where the tree was deformed due to abnormal growth or damage caused by the presence of chancre (*Cryphonectria parasitica* (Murr.) Barr.). Since taper functions are not intended for deformed stems, these data points were excluded from further analysis, resulting in a final total number of observations of 3,188, from 190 trees.

Figure 3a, b shows relative height against relative diameter together with the LOESS regression curve, the upper graphic showing all the collected data and that below, the data excluding outliers, respectively. Summary statistics of the final data used in this study for tree and stand variables, together with model validation data, are shown in Table 1.

2.2 Equations tested

We analyzed a total of five models, which are described below and whose expressions are shown in Table 2:

- Fang et al. (2000). Compatible system formed by a taper function, a total volume equation, and a merchantable volume equation. The taper equation is segmented with two attachment points and three form factors, one for each segment.
- Bi (2000). Non-compatible variable-exponent taper function.

Table 2 Fitted taper equations and their corresponding mathematical expression

Model	Expression		
Fang et al. (2000)	$d = c_1\sqrt{H^{(k-b_1)/b_1}(1-q)^{(k-\beta)/\beta}\alpha_1^{I_1+I_2}\alpha_2^{I_2}}$ $c_1 = \sqrt{\frac{a_0 D^{a_1} H^{a_2-k/b_1}}{b_1(r_0-r_1)+b_2(r_1-\alpha_1 r_2)+b_3\alpha_1 r_2}}$		
	$r_0 = \left(1-h_{\text{stump}}/H\right)^{k/b_1}$	$r_1 = (1-p_1)^{k/b_1}$	$r_2 = (1-p_2)^{k/b_2}$
	$\beta = b_1^{1-(I_1+I_2)} b_2^{I_1} b_3^{I_2}$	$\alpha_1 = (1-p_1)^{\frac{(b_2-b_1)k}{b_1 b_2}}$	$\alpha_2 = (1-p_2)^{\frac{(b_3-b_2)k}{b_2 b_3}}$
	$I_1=1$ if $p_1 \le q \le p_2$, 0 in all other cases $I_2=1$ if $p_2 < q \le 1$, 0 in all other cases $p_1=h_1/H$ y $p_2=h_2/H$		
Bi (2000)	$d = D\left[\frac{\ln\sin\left(\frac{\pi}{2}q\right)}{\ln\sin\left(\frac{1.3\pi}{2H}\right)}\right]^{a_1+a_2\sin\left(\frac{\pi}{2}q\right)+a_3\cos\left(\frac{3\pi}{2}q\right)+\frac{a_4\sin\left(\frac{\pi}{2}q\right)}{q}+a_5 D+a_6 q\sqrt{D}+a_7 q\sqrt{H}}$		
Kozak (2004)	$d = a_0 D^{a_1} H^{a_2} X^{b_1 q^4+b_2\left(1/e^{D/H}\right)+b_3 x^{0.1}+b_5 H^w+b_6 x}$		
Demaerschalk (1972)	$d_i = b_0 d^{b_1}(h-h_i)^{b_2} h^{b_3}$		
Thomas and Parresol (1991)	$\left(\frac{d_i}{d}\right)^2 = b_1(q-1) + b_2\sin(b_4\pi q) + b_3\text{cotan}\left(\frac{\pi q}{2}\right)$		

D over bark diameter at breast height (at 1.30 m above the top of the stool, cm), *d* over bark diameter at height *h* (cm), *H* total tree height (m), *h* height from top of the stool to top diameter *d* (m), h_{stump} stump height (m), *V* total over bark stem volume (m^3), a_0, ..., a_2, ..., b_0, ..., b_6, p_1, p_2 parameters to be estimated, *k* equal to $\pi/40000$, *q* is equal to h/H

- Kozak (2004). Non-compatible variable-exponent taper function.
- Demaerschalk (1972). Power function whose main advantage is that the volume equations obtained by integrating are algebraically compatible with classic taper functions.
- Thomas and Parresol (1991). Trigonometric compatible model.

Table 4 Goodness-of-fit statistics and condition number of the taper functions evaluated

Model	RMSE	*AICd*	R^2_{adj}	CN
Fang et al. (2000)	1.188	0	0.9838	62.40
Kozak (2004)	1.223	184.24	0.9828	62.57
Demaerschalk (1972)	1.537	1638.71	0.9728	62.81
Thomas and Parresol (1991)	2.055	3490.69	0.9515	3.74

RMSE root mean square error, *AICd* Akaike's information criterion in differences, R^2_{adj} adjusted coefficient of determination, *CN* condition number

2.3 Model fitting and selection

The models tested were fitted by non-linear regression with the MODEL procedure of SAS/ETS® (SAS Institute Inc. 2004b) using generalized least squares for non-linear models.

Of the different options to estimate the parameters in the systems where the taper equation includes a total volume equation (Fang and Bailey 1999; Fang et al. 2000; Goulding and Murray 1976), in this study we prioritized the taper function, setting this first and subsequently performing the predicted volume calculation from the estimation parameters obtained.

To avoid problems in the estimation of the parameters, a value of 0.001 was assigned to the final diameter of the top section. Similarly, a value of 0.001 was also subtracted from the heights equal to the total height, that is $h=H-0.001$; values which are lower than the appreciation limit are used in the data collection. This approach allows the use of the entire data set for fitting and does not significantly change parameter estimates (Diéguez-Aranda et al. 2006).

There are several problems associated with stem taper and volume equation analyses that violate the fundamental least squares assumption of independence and equal distribution of errors with zero mean and constant variance. One of the most common is the presence of autocorrelation in the data as a result of working with multiple observations on each tree. To resolve this problem, the error term was modeled using a continuous autoregressive error structure (CAR(x)), which allows the model to be applied to irregularly spaced, unbalanced data (Zimmerman and Nuñez-Antón 2001).

Another problem in taper functions is multicollinearity, which refers to the existence of high intercorrelations among the independent variables in multiple linear or non-linear regression analyses. To evaluate the presence of multicollinearity, we used the condition number (CN). According to Belsey (1991), if the condition number is between 5 and 10, collinearity is not a major problem; if it is in the range of 30–100, then there are problems associated with collinearity; and if it is in the range of 1,000–3,000, the problems are severe.

The criteria used for the comparison of the models were based on the residual plot analysis and statistical analysis of the goodness-of-fit statistics: adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), and Akaike's information criterion in differences (*AICd*).

Table 3 Parameter estimates (approximated standard error in parentheses) for the models analyzed

Parameter	Fang et al. (2000)	Bi (2000)	Kozak (2004)	Demaerschalk (1972)	Thomas and Parresol (1991)
a_0	5.542×10^{-5} (3.7×10^{-6})		0.8600 (0.029)		
a_1	1.914 (0.015)		0.9781 (0.0084)		
a_2	0.936 (0.027)		0.08444 (0.015)		
b_0				1.520 (0.061)	
b_1	9.869×10^{-6} (1.61×10^{-7})	Convergence was not achieved	0.7844 (0.029)	0.9567 (0.0098)	−1.00228 (0.0065)
b_2	3.362×10^{-5} (2.99×10^{-7})		−0.3341 (0.040)	0.8898 (0.0070)	0.1107 (0.0036)
b_3	2.667×10^{-5} (3.79×10^{-7})		0.4866 (0.016)	−0.9378 (0.019)	3.851×10^{-7} (2.93×10^{-8})
b_5			−0.01954 (0.0021)		
b_6			0.2318 (0.026)		
p_1	0.07191 (0.0014)			0.7258 (0.025)	0.8367 (0.024)
p_2	0.5590 (0.0101)			0.3936 (0.020)	0.3639 (0.019)

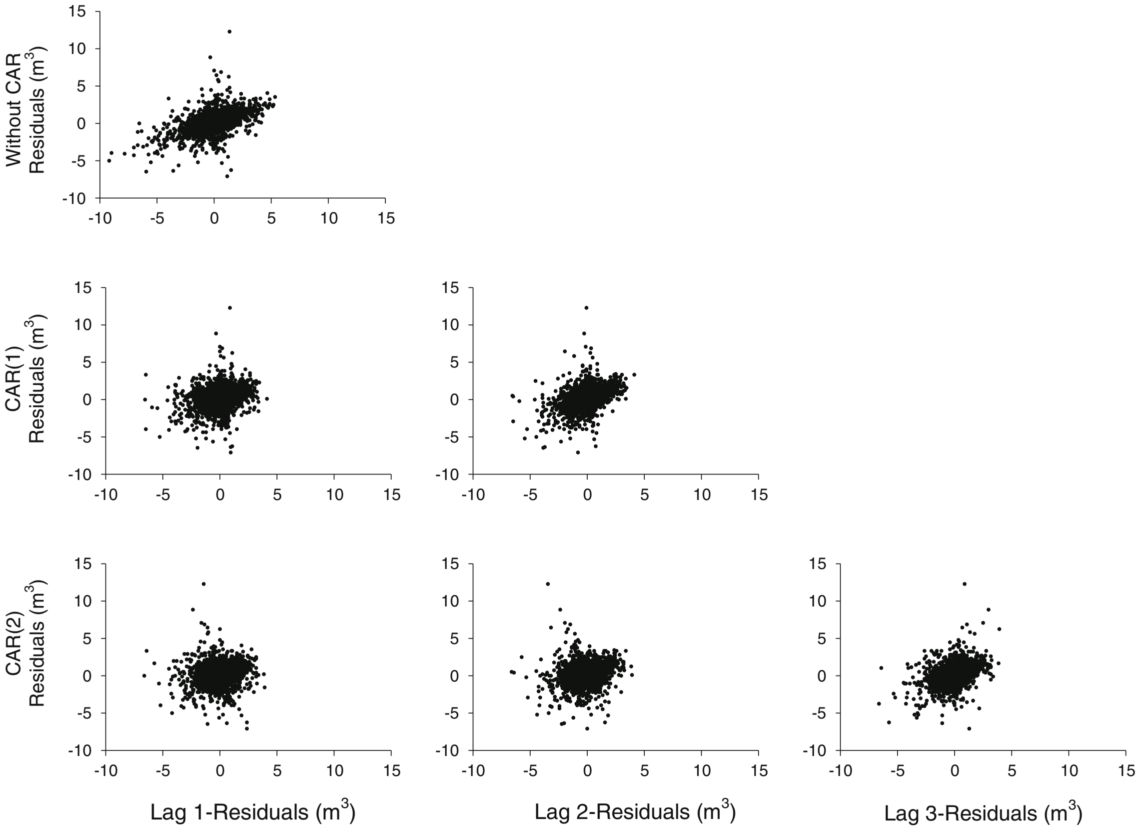


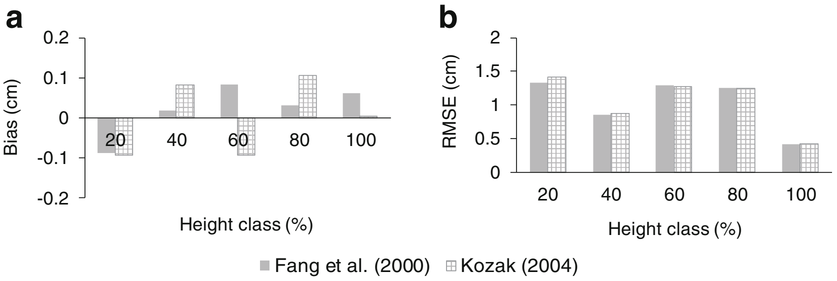
Fig. 4 Residuals against: Lag1-residuals (*left column*), Lag2-residuals (*middle column*), and Lag3-residuals (*right column*) for the model of Fang et al. (2000) fitted without considering the autocorrelation parameters (*first row*) and using continuous time autoregressive error structures of first and second order (*second and third rows*, respectively)

Although the goodness-of-fit statistics reflect the behavior of the data for the different models evaluated, they may not indicate which model is the best for practical purposes (Diéguez-Aranda et al. 2006); hence, this decision should be made after analyzing each model's behavior according to the different stem sections. To evaluate this, the bias and the root mean square error were calculated and plotted for diameter estimation by relative height classes (intervals of 15 %) and for height estimation by diameter classes (intervals of 5 cm). To estimate the height at which the different diameters are achieved, the iterative bisection method was used.

2.4 Model validation

Quality of fit does not necessarily reflect the quality of future prediction (Myers 1990). Only validation with an independent data set enables the accuracy of the selected model to be known (Huang et al. 2003; Kozak and Kozak 2003). In this study, the validation process was carried out with an independent data set consisting of 70 trees (from a network of plots established by the Atlantic Forest Systems Research Group (GIS-Forest), Department of Organism and Systems Biology, University of Oviedo), which produced a total of 719 height/diameter data pairs. Trees

Fig. 5 Bias (**a**) and root mean square error (RMSE) evolution (**b**) for diameter (cm) by relative height class (percentages) for the compatible system of Fang et al. (2000) and the non-compatible taper function of Kozak (2004)



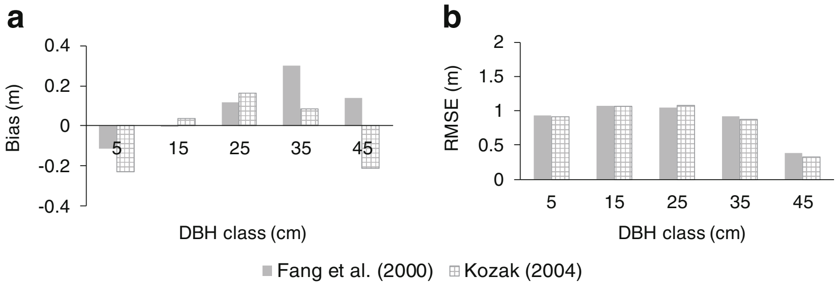


Fig. 6 Bias (**a**) and root mean square error (RMSE) evolution (**b**) for height (m) by relative diameter class (DBH class) for the compatible system of Fang et al. (2000) and the non-compatible taper function of Kozak (2004)

were felled and destructively sampled following the same methodology as used for the fitting data set. Two validation statistics were calculated to assess the overall prediction performance of the fitted equations on this validation data set: (a) an estimate of the average prediction error (APE) (Eq. 1) (Weisberg 1985) and (b) mean bias (Eq. 2) estimated as an overall average and summarized by diameter class, similar to that used by Zhang (1997). Both statistics present errors in the same units as the variable used, in this case centimeter for diameters and cubic meter for volumes. The APE statistic in the validation process is similar to the RMSE in the fitting.

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

$$\overline{\mathrm{Bias}} = \frac{\sum_{i=1}^{n}\left(Y_i - \widehat{Y}_i\right)}{n} \tag{2}$$

where Y_i is the observed or real value, $\widehat{Y}_i$ is the estimated value with the model, and n is the sample size of the validation data.

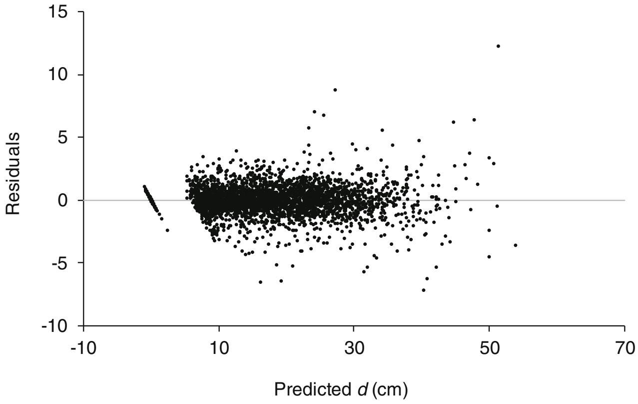


Fig. 7 Plot of residuals against predicted diameter from the taper function proposed by Fang et al. (2000)

To examine the performance of the models in greater detail, the values of $\overline{\mathrm{Bias}}$ were plotted against diameter and total volume. These graphs are of interest since they illustrate areas in which the adjusted models provide poor or good predictions according to the diameter class of the evaluated trees.

3 Results

Table 3 shows the parameters for the taper functions fitted, all of which were significant at the 5 % level, except for the Bi (2000) model, where convergence was not achieved. The model of Kozak (2004) was modified by removing the b_4 parameter in order to adapt it to local and species conditions (Kozak 2004).

All models performed well, each explaining more than 95 % of the total variability, with mean error below 2.05 cm (Table 4). Comparison of goodness-of-fit statistics indicates

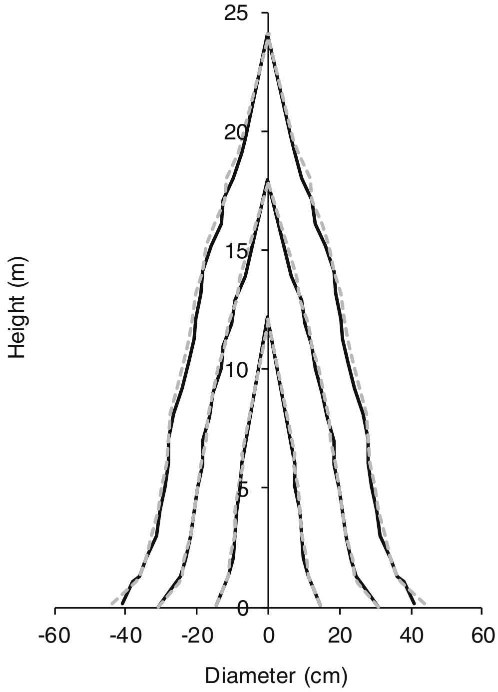


Fig. 8 Observed (*solid line*) and predicted (*dashed line*) profiles of three trees (as examples) using the taper function of Fang et al. (2000)

that the best-fitting models are those of Kozak (2004) and Fang et al. (2000), which each explaining more than 98 % of the total variability. In both cases, the presence of multicollinearity was observed (CN around 62) but it was considered to be within acceptable limits.

A trend in the residuals depending on the distance and the relative position of the measurement along the stem was found in the model fitting. Therefore, autocorrelation was corrected applying a second-order autoregressive structure (because using a first-order structure proved to be insufficient) with the aim of obtaining unbiased and efficient estimates, which did not invalidate statistical tests. Following this correction, the trends in residuals virtually disappeared. Figure 4 provides an example using the model of Fang et al. (2000).

Statistics are good indicators of the global performance of the taper function, but alone, they do not allow the best model to be selected. To do this, the evolution of bias and mean square root error in diameter estimation by relative height classes at intervals of 20 % (Fig. 5a, b) and in height estimation by diameter class (Fig. 6a, b) was analyzed for the two best-fit models, Fang et al. (2000) and Kozak (2004).

Graphical analysis of the bias in predicting diameters (Fig. 5a) confirmed the good performance of both models (with bias under ±0.1), with a certain advantage seen for the model of Fang et al. (2000), which showed lower bias at different heights, especially in the lower part of the stem (that with the highest merchantable value). In relation to the evolution of RMSE in predicting diameters (Fig. 5b), both models were very similar, although the model of Fang et al. (2000) was slightly better.

With regard to the evaluation of bias in predicting heights (Fig. 6a), the model of Fang et al. (2000) showed lower bias until diameter class 35, at which point the model of Kozak (2004) performed better, although the model of Fang et al. (2000) again showed the best fit at class 45. For both models, however, there was bias, although up to and including diameter class 25 it was always below 0.3 cm, and for the classes above this, always less than 0.4 cm. The behavior of both models in terms of RMSE was very similar (Fig. 6b).

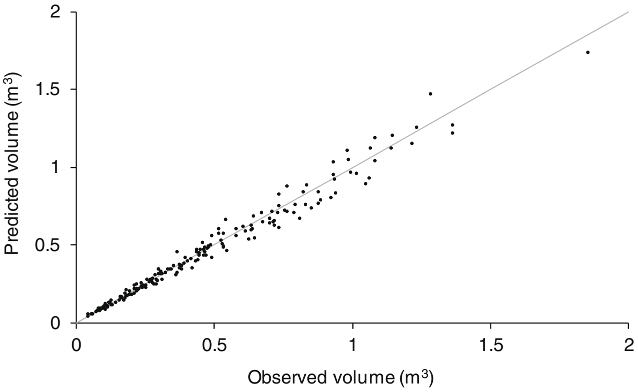


Fig. 9 Plot of predicted values against observed values for total tree volume from the taper function proposed by Fang et al. (2000)

Table 5 APE and $\overline{\text{Bias}}$ statistics generated from the assessment of prediction error for the taper function fitted in the validation process

	APE	$\overline{\text{Bias}}$
Diameter (*d*)	2.14	−0.41
Total volume (*V*)	0.059	−0.019

APE average prediction error, $\overline{\text{Bias}}$ mean bias

Taking into account the results and in particular the practical utility of the compatibility between the classic two inputs volume equation and the taper function, the model of Fang et al. (2000) was selected as the most appropriate for chestnut coppice stands in northwest Spain.

The plotting of values from predicted diameter in the selected taper function against the residuals is shown in Fig. 7, where no systematic trend in the distribution of residuals was observed. Figure 8 shows, as an example, the profile of three trees—one small (d=11.15 cm and h=12.19 m), one medium sized (d=24.5 cm and h=18 m), and one large (d=36 cm and h=24.12 m) generated from the observed values (solid lines) and predicted values (dashed lines) for the model of Fang et al. (2000). Figure 9 shows predicted values of total volume for the selected taper function against the observed volume values, verifying the accuracy of the estimates (accounting for 98.38 % of the total variability).

3.1 Model validation

Table 5 shows the statistics used in model validation, calculated for different diameter classes. APE generally increased with diameter class in the trees evaluated for the variable diameter and volume and provided good results (average prediction error of 2.14 cm for diameter and 0.059 m^3 for volume).

The graphs of mean prediction bias are shown in Fig. 10. All values obtained, in the case of both diameter and volume, were similar and close to zero, indicating that the selected equation fits well with the real profile of the tree. Up to diameter class 25, the statistics were very close to zero, although, it is important to note that from diameter class 35, the $\overline{\text{Bias}}$ values in predicting diameter were far from zero. $\overline{\text{Bias}}$ values indicate that both diameter and total tree volume are overestimated (negative values).

4 Discussion

Currently, detailed information is available as regards the different functions and methodologies for the correct estimation of diameters at different heights and total or merchantable

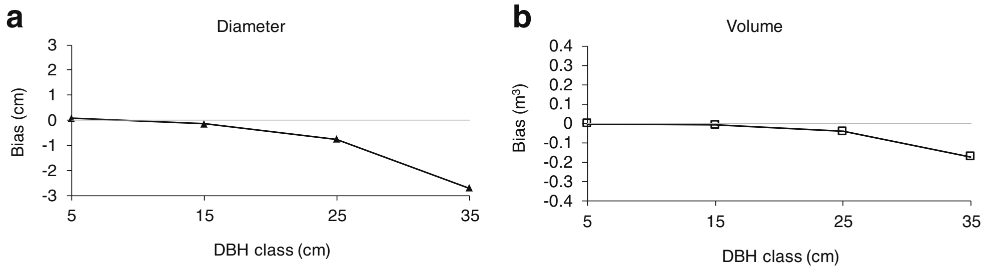


Fig. 10 Plot of DBH class against mean prediction bias for diameter (*left*) and total volume (*right*)

stem volume for different species (e.g., Barrio et al. 2007; Diéguez-Aranda et al. 2006). However, no such tools are yet available for chestnut, neither for high forest nor for coppice stands, hence the relevance of this work, which facilitates a better understanding and management of the species.

The final selected model explained more than 98.4 % of total variability and had mean errors below 1.20 cm. The estimates obtained in the models analyzed were similar to those obtained for other species. The model of Fang et al. (2000) has shown good performance, as much for broadleaf species as for conifers (e.g., Barrio-Anta et al. 2007; Diéguez-Aranda et al. 2006; Pompa-García et al. 2009).

Significant variability in chestnut stem profiles occurs in this study due to the high number of stems (up to eight) which were growing from each stool. Previous studies (e.g., Muhairwe 1994) have already demonstrated that factors such as site index, size and position of the crown, and stand density affect the profile of the tree. Modeling the profile of chestnut, in particular in coppice stands, presents an additional difficulty. Due to the fact that often many stems come from the same stool, it seems logical that stool density (number of stems per stool) as well as stand density might also be a key factor because internal competition affects the profile of the tree. Despite this, the selected model explained over 98 % of total variability, above the values obtained in previous broadleaf studies (Barrio-Anta et al. 2007; Pompa-García et al. 2009). Moreover, as the bias values in predicting diameters show, the results perform well in relation to the basal part of the tree, thereby solving one of the main problems associated with the use of taper functions in trees with prominent basal zones.

Validation with an independent data set confirmed the applicability of the selected taper function and the compatible volume equation for chestnut coppice stands in northwest Spain. Both statistics, APE and $\overline{\text{Bias}}$, increased with diameter class in the trees evaluated. $\overline{\text{Bias}}$ values did not vary greatly until diameter class 35, after which range slightly increased. This can be attributed in part to a relatively lower number of sampled trees in this diameter class, that is, 4 trees from a total of 70 in the whole validation data set.

5 Conclusions

A taper function for chestnut coppice stands in northwest Spain was developed to estimate diameter at any point along the stem, along with a total volume equation compatible with the fitted taper function. A total of five models were evaluated: the segmented model of Fang et al. (2000), the variable exponent functions proposed by Bi (2000) and Kozak (2004), the power function proposed by Demaerschalk (1972), and the trigonometric compatible model proposed by Thomas and Parresol (1991). In the end, the Bi (2000) model was not compared to the other models because convergence was not achieved in this case. All the other functions analyzed had good performance in estimating diameter along the stem, all of them appropriately describing the stem profile for chestnut coppice stands.

The compatible system to estimate volume proposed by Fang et al. (2000) was finally selected as the best taper function to explain the profile of chestnut coppice, as much for its goodness-of-fit statistics (R^2_{adj} of 0.98 and mean error of 1.19 cm) as for its prediction ability for diameter and height along the stem. This system has the advantage of being formed by a taper function, a total volume equation, and a merchantable volume equation, all of which are compatible between themselves.

Validation using an independent data set reflected the quality of predictions and confirmed the ability of the selected taper function to describe the stem profile in chestnut coppice stands in northwest Spain.

The taper function finally selected could be used for coppice stands in the rest of the country or elsewhere in the first instance, until new adjusted taper functions are developed to ensure the most accurate estimations possible for specific areas.

Acknowledgments The authors thank Forest Services (Government of the Principality of Asturias) and the private owners who allowed the establishment of the permanent plots necessary for the development of the study. The authors are grateful to the University of Oviedo, which provided the validation data.

Funding This study was supported by the Spanish Ministry of Science and Innovation (MICIN) and the Plan for Science, Technology and Innovation of the Principality of Asturias (PCTI) as part of the research project "Forest and industrial evaluation of Spanish chestnut" (VALOCAS).

References

Álvarez P, Barrio M, Castedo F, Díaz R, Fernández JL, Mansilla P, Pérez R, Pintos C, Riesgo G, Rodríguez R, Salinero MC (2000) Manual de selvicultura del castaño en Galicia. University of Santiago Press, Santiago, España

Barrio-Anta M, Diéguez-Aranda U, Castedo-Dorado F, Álvarez-González JG, Von Gadow K (2007) Merchantable volume system for pedunculate oak in northwestern Spain. Ann For Sci 64:511–520. doi:10.1051/forest:2007028

Belsey DA (1991) Conditioning diagnostics, collinearity and weak data in regression. Wiley, New York

Bi H (2000) Trigonometric variable-form taper equations for Australian eucalypts. For Sci 46:397–409

Brink C, Gadow KV (1986) On the use of growth and decay functions for modeling stem profiles. EDV in Medizin u Biologie 17:20–27. doi:10.1080/02827580410019562

Burkhart H (1977) Cubic-foot volume of loblolly pine to any merchantable top limit. Sout J Appl For 1:7–9

Clutter JL (1980) Development of taper functions from variable-top merchantable volume equations. For Sci 26:117–120

Conedera M, Manetti MC, Giudici F, Amorini E (2004) Distribution and economic potential of the sweet chestnut (*Castanea sativa* Mill.) in Europe. Ecologia Mediterranea 30:179–193

Crecente-Campo F, Rojo A, Diéguez-Aranda U (2009) A merchantable volume system for *Pinus sylvestris* L. in the major mountain ranges of Spain. Ann For Sci 66:808. doi:10.1051/forest/2009078

Demaerschalk J (1972) Converting volume equations to compatible taper equations. For Sci 18:241–245

DGCONA (2013). III Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España

Díaz Varela RA, Calvo Iglesias MS, Díaz Varela ER, Ramil Rego P, Crecente Maseda R (2009) *Castanea sativa* forests: a threatened cultural landscape in Galicia NW Spain. In: O'Connell M, Küster H (eds) Cultural Landscapes of Europe. Fields of Demeter Haunts of Pan (Krzywinski K. Aschembeck Media UG, Bremen, pp 94–95

Diéguez-Aranda U, Castedo-Dorado F, Álvarez-González JG, Rojo A (2006) Compatible taper function for Scots pine plantations in northwestern Spain. Can J For Res-Rev Can Rech For 36:1190–1205. doi:10.1139/X06-008

Diéguez-Aranda U, Rojo Alboreca A, Castedo-Dorado F, Álvarez-González JG, Barrio-Anta M, Crecente-Campo F, González-González JM, Pérez-Cruzado C, Rodríguez-Soalleiro R, López-Sánchez CA, Balboa-Murias MA, Gorgoso Varela JJ, Sánchez Rodríguez F (2009). Consellería do Medio Rural, Xunta de Galicia. 268 pp+CD-Rom.

Fang Z, Bailey RL (1999) Compatible volume and taper models with coefficients for tropical species on Hainan Island in Southern China. For Sci 45:85–100

Fang Z, Borders BE, Bailey RL (2000) Compatible volume-taper models for loblolly and slash pine based on a system with segmented-stem form factors. For Sci 46:1–12

Gallardo JF, Rico M, González MI (2000) Some ecological aspects of a chestnut coppice located at the Sierra de Gata mountains (Western Spain) and its relationships with a sustainable management. Ecologia Mediterranea 26:53–69

Giudici F, Amorini E, Manetti MC, Chatziphilippidis G, Pividori M, Sevrin E, Zingg A (2000) Sustainable management of sweet chestnut (*Castanea sativa* Mill.) coppice forest by means of the production of quality timber. Ecologia Mediterranea 26:8–26

Goulding CJ, Murray J (1976) Polynomial taper equations that are compatible with three volume equations. N Z J For Sci 5:313–322

Huang S, Yang Y, Wang Y (2003) A critical look at procedures for validating growth and yield models. In: Amaro A, Reed D, Soares P (eds) Modelling forest systems. CAB International, Wallingford, Oxfordshire, UK

Kerr G, Evans J (1993). Growing broadleaves for timber. Forestry Commission Handbook 9, London.

Kozak A (1988) A variable-exponent taper equation. Can J For Res-Rev Can Rech For 18:1363–1368. doi:10.1139/X88-213

Kozak A (2004) My last words on taper equations. For Chron 80:507–515. doi:10.5558/tfc80507-4

Kozak A, Kozak R (2003) Does cross validation provide additional information in the evaluation of regression models? Can J For Res 33:976–987. doi:10.1139/X03-022

Lindstrom MJ, Bates DM (1990) Nonlinear mixed effects models for repeated measures data. Biometrics 46:673–687. doi:10.2307/2532087

MARM (2011) Avance del Anuario de Estadística Forestal. Área de Medio Ambiente, Madrid, España

Muhairwe CK (1994) Tree form and taper variation over time for interior lodgepole pine. Can J For Res 24:1904–1913. doi:10.1139/X94-245

Myers RH (1990) Classical and modern regression with applications, 2nd edn. Duxbury Press, Belmont, CA

Pompa-García M, Corral-Rivas JJ, Hernández-Díaz JC, Álvarez-González JG (2009) A system for calculating the merchantable volume of oak trees in the northwest of the state of Chihuahua, Mexico. J For Res 20:293–300. doi:10.1007/s11676-009-0051-x

Reed DD, Green E (1984) Compatible stem taper and volume ratio equations. For Sci 30:977–990

Riemer T, Gadow KV, Sloboda B (1995) Eim modell zur Beschreibung von Baumschäften. Allg Forst Jagdztg 166:144–147

Rodríguez F, Broto M, Lizarralde I (2008). CubiFOR: herramienta para cubicar, clasificar productos, calcular biomasa y CO_2 en masas forestales de Castilla y León. Revista Montes: 33–3

SAS Institute Inc (2004a) SAS/STAT®, 0.1. User's Guide. SAS Institute Inc., Cary, NC

SAS SAS Institute Inc (2004b) SAS/ETS®, 0.1. User's Guide. SAS Institute Inc., Cary, NC

Thomas CE, Parresol BR (1991) Simple, flexible, trigonometric taper equations. Can J For Res 21:1132–1137. doi:10.1139/X91-157

Weisberg S (1985) Applied linear regression, 2nd edn. Wiley, Inc

Zhang D (1997) Cross-validation of non-linear growth functions for modeling tree height-diameter relationships. Ann Bot 79:251–257. doi:10.1006/anbo.1996.0334

Zimmerman DL, Núñez-Antón V (2001) Parametric modeling of growth curve data: an overview (with discussion). Test 10:1–73. doi:10.1007/BF02595823

Basic tools for silvicultural management of *Castanea sativa* Mill. coppice stands in northwestern Spain

iForest - Biogeosciences and Forestry

Basic tools for silvicultural management of Castanea sativa Mill. coppice stands in northwestern Spain

Manuscript Draft

Manuscript ID:	#ms15/1593
Article Type:	Research Articles
Full Title:	Basic tools for silvicultural management of Castanea sativa Mill. coppice stands in northwestern Spain
Corresponding Author:	MARÍA MENÉNDEZ-MIGUÉLEZ SUSTAINABLE FOREST MANAGEMENT AREA, FOREST AND WOOD TECHNOLOGY RESEARCH CENTRE GRADO (Spain)
Keywords:	Chestnut Coppice; Yield Tables; Stand Density Management Diagrams; Site Index; Silvicultural Models
Abstract:	The importance of chestnut coppice stands in northwestern Spain, together with the almost total lack of growth and yield studies, makes necessary the development of basic, widely applicable tools to facilitate forest management by stakeholders and Public Administrations. The following models were developed for this purpose: a site index model (from stem analysis data); two models for estimating variation in tree density (the heterogeneous silvicultural state of the stands force division of the data into two groups - high and low density); and equations for estimating quadratic mean diameter, total and merchantable volume and several biomass components. These equations were used to develop two useful tools for designing and evaluating future management options: yield tables and stand density management diagrams (SDMDs). Two yield tables were developed for each of the previously defined site quality indices (10, 14, 18 and 22 m at a reference age of 22 years) - one for each density class (high and low). Average growth in the rotation producing the maximum sustainable yield varied depending on tree density and site quality: 32.0 m3 ha-1 year-1 for the highest density and best quality, compared with 4.4 m3 ha-1 year-1 for the lowest density and poorest quality. Rotation lengths producing maximum sustainable yield ranged between 27 and 46 years. The SDMDs developed allow estimation of total stand volume, biomass and carbon stocks for chestnut coppice stands in northwestern Spain. The basic tools developed in this study represent a starting point for development of dynamic growth models and for future studies of different management regimes, which will improve knowledge about chestnut coppice stands in northwestern Spain
Authorship:	Menéndez-Miguélez M (Spain) Alvarez-álvarez P (Spain) Majada J (Spain) Canga E (Spain)
Submission Date:	Feb 10, 2015 (09:13 CET)

Basic tools for silvicultural management of *Castanea sativa* Mill. coppice stands in northwestern Spain

Short title: Basic tools for chestnut coppice stands

María MENÉNDEZ-MIGUÉLEZ*[1,2], Pedro ÁLVAREZ-ÁLVAREZ[2], Juan MAJADA[1], Elena CANGA[1]

[1]*Forest and Wood Technology Research Centre (CETEMAS) / Finca Experimental "La Mata" s/n, Grado, Asturias, Spain / Tel. 00 34 985 75 47 25*

[2]*Research Group in Atlantic Forests (GIS-Forest). Department of Organisms and Systems Biology, University of Oviedo, Escuela Politécnica de Mieres (E.P.M.), Campus Universitario de Mieres, C/Gonzalo Gutiérrez Quirós, 33600 Mieres, Spain*

***Corresponding author:**

E mail: mmenendez@cetemas.es

Current address: CETEMAS/ Forest and Wood Technology Research Centre/ Finca Experimental "La Mata" s/n, Grado, Asturias, Spain / Tel. 00 34 985 75 47 25 / http://www.cetemas.es

Total number of characters: 45,854

Number of Tables: 14

Number of Figures: 5

Keywords: chestnut coppice, yield tables, stand density management diagrams, site index, silvicultural models

Abstract

The importance of chestnut coppice stands in northwestern Spain, together with the almost total lack of growth and yield studies, makes necessary the development of basic, widely applicable tools to facilitate forest management by stakeholders and Public Administrations.

The following models were developed for this purpose: a site index model (from stem analysis data); two models for estimating variation in tree density (the heterogeneous silvicultural state of the stands force division of the data into two groups - high and low density); and equations for estimating quadratic mean diameter, total and merchantable volume and several biomass components.

These equations were used to develop two useful tools for designing and evaluating future management options: yield tables and stand density management diagrams (SDMDs). Two yield tables were developed for each of the previously defined site quality indices (10, 14, 18 and 22 m at a reference age of 22 years) - one for each density class (high and low). Average growth in the rotation producing the maximum sustainable yield varied depending on tree density and site quality: 32.0 m^3 ha^{-1} $year^{-1}$ for the highest density and best quality, compared with 4.4 m^3 ha^{-1} $year^{-1}$ for the lowest density and poorest quality. Rotation lengths producing maximum sustainable yield ranged between 27 and 46 years. The SDMDs developed allow estimation of total stand volume, biomass and carbon stocks for chestnut coppice stands in northwestern Spain.

The basic tools developed in this study represent a starting point for development of dynamic growth models and for future studies of different management regimes, which will improve knowledge about chestnut coppice stands in northwestern Spain.

1. Introduction

More than 90% of all chestnut stands of Spain are located in the northwest of the country (DGCONA 2013). Together with the historical, economic and productive importance of this species, this makes current concern about abandonment of these stands of particular relevance. Public Administrations and stakeholders, aware of this situation, are now demanding active management to yield the best performance in this type of stand, in terms of both profitability and long-term sustainability.

Accurate estimation of forest site quality, timber volume stocks and aboveground stand biomass is essential in forest management. Basic equations (site index curves and merchantable volume equations) and tools (yield tables and stand density management diagrams) are therefore need to enable reliable estimation of these variables and thus establish the current situation of the stands, as well as to optimize stand management and predict one or more future scenarios.

The first step in the study of stand yield and growth for any species is the classification of sites according to their quality. Two concepts can be used to define the quality of a forest site: site quality and site productivity. The first is related to the potential productivity, which is the inherent ability of a site to provide resources that support growth and can be defined in terms of timber management as "the timber production potential of a site for a particular species". The second refers to the expected productivity, which is the potential growth that a site can support following its modification (Clutter et al. 1983).

Methods of estimating productivity (site quality) and of projecting stand height are important components of silvicultural and management modelling systems. The most accurate and commonly used productivity assessment methods for even-aged stands are based on height growth of dominant trees (Weiskittel et al. 2011, Burkhart & Tomé 2012). Typically, the site quality for a certain species is described by a *site index*, i.e. the predicted dominant or top height at a given reference age.

The second step involves acquiring information about the growing stock in relation to the initial spacing and/or subsequent thinning that are required to achieve specific management objectives. The process of information gathering and control is characterized by a multitude of treatment options available to forest managers (Newton

1997, Newton et al. 2005). However, it can be done with two types of static growth and yield models: yield tables and stand density management diagrams.

Development of static models, less accurate than dynamic models, represents the first step in studying the growth and development of a species or a type of stand when there is no other information available.

Yield tables have been defined by Madrigal et al. (1991) as numerical tables that represent the changes that occur over time in a regular or contemporary stand, for a particular species, different site index classes and one or more different silvicultural treatments.

Stand density management diagrams (SDMDs) are average stand-level models that graphically illustrate and integrate relationships between yield, density and mortality throughout all stages of stand development, thus linking quantitative silviculture with population ecology, production ecology and biometrics (Newton & Weetman 1994, Jack & Long 1996). Use of these diagrams is one of the most effective methods of designing and evaluating alternative density management regimes in even-aged stands (Jack & Long 1996).

The diagrams are constructed by characterizing the growing stocks by use of indices that relate density (e.g. number of stems per hectare) to the average tree size (e.g. volume, height or diameter). Several density indices have been developed: the stand density index (Reineke 1933), the relative density index (Drew & Flewelling 1979), the self-thinning rule (Yoda et al. 1963) and the relative spacing index (RS) (Wilson 1946). The great advantage of these density indices is that they are independent of stand age and site quality (Long 1985, McCarter & Long 1986).

The aims of the present study were as follows: (i) to develop basic equations to represent as realistically as possible the growth and behaviour of chestnut coppice stands in northwestern Spain; and (ii) to develop tools – yield tables and practical SDMDs – for estimating total volume and other stand variables of interest, to aid forest managers in the decision-making process.

2. Materials and methods

2.1 Data

A network of 70 permanent plots was established in chestnut coppice stands to cover the existing range of sites, ages and stand densities in the area of distribution of the species in northwestern Spain.

All plots were labelled, and diameter at breast height (dbh) (*d*, cm) and total height (*h*, m) of the trees were measured. Information including stand health, age, stool identification, vegetation and physiographical factors were also recorded – see Menéndez-Miguélez et al. (2013) for more details.

Stem analysis data were obtained by felling dominant trees in areas adjoining 58 of these plots. The trees were selected according to the methodology of Madrigal et al. (1992), whereby diameter and height of the selected trees do not differ by more than 5% of the mean diameter and mean height of the dominant trees in the plot. All selected trees were healthy, well-shaped and belong to the upper canopy of the stand. Dominant height, which is conventionally calculated from the 100 thickest trees per hectare, was calculated as the mean height of the 7 thickest (largest-dbh) trees per plot (Assmann 1970).

Cross-sectional disks were obtained at the stem base just above the stool (Figure 1), and at 1 metre intervals thereafter until a top diameter of 7 cm. The exact height above ground and the diameters (with and without bark) at the points where the disks were removed were measured, and growth rings were counted. Growth ring counts and heights for the cross section disks were used to estimate height-age pairs, to reconstruct past tree growth.

The plots used to develop the models proposed in this study should belong to pure stands. However, examination of the data collected revealed that some of the plots were not exactly pure stands. As a consequence, 15 of the plots were finally removed from the data set (final number of plots of 55). Two of the permanent plots were cut before the end of this study. Their ages and therefore their site indexes were not known, and these plots also were not taken into account in some of the equations tested (final number of plots in these cases, 53). Summary statistics of the main plot variables are shown in Tab. 1.

2.2 Basic equations

Site index

Stem analysis carried out with the method described above underestimated the heights of each section because cross section lengths did not coincide with periodic height growth. This bias was corrected by using Carmean's algorithm (1972) with the modification proposed by Newberry (1991) for the topmost section of the tree. Data were further examined to detect abnormalities, and 111 trees were finally selected (1663 height-age observations) to model the variation in dominant height with age.

The site curves were developed using the simplified approach of mixed-effects modelling proposed by Cieszewski (2003), by applying the GADA (Generalized Algebraic Difference Approach) to develop the equation and the dummy variables method, as described by Cieszewski et al. (2000), to estimate the parameters. Direct use of data, such as constants, does not violate regression assumptions as environmental and measurement errors associated with these data are estimated at the same time as all other parameters of the model (Cieszewski 2003).

Three-parameter models were evaluated, and several variants of each were tested using the simplified approach of Cieszewski’s mixed-effects model (2003). Both one and two site-specific parameters were considered. The first two models are based on the differential function proposed by Bertalanffy (1949, 1957) and studied by Richards (1959), considering one or two parameters of the base model as site-specific, and providing polymorphic curves with a single or variable asymptotes, respectively. The third model (McDill & Amateis 1992) considers only one parameter as site specific in the base model and yields polymorphic curves with a single asymptote. The final model tested, i.e. that proposed by Cieszewski (2002), yields polymorphic curves with multiple asymptotes and considers two parameters as site specific.

Evaluation of the growth of an individual tree over time with single time series equations often generates autocorrelation. To overcome this, a continuous autoregressive structure CAR (*x*) was used to model the error terms and estimate the model parameters. The structure was implemented using the MODEL procedure of SAS/ETS® (SAS Institute Inc. 2004b).

The base age for site index equations was selected according to the following considerations (Goelz & Burk 1992): i) the base age should be less than or equal to the youngest rotation age under typical management, ii) the base age should be close to the rotation age, and iii) the base age should be chosen so that it is a reliable predictor of height at other ages. To address the third point, different base ages and their corresponding observed heights were used to estimate heights at other ages for each plot or tree. The results were compared with the values obtained from stem analyses and the relative error in predictions (RE%) was calculated as follows:

$$\mathrm{RE\%}=\frac{\sqrt{\sum_{i=0}^{i=n}\left(Y_i-\widehat{Y}_i\right)^2/(n-p)}}{\overline{Y}}\cdot 100 \qquad [1]$$

where Y_i, $\widehat{Y}_i$ and $\overline{Y}$ are the observed, estimated and average values of tree height, respectively; *n* is the total number of observations used to fit the model; and *p* is the number of model parameters.

Stand density

A stand density model requires a certain degree of homogeneity in the silvicultural management of the study plots, otherwise it will be difficult to develop an accurate model, and the results may lack practical value (Sánchez et al. 2003).

The silvicultural stages of chestnut coppice stands in northwest Spain are very heterogeneous, as reflected by the variation in stand density with different stand variables such as dominant height, quadratic mean diameter and age.

The method used in this study to develop a stand density equation is based on that reported by Sánchez et al. (2003), which considers the density and its most probable development as the basis of classification. Principal components analysis was applied, using the PRINCOMP procedure of SAS/ETS® (SAS Institute Inc. 2004b), with the aim of obtaining the rotation of axes that yields the first component with maximum variance. Adequate delimitation of the second principal component value enabled classification of the plots into two density classes: (i) "*low density plots*" and (ii) "*high density plots*".

Different equations were tested for each group, using dominant height and stand age as independent variables.

Quadratic mean diameter

This relation is used to predict the quadratic mean diameter (d_g) of a stand on the basis of different stand variables such as density (N), dominant height (H_0) and age (t). Different linear models were tested for all data. The models were not tested in relation to density classes because stand density was included as one of the independent variables, and therefore it was not necessary to classify data according to a silvicultural indicator, even considering that plots could be managed by different schemes.

Total and merchantable volume

This relation predicts the total stand volume (m^3 ha^{-1}) on the basis of different stand variables, which often include basal area (G) and dominant height. The first step consisted of estimating the total tree volume, for which the total volume equation of the compatible system of Fang et al. (2000), as reported by Menéndez-Miguélez et al. (2014), was used. Once the total tree volume was known, the total volume of each plot was estimated and a total volume stand equation was developed.

Several models were analysed by using basal area, dominant height, quadratic mean diameter or stand density as explanatory variables. Mean height (H_m) was also considered as an explanatory variable but proved less accurate, possibly because it was more sensitive to silvicultural treatments used to reduce stand density.

The merchantable volume equation developed by Menéndez-Miguélez et al. (2014) was also used to estimate total tree volume for different top diameters (between 0.5 and 40 cm, with intervals of 0.5 cm). Summing these volumes provides estimates of stand volumes for the different top diameters. Different volume ratio equations, similar to those proposed by Burkhart (1977) and Van Deusen et al. (1981), were used to estimate the merchantable stand volume equation, using quadratic mean diameter and/or dominant height as independent variables.

Finally, the merchantable stem volume equation was fitted with a single equation [2] formed by a total volume equation and the volume ratio equation, as follows:

$$V_{mi}=V_m \cdot R_i \qquad [2]$$

where V_{mi} is the merchantable stand volume (m^3 ha^{-1}) up to a diameter d_i (cm), V_m is the total stand volume (m^3 ha^{-1}) and R_i is the stand volume ratio equation for this diameter.

Stand biomass

Additional equations for estimating the biomass (t ha^{-1}) of different aboveground stand components (wood, bark, crown and total biomass) were also considered in the study. Some of these equations were fitted in a previous study (Menéndez-Miguélez et al. 2013). New models with stand density and dominant height as independent variables were also tested, because of the need to include these as explanatory variables in the SDMD. The procedure for developing these equations was as previously reported (Menéndez-Miguélez et al. 2013), and simultaneous fitting was used to guarantee the additivity of the tree biomass components.

2.2 Model fitting and comparison

Linear models were fitted by least squares method using the REG procedure of SAS/STAT® (SAS Institute Inc. 2004a). Nonlinear models were fitted by least squares with the NLIN procedure of the same program, using the iterative method of Gauss-Newton (Hartley 1961).

Model performance was compared on the basis of numerical and graphical analysis of the residuals. The following goodness-of-fit statistics were calculated to select the best models: adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE) and Akaike's information criterion in differences (AICd).

3. Results

3.1 Basic equations

Site index

A trend in the residuals (caused by age-lag-residuals within the same tree) was detected in all models, as expected because of the longitudinal nature of the data. This trend disappeared after correction of autocorrelation.

The GADA formulation derived from the Cieszewski (2002) model with two site-specific parameters was finally selected after comparison of goodness-of-fit statistics and graphical analysis of the four models evaluated. This dynamic equation enables direct prediction of dominant height SI (m) at any age t (years), from any other dominant height H_0 (m) at any other age t_0 (years).

The parameter estimates for the selected model and their corresponding goodness-of-fit statistics are shown in Tab. 2. All parameters were significant at the 5% level.

Regarding selection of the base age for site quality classification, ages between 20 and 30 years were superior for predicting height at other ages. As selection of the youngest base age possible is valuable for early decision making in stand management, a base age of 22 years was selected as the best option (Fig. 2).

Stand density

Comparison of the different equations evaluated showed that age was the best explanatory variable for the variation in stand density, independently of whether the stand was high or low density. The selected equation, the parameter estimates for each density class and their corresponding goodness-of-fit statistics are shown in Tab. 3. All parameter estimates were significant at $P < 0.05$.

Quadratic mean diameter

Dominant height, age and stand density proved to be the best explanatory variables for the quadratic mean diameter equation. For SDMDs, it is preferable to develop equations that only depend on dominant height and stand density. Therefore, with the aim of maximizing the accuracy of the system, the equations selected for later inclusion in the yield tables are different from the equation later included in the SDMDs.

Selected equations, for both yield tables and SDMDs, explained more than 77% of the total variance (Equation [7] and [8], respectively, Tab. 4). All parameter estimates were significant at $P < 0.05$.

Total and merchantable volume

Comparison of the different stand volume models analysed revealed that basal area, stand density and dominant height were the best explanatory variables. Two different equations were developed to estimate volume: one for inclusion in the yield tables and the second for inclusion in the SDMSs. In the first case, a merchantable volume equation was developed which explained more than 99% of total variance and in which all the parameter estimates were significant at $P < 0.05$ (Equation [9], Tab. 5). It was not possible to fit a merchantable volume equation that only depended on stand density and dominant height in the total stand volume part. Therefore, for inclusion in the SDMSs another total stand volume equation that only depended on stand density and dominant height was developed. This equation may explain less of the variation in the whole sample (about 61%) and all the parameter estimates were significant at $P < 0.05$ (Equation [10], Tab. 5).

Stand biomass

Two set of stand biomass equations are presented in this study. Previously fitted equations (Menéndez-Miguélez et al. 2013) were used for inclusion in the yield tables. These equations were fitted simultaneously to ensure additivity of the different components. They explain more than 60% of the total variance and enable estimation of the biomass of wood, bark, crown and total biomass (Equations [11]-[14], Tab. 6). Additional equations were also tested for inclusion in the SDMDs because, as previously explained, it is preferable that these equations only depend on stand density and dominant height as independent variables. As fitting biomass equations that depended only on these two variables was more difficult than using other explanatory variables, it was not possible to develop crown biomass equation or an independent equation for wood and bark biomass. Therefore, it was only possible to fit a stem biomass equation – combining wood and bark components in order to improve the fit – and a total biomass equation. The fitted equations explained more than 67% and 57% of the variance in stem and total biomass, respectively. All parameter estimates were significant at $P < 0.05$ (Equations [11] - [16], Tab. 6).

3.2 Management tools

Yield tables

The previously fitted equations were used to construct the yield tables for chestnut coppice stands in northwestern Spain, to obtain the following different stand variables:

- ✓ Input variables: age (t, years), dominant height (H_0, m).
- ✓ Output variables (stand before thinning): density (N, trees ha^{-1}), quadratic mean diameter (d_g, cm), basal area (G, m^2 ha^{-1}), total volume (V, m^3 ha^{-1}), merchantables volumes (V_{15}, V_{20}, V_{40}, m^3), wood (W_w, t ha^{-1}), crown (W_c, t ha^{-1}) and total biomass (W_t, t ha^{-1}).
- ✓ Output variables (removed stand, stand after thinning, total stand): number of trees extracted of each age (N_e), quadratic mean diameter extracted (d_{ge}), quadratic mean diameter after thinning (d_{gat}), basal area extracted (G_e), basal area after thinning (G_{at}), total volume extracted (V_e), accumulate volume (V_{ac}), total volume after thinning (V_{at}), wood (W_{we}), crown (W_{ce}) and total biomass extracted (W_{te}), wood (W_{wat}), crown (W_{cat}) and total (W_{tat}) biomass after thinning, total stand volume (V_t).
- ✓ Output variables (growth): mean annual increment (MAI, m^3 ha^{-1} year^{-1}), periodic annual increment (PAI, m^3 ha^{-1} year^{-1}).

Tab. 7 to Tab. 14 show the eight yield tables developed according to four site index classes and two densities (high and low) for chestnut coppice stands in northwestern Spain. Although the merchantable volumes included in these tables are the most useful according to the current wood market in northwestern Spain, the yield tables can be developed for any top diameter, depending on market conditions.

Stand density management diagrams

Four SDMDs were developed by superimposing the expected size-density trajectories on a bivariate graph, with dominant height on the *x*-axis and number of stems per hectare on the *y*-axis. The range of values represented by the axes and the isolines were similar to the range of values included in the data used to construct the diagram (Tab. 1). The values of relative spacing index were used to plot the isolines for each of the previously estimated variables (d_g, V_m, W_{stem}, W_{total} – Figure 3, Figure 4, Figure 5).

4. Discussion

Despite the importance of sweet chestnut coppice stands in northwestern Spain, some of the tools required for determining the growth and yield of this species are not yet available either for this region or any other.

Good forest management is based on knowledge and diagnosis of the current situation of the stand, for which SI is a key tool. Cabrera & Ochoa (1997) used the guide curve approach to determine SI in chestnut coppice stands in Asturias (NW Spain). Nevertheless, in the present study, we used the generalized algebraic difference approach (GADA) (Cieszewski & Bailey 2000) to generate polymorphic curves, with data derived from permanent plots and stem analysis. Examination of the graphs showed that the SI curves provided the best description of individual growth trends for chestnut in coppice stands in northwestern Spain.

The rotation length that produces the maximum sustainable yield varied from 46 years for the lowest quality to 27 for the highest. The estimated highest qualities are greater than those reported by Cabrera & Ochoa (1997) (31 years) and by Elorrieta (1949) (30 years) and those proposed by Bourgeois (1992) and Lemaire (2008) for high quality timber in France (40-45 years). Nevertheless, for the lowest qualities, the estimates differ by 8-9 years depending on the stand density class: Cabrera & Ochoa

(1997) estimated that a rotation of 37 years would provide the maximum sustainable yield. The differences in the lowest qualities may be explained by the different SI equations developed in both studies and the fact that yield tables developed by Cabrera & Ochoa (1997) do not use an equation to explain density evolution over time. For the lowest qualities, Bourgeois et al. (2004) and Lemaire (2008) proposed clear cutting the stand at 20-40 years and not carrying out any type of silvicultural treatment.

The productivity (periodic annual increment in the rotation of maximum sustainable yield) in chestnut coppice stands is remarkably high, typical of fast growing species, and therefore very profitable. Comparison of the productivity data with that reported by Cabrera & Ochoa (1997) revealed similar results, thus confirming the validity of the model predictions. Comparison with data from other countries shows that the predicted productivity is even higher, with values for the best qualities of 11 m^3 ha^{-1} $year^{-1}$ at 40 years in the Dean Forest in the South of England (Everard & Christie 1995), 10 m^3 ha^{-1} $year^{-1}$ at 30 years in Italy (Elorrieta 1949) and 16 m^3 ha^{-1} $year^{-1}$ at 30 years in France (Bourgeois et al. 2004). These results also show that chestnut coppice stands in northwestern Spain appear to being growing on better quality sites than in France, Italy or England.

Even taking into account high productivity in northwestern Spain, the final products obtained are not as large as in France – quadratic mean diameter of 24.2 cm compared with 42.39 cm, respectively – (Bourgeois et al. 2004, Lemaire 2008), mainly because of the stand densities – 947 trees ha^{-1} for the lowest density compared with 180 trees ha^{-1}, respectively. To obtain similar products in this area, the thinning intensity must be increased to reduce stand density to similar levels as in France. More intensive management, together with higher quality sites, would allow production of high quality timber, which would be greatly appreciated in the timber market.

SDMDs and management options have been developed in many studies (e.g. Vacchiano et al. (2008) for *Pinus sylvestris* L., Pérez-Cruzado et al. (2011) for

Eucalyptus globulus and *Eucalyptus nitens*, Castaño-Santamaría et al. (2013) for *Quercus pyrenaica* in northwestern Spain). Nevertheless, this study only presents SDMDs for chestnut coppice stands in northwestern Spain (until now non-existent), without proposing any type of management scenes or thinning regimes. Thus, an extension of this study should be carried out to provide with additional data, to enable proposal of different management scenes and to improve knowledge about these types of stands in northwestern Spain.

5. Conclusions

Different growth and yield models were developed as basic tools to simplify management of chestnut coppice stands in northwestern Spain and help determine the most appropriate practices for this type of stand. Estimation of stand volume, stand biomass, site quality and carbon pools could help foresters test several indicators of sustainable forest management related to growing stock.

The first step involved was development of a site index equation. The system based on the dynamic equation proposed by Cieszewski (2002) was the most accurate for explaining site index and height-growth estimates for chestnut coppice stands in northwestern Spain. A reference age of 22 years was selected as the most suitable for predicting dominant height at other ages.

The second equation developed was a stand density model. Stand density is one of the most important factors in chestnut coppice stands because many stems grow in the same stool and compete for nutrients, water and space. This property, together with the fact that stand density in coppice stands is closely related to historical silvicultural management, strengthens the importance of the developed equations for this variable, which explained more than 64% of the total variance.

Different equations for estimating quadratic mean diameter, total and merchantable volume and several biomass components were also developed for direct use or for constructing yield tables or SDMDs.

Two yield tables were constructed for each of the site quality indices previously defined (10, 14, 18 and 22 m at a reference age of 22 years), one for each density class (high and low). Yield tables include total volume, the estimated merchantable stand volume with bark up to several top diameters without bark – 15, 20 and 40 cm – for which a volume ratio equation was fitted, as well as stem biomass and total stand biomass.

The stand density management diagrams developed can be used to estimate total stand volume, biomass and carbon stock for chestnut coppice stands in northwestern Spain. Here, we only show the diagrams for total stand volume, stem biomass and total biomass. However, the other diagrams are available upon request.

These management tools are very effective for the design, display and evaluation of alternative density management regimes in forest stands and can help stakeholders and Public Administrations to obtain the best performance of different chestnut coppice stands in northwestern Spain.

As additional information becomes available, it can be overlaid on the SDMDs to facilitate management decisions, and dynamic growth models can be developed.

6. Acknowledgements

The authors thank Forest Services (Government of the Principality of Asturias), and the private owners who allowed the establishment of the permanent plots necessary for the development of the study. This study was supported by the Spanish Ministry of Science and Innovation (MICIN) and the Plan for Science, Technology and Innovation of the Principality of Asturias (PCTI) as part of the research project “Forest and industrial evaluation of Spanish chestnut” (VALOCAS).

7. References

Assman E (1970). The Principles of Forest Yield Study. Pergamon Press, Oxford, pp. 506.

Barrio-Anta M, Balboa-Murias MA, Castedo-Dorado F, Diéguez-Aranda U, Álvarez-González JG (2006). An ecoregional model for estimating volume, biomass and carbon pools in maritime pine in Galicia (northwestern Spain). Forest Ecology and Management 223: 24–34. doi: 10.10167j.foreco.2005.10.073.

Bourgeois C, Sevrin É, Lemaire J (2004). Les guides du sylviculteur. Le châtaignier un arbre, un bois. Deuxième édition. Institut pour le Développement Forestier.

Brooks JR, Wiant HV (2004). A simple technique for estimating cubic foot volume yields. Forest Ecology and Management 203: 373–380. doi:10.1016/j.foreco.2004.08.006.

Burkhart HE (1977). Cubic-foot volume of loblolly pine to any merchantable top limit. Southern Journal of Applied Forestry 1: 7-9.

Burkhart HE, Tomé M (2012). Modelling forest trees and stands. Springer, pp. 471.

Cabrera BM, Ochoa F (1997). Tablas de producción de castaño (*Castanea sativa* Mill.) tratado en monte bajo, en Asturias. In II Congreso Forestal Español-Irati 97. Puertas F., Rivas M. (eds). Pamplona, Spain, pp 131-136.

Carmean WH (1972). Site Index Curves for Upland Oaks in the Central States. Forest Science 18: 109–120.

Castaño-Santamaría J, Barrio-Anta M, Álvarez-Álvarez P (2013). Regional-scale stand density management diagrams for Pyrenean oak (*Quercus pyrenaica* Willd.) stands in north-west Spain. iForest 6: 113-122. doi: 10.3832/ifor0880-006.

Castedo-Dorado F, Crecente-Campo F, Álvarez-Álvarez P, Barrio-Anta M (2009). Development of a stand density management diagram for radiata pine stands including assessment of stand stability. Forestry 82: 1–16. doi:10.1093/forestry/cpm032.

Cieszewski CJ (2002). Comparing fixed-and variable-base-age site equations having single versus multiple asymptotes. Forest Science 48: 7–23.

Cieszewski CJ (2003). Developing a Well-Behaved Dynamic Site Equation Using a Modified Hossfeld IV Function $Y^3 = (ax^m)/(c+x^{m-1})$, a Simplified Mixed-Model and Scant Subalpine Fir Data. Forest Science 49: 539–554.

Cieszewski CJ, Bailey RL (2000). Generalized algebraic difference approach: a new methodology for derivation of biologically based dynamic site equations. Forest Science 46: 116-126.

Cieszewski CJ, Harrison M, Martin SW (2000). Practical methods for estimating non-biased parameters in self-referencing growth and yield models. Plant Management Research Cooperative Technical Report 2000-7. University of Georgia. Athens, Georgia.

Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL (1983). Timber management: a quantitative approach. Wiley New York.

DGCONA (2013). III Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España.

Everard J, Christie JM (1995). Sweet chestnut: silviculture, timber quality and yield in the Forest of Dean. Forestry 68, 2: 133-144. doi: 10.1093/forestry/68.2.133.

Fang Z, Borders BE, Bailey RL (2000). Compatible volume-taper models for Loblolly and Slash pine based on a system with segmented-stem form factors. Forest Science 46 (1): 1–12.

Goelz JCG, Burk TE (1992). Development of a well-behaved site index equation: jack pine in north central Ontario. Canadian Journal of Forest Research 22: 776–784. doi: 10.1139/x00-086.

Hartley HO (1961). The modified Gauss-Newton method for the fitting of nonlinear regression functions by least squares. Technometrics 3: 269-280.

Jack SB, Long JN (1996). Linkages between silviculture and ecology: an analysis of density management diagrams. Forest Ecology and Management 86: 205–220. doi:10.1016/S0378-1127(96)03770-X.

Madrigal A (1991). Tablas de producción. Seminario sobre inventario y ordenación de montes, Valsaín, Segovia. Vol. II: 32-70.

Madrigal A, Puertas F, Martínez-Millán FJ (1992). Tablas de producción para *Fagus sylvativa* L. en Navarra, Serie Agraria Nº3. Departamento de Agricultura, Ganadería y Montes, Gobierno de Navarra. Pamplona, España, pp. 122.

McDill ME, Amateis RL (1992). Measuring forest site quality using the parameters of a dimensionally compatible height growth function. Forest Science 38: 409–429.

Menéndez-Miguélez M, Canga E, Barrio-Anta M, Majada J, Álvarez-Álvarez P (2013). A three level system for estimating the biomass of *Castanea sativa* Mill. coppice stands in north-west Spain. Forest Ecology and Management 291: 417–426. doi:10.1016/j.foreco.2012.11.040.

Menéndez-Miguélez M, Canga E, Álvarez-Álvarez P, Majada J (2014). Stem taper function for sweet chestnut (*Castanea sativa* Mill.) coppice stands in northwest Spain. Annals of Forest Science 71: 761-770. doi:10.1007/s13595-014-0372-6.

Newberry JD (1991). Note: A Note on Carmean's Estimate of Height from Stem Analysis Data. Forest Science 37: 368–369.

Newton PF (1997). Stand density management diagrams: Review of their development and utility in stand-level management planning. Forest Ecology and Management 98: 251–265. doi:10.1016/S0378-1127(97)00086-8.

Newton PF, Lei Y, Zhang SY (2005). Stand-level diameter distribution yield model for black spruce plantations. Forest Ecology and Management 209: 181–192. doi:10.1016/j.foreco.2005.01.020.

Newton PF, Weetman GF (1994). Stand density management diagram for managed black spruce stands. The Forestry Chronicle 70: 65–74.

Pérez-Cruzado C, Merino A, Rodríguez-Soalleiro R (2011). A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass and Bioenergy 35: 2839–2851. doi:10.1016/j.biombioe.2011.03.020.

Richards FJ (1959). A flexible growth function for empirical use. Journal of Experimental Botany 10: 290–301.

Sánchez F, Rodríguez R, Rojo A, Álvarez JG, López CA, Gorgoso JJ, Castedo F (2003). Crecimiento y tablas de producción de *Pinus radiata* D. Don en Galicia. Investigación Agraria: Sistemas y Recursos Forestales 12 (2): 65–83.

SAS Institute Inc. (2004a). SAS/STAT®. 9.1. User's Guide. SAS Institute Inc., Cary, NC.

SAS Institute Inc. (2004b). SAS/ETS®. 9.1. User's Guide. SAS Institute Inc., Cary, NC.

Vacchiano G, Motta R, Long JN, Shaw JD (2008). A density management diagram for Scots pine (*Pinus sylvestris* L.): A tool for assessing the forest's protective effect. Forest Ecology and Management 255 (7): 2542-2554. doi: 10.1016/j-foreco.2008.01.015.

Van Deusen PC, Sullivan AD, Matvey TG (1981). A prediction system for cubic foot volume of Loblolly pine applicable through much of its range. Southern Journal of Applied Forestry 5 (4): 186-189.

von Bertalanffy L (1949). Problems of organic growth. Nature 163: 156–158.

von Bertalanffy L (1957). Quantitative laws in metabolism and growth. The Quarterly Review of Biology 32 (3): 217-231.

Weiskittel AR, Hann DW, Kershaw Jr JA, Vanclay JK (2011). Forest growth and yield modeling. John Wiley & Sons.

Figures

Figure 1. Chestnut stool with two stems: the dominant stem has been extracted for stem analysis.

Figure 2**.** Dominant height growth curves for SI values of 10, 14, 18 and 22 m at a reference age of 22 years, overlaid on the trajectories of the observed heights over time for dynamic equation developed for northwestern Spain.

Figure 3. Stand density management diagram for chestnut coppice stands in NW Spain in relation to stand volume (m^3 ha^{-1}).

Figure 4. Stand density management diagram for chestnut coppice stands in NW Spain in relation to stem biomass (t ha^{-1}).

Figure 5. Stand density management diagram for chestnut coppice stands in NW Spain in relation to total aboveground biomass (t ha^{-1}).

Tables

Table 1. Descriptive statistics of main stand variables

	n	Mean	Min	Max	Std. dev.
t	53	39.57	15	55	9.758
N	55	1230.80	396.12	3154.80	541.70
d_g	55	21.21	9.56	30.98	4.41
G	55	39.53	16.33	58.76	9.81
H_m	55	17.49	10.63	23.44	2.84
H_0	55	20.36	12.37	28.17	3.15
SI	53	15.03	10.59	24.76	2.75
V_m	55	334.41	97.82	543.17	104.74

Note: t age (years), N number of stems per hectare (stems ha^{-1}), d_g quadratic mean diameter (cm), G basal area (m^2 ha^{-1}), H_m mean height (m), H_0 average height of the 100 thickest trees per hectare (m), SI site index (m, at a reference age of 22 years), V_m volume per hectare (m^3 ha^{-1}).

Table 2. Parameter estimates, associated approximate standard errors and goodness-of-fit statistics for the selected SI model

	Equation	b_{ij}	Estimate	Std. error	RMSE	R^2_{adj}
[3]	$SI=\frac{(b_{01}+X_0)\cdot X_0\cdot t^{-b_{21}}}{1+b_{11}}$	b_{01}	17.34	6.326		
		b_{11}	802.6	266.4	0.5799	0.9891
[4]	$X_0=0.5\cdot\left[H_0-b_{01}+\sqrt{(H_0-b_{01})^2+4H_0\cdot b_{11}\cdot t_0^{-b_{21}}}\right]$	b_{21}	1.077	0.01740		

Note: H_0 dominant height (m) at age t_0 (years), SI estimated height (m) at age t (years), b_{ij} fitting parameters, R^2_{adj} adjusted coefficient of determination, RMSE root mean square error.

Table 3. Equation, parameter estimates, associated approximate standard errors and goodness-of-fit statistics for the selected density equations in the low [5] and high [6] density plots, respectively

	Equation	b_{ij}	Estimate	Std. error	RMSE	R^2_{adj}
[5]	$Ln\ N = b_{01} + b_{11} \cdot t$	b_{01}	10.61	1.218	271.42	0.7363
		b_{11}	-1.0825	0.40406		
[6]	$Ln\ N = b_{02} + b_{12} \cdot t$	b_{02}	11.58	1.06804	337.36	0.6438
		b_{12}	-1.172	0.3568		

Note: N stand density (trees ha^{-1}), t stand age (years), b_{ij} fitting parameters, R^2_{adj} adjusted coefficient of determination, RMSE root mean square error.

Table 4. Equation, parameter estimates, associated approximate standard errors and goodness-of-fit statistics for the quadratic mean diameter equations selected for the yield tables [7] and SDMS [8], respectively

	Equation	b_{ij}	Estimate	Std. error	RMSE	R^2_{adj}
[7]	$d_g=b_{01}\cdot N^{b_{11}}\cdot {H_0}^{b_{21}}\cdot t^{b_{31}}$	b_{01}	5.0785	2.588	1.867	0.8205
		b_{11}	-0.1775	0.03580		
		b_{21}	0.6622	0.1003		
		b_{31}	0.1839	0.05440		
[8]	$Ln\ d_g=b_{02}+b_{12}\cdot Ln\ N+b_{22}\cdot Ln\ H_0$	b_{02}	2.143	0.6501	2.118	0.7688
		b_{12}	-0.2291	0.04490		
		b_{22}	0.8327	0.1342		

Note: d_g quadratic mean diameter (cm^2), N stand density (trees ha^{-1}), H_0 dominant height (m), t stand age (years), b_{ij} fitting parameters, R^2_{adj} adjusted coefficient of determination, RMSE root mean square error.

Table 5. Equation, parameter estimates, associated approximate standard errors and goodness-of-fit statistics for the merchantable volume equation selected for the yield tables [9] and the total stand volume equation selected for the SDMDs [10], respectively

	Equation	b_{ij}	Estimate	Std. error	RMSE	R^2_{adj}
[9]	$V_{mi}=b_{01}\cdot G^{b_{11}}\cdot {H_0}^{b_{21}}\cdot e^{b_{31}\cdot\left(\frac{d_i}{d_g}\right)^{b_{41}}}$	b_{01}	0.7901	1.7096	13.94	0.9916
		b_{11}	1.0106	0.00163		
		b_{21}	0.7729	0.05940		
		b_{31}	-0.9259	0.02790		
		b_{41}	3.360	0.03090		
[10]	$Ln\ V_m=b_{02}+b_{12}\cdot Ln\ N+b_{22}\cdot Ln H_0$	b_{02}	-5.285	1.445	65.22	0.6122
		b_{12}	0.5220	0.0991		
		b_{22}	2.455	0.2922		

Note: V_{mi} merchantable stand volume (m^3 ha^{-1}), V_m total stand volume (m^3 ha^{-1}), G basal area (m^2 ha^{-1}), H_0 dominant height (m), d_i limit diameter (cm), d_g quadratic mean diameter (cm^2), N stand density (trees ha^{-1}), b_{ij} fitting parameters, R^2_{adj} adjusted coefficient of determination, RMSE root mean square error.

Table 6. Equation, parameter estimates, associated approximate standard errors and goodness-of-fit statistics for the stand biomass equations for the yield tables [11]-[14] and for the SDMS [15]-[16], respectively

	Equation	b_{ij}	Estimate	Std. error	RMSE	R^2_{adj}
[11]	$W_{wood}=b_{01} \cdot d_0^{b_{11}} \cdot G^{b_{21}}$	b_{01}	0.8582	0.1946	24.72	0.7269
		b_{11}	0.8474	0.08490		
		b_{21}	0.5537	0.06340		
[12]	$W_{bark}=b_{02} \cdot H_0^{b_{12}} \cdot G^{b_{22}}$	b_{02}	0.2449	0.09660	2.147	0.6847
		b_{12}	0.4847	0.1723		
		b_{22}	0.6431	0.08690		
[13]	$W_{crown}=b_{03} \cdot d_0^{b_{13}} \cdot H_0^{b_{23}} \cdot G^{b_{33}}$	b_{03}	14.31	2.943	7.299	0.6347
		b_{13}	1.221	0.09180		
		b_{23}	-1.649	0.1108		
		b_{33}	0.4965	0.05930		
[14]	$W_{total}=W_{wood}+W_{bark}+W_{crown}$	-	-	-	33.56	0.6864
[15]	$Ln\ W_{stem}=b_{04}+b_{14} \cdot Ln\ H_0+b_{24} \cdot Ln\ N$	b_{04}	-6.735	1.729	27.97	0.6743
		b_{14}	2.616	0.3041		
		b_{24}	0.5386	0.1356		
[16]	$Ln\ W_{total}=b_{05}+b_{15} \cdot Ln\ H_0+b_{25} \cdot Ln\ N$	b_{05}	-5.186	1.673	37.64	0.5683
		b_{15}	2.229	0.2984		
		b_{25}	0.5231	0.1346		

Note: W_i dry weight of the *i* biomass component (kg), d_0 dominant diameter (cm), H_0 dominant height (m), G basal area (m^2 ha^{-1}), N stand density (trees ha^{-1}), b_{ij} are fitting parameters, RMSE is the root mean square error, R^2 is the coefficient of determination

Table 7. Yield table for high density and SI = 10 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	5.2	7183	4.8	13.0	38.1	0.0	0.0	0.0	20.5	64.9	2717	4.0	3.4	10.1	10.1	3.2	9.6	4466	5.2	9.6	27.9	17.3	55.3	38.1	3.8	
15	7.4	4466	7.1	17.6	67.7	0.0	0.0	0.0	32.6	78.2	1278	5.9	3.4	13.4	23.5	3.7	8.5	3188	7.5	14.2	54.4	28.9	69.8	77.9	5.2	8.0
20	9.3	3188	9.2	21.3	97.6	0.8	0.0	0.0	43.8	90.4	734	7.6	3.3	15.3	38.8	3.9	7.8	2454	9.7	18.0	82.3	39.9	82.6	121.1	6.1	8.6
25	11.0	2454	11.2	24.2	125.8	10.7	0.2	0.0	53.9	101.2	472	9.2	3.1	16.4	55.2	4.0	7.2	1982	11.6	21.1	109.5	49.9	94.0	164.6	6.6	8.7
30	12.4	1982	13.1	26.5	151.7	34.6	3.1	0.0	62.9	110.6	328	10.6	2.9	16.9	72.0	3.9	6.7	1655	13.5	23.6	134.9	59.0	103.9	206.9	6.9	8.5
35	13.6	1655	14.8	28.4	175.0	66.1	13.6	0.0	70.9	118.9	240	12.0	2.7	17.0	89.0	3.9	6.3	1415	15.2	25.7	158.1	67.0	112.6	247.1	7.1	8.0
40	14.7	1415	16.4	29.9	195.9	98.6	32.3	0.0	77.9	126.2	182	13.3	2.5	16.9	105.8	3.7	5.9	1232	16.8	27.3	179.0	74.1	120.3	284.8	7.1	7.6
45	15.7	1232	17.9	31.1	214.3	128.8	56.2	0.0	84.1	132.6	143	14.6	2.4	16.6	122.4	3.6	5.6	1089	18.3	28.7	197.8	80.5	127.0	320.2	7.1	7.1
50	16.6	1089	19.4	32.1	230.7	155.8	82.2	0.0	89.6	138.1	115	15.7	2.2	16.2	138.6	3.5	5.3	974	19.8	29.8	214.5	86.1	132.8	353.1	7.1	6.6
55	17.4	974	20.7	32.9	245.1	179.3	107.8	0.1	94.5	143.1	94	16.8	2.1	15.8	154.4	3.4	5.0	880	21.1	30.8	229.3	91.1	138.0	383.7	7.0	6.1
60	18.1	880	22.0	33.5	257.8	199.8	131.9	0.3	98.8	147.4																

Table 8. Yield table for high density and SI = 14 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	7.7	7183	6.2	21.7	86.0	0.0	0.0	0.0	37.7	87.8	2717	5.2	5.7	22.9	22.9	5.9	13.1	4466	6.8	16.0	63.1	31.8	74.7	86.0	8.6	
15	10.7	4466	9.0	28.5	145.7	0.9	0.0	0.0	57.8	109.6	1278	7.5	5.6	28.7	51.6	6.6	12.0	3188	9.6	23.0	117.0	51.2	97.6	168.6	11.2	16.5
20	13.1	3188	11.6	33.6	201.5	22.1	0.6	0.0	75.3	128.3	734	9.5	5.2	31.6	83.2	6.7	11.2	2454	12.1	28.4	169.9	68.6	117.2	253.1	12.7	16.9
25	15.2	2454	13.9	37.3	250.9	76.2	10.9	0.0	90.3	144.1	472	11.4	4.8	32.6	115.8	6.6	10.4	1982	14.5	32.5	218.2	83.7	133.8	334.1	13.4	16.2
30	16.9	1982	16.1	40.1	293.5	140.5	42.3	0.0	103.1	157.4	328	13.1	4.4	32.6	148.4	6.4	9.7	1655	16.6	35.7	260.9	96.6	147.7	409.4	13.6	15.1
35	18.4	1655	18.0	42.2	330.0	200.4	88.9	0.0	113.9	168.6	240	14.7	4.1	32.0	180.4	6.2	9.0	1415	18.5	38.2	298.0	107.7	159.5	478.4	13.7	13.8
40	19.7	1415	19.9	43.9	361.0	251.8	140.0	0.0	123.1	178.0	182	16.1	3.7	31.1	211.5	5.9	8.4	1232	20.4	40.1	329.9	117.2	169.5	541.4	13.5	12.6
45	20.8	1232	21.6	45.1	387.2	294.7	188.9	0.2	130.9	185.9	143	17.5	3.4	29.9	241.4	5.6	7.9	1089	22.1	41.6	357.3	125.3	178.0	598.7	13.3	11.5
50	21.8	1089	23.2	46.0	409.4	330.4	232.9	1.3	137.7	192.7	115	18.8	3.2	28.7	270.2	5.4	7.4	974	23.6	42.8	380.6	132.3	185.2	650.8	13.0	10.4
55	22.7	974	24.7	46.6	428.2	360.0	271.3	4.0	143.4	198.4	94	20.0	3.0	27.5	297.7	5.1	7.0	880	25.1	43.7	400.6	138.3	191.4	698.3	12.7	9.5
60	23.4	880	26.1	47.1	444.0	384.6	304.4	9.2	148.4	203.3																

Table 9. Yield table for high density and SI = 18 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	10.33	7183	7.5	32.0	159.3	0.0	0.0	0.0	59.8	115.4	2717	6.3	8.4	42.4	42.4	9.3	17.4	4466	8.2	23.5	116.9	50.5	97.9	159.3	15.9	
15	14.03	4466	10.8	40.9	259.1	15.9	0.2	0.0	88.9	146.6	1278	8.9	8.0	51.1	93.6	10.1	16.3	3188	11.5	32.9	208.0	78.8	130.3	301.5	20.1	28.4
20	16.98	3188	13.7	47.2	346.5	99.5	13.0	0.0	113.0	172.1	734	11.3	7.3	54.3	147.9	10.1	15.1	2454	14.4	39.8	292.2	103.0	157.0	440.0	22.0	27.7
25	19.38	2454	16.4	51.5	419.7	209.9	67.9	0.0	132.8	192.8	472	13.4	6.6	54.6	202.4	9.8	14.0	1982	17.0	44.9	365.1	123.0	178.8	567.6	22.7	25.5
30	21.37	1982	18.7	54.6	479.9	309.4	151.4	0.0	149.0	209.5	328	15.3	6.0	53.3	255.7	9.3	12.9	1655	19.3	48.6	426.6	139.6	196.5	682.4	22.7	23.0
35	23.03	1655	20.9	56.8	529.1	390.7	238.4	0.1	162.2	223.0	240	17.0	5.5	51.3	307.0	8.8	12.0	1415	21.5	51.4	477.8	153.4	211.0	784.9	22.4	20.5
40	24.43	1415	22.9	58.4	569.2	455.4	316.7	1.4	173.1	234.1	182	18.6	5.0	49.0	356.0	8.3	11.2	1232	23.5	53.4	520.2	164.8	223.0	876.2	21.9	18.3
45	25.64	1232	24.8	59.4	601.8	507.0	383.4	5.9	182.2	243.2	143	20.1	4.5	46.5	402.6	7.9	10.4	1089	25.3	54.9	555.3	174.3	232.8	957.8	21.3	16.3
50	26.69	1089	26.5	60.2	628.4	548.2	438.8	15.8	189.7	250.7	115	21.5	4.2	44.1	446.7	7.4	9.7	974	27.0	56.0	584.2	182.3	241.0	1030.9	20.6	14.6
55	27.61	974	28.1	60.6	650.0	581.2	484.5	31.9	196.1	256.9	94	22.8	3.9	41.8	488.5	7.0	9.1	880	28.7	56.8	608.2	189.0	247.8	1096.6	19.9	13.1
60	28.41	880	29.7	60.9	667.5	607.9	522.1	53.6	201.4	262.1																

Table 10. Yield table for high density and SI = 22 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	13.1	7183	8.8	43.7	261.8	1.0	0.0	0.0	86.8	147.6	2717	7.3	11.5	69.7	13.5	22.5	4466	9.6	32.1	192.1	69.7	73.2	125.1	261.8	26.2	
15	17.5	4466	12.5	54.7	410.9	74.0	4.5	0.0	125.6	189.0	1278	10.3	10.7	150.8	14.2	21.1	3188	13.3	44.0	329.9	81.1	111.3	167.9	480.7	32.0	43.8
20	20.8	3188	15.7	61.9	534.4	242.4	66.9	0.0	156.4	221.4	734	12.9	9.6	234.6	13.9	19.5	2454	16.5	52.3	450.6	83.7	142.4	201.9	685.2	34.3	40.9
25	23.5	2454	18.6	66.7	632.9	403.7	194.1	0.0	180.6	246.6	472	15.2	8.6	316.8	13.3	17.9	1982	19.3	58.1	550.6	82.3	167.3	228.6	867.5	34.7	36.5
30	25.7	1982	21.2	69.9	710.5	531.5	331.2	0.3	199.8	266.3	328	17.3	7.7	395.8	12.5	16.5	1655	21.9	62.2	631.6	78.9	187.3	249.8	1027.4	34.2	32.0
35	27.5	1655	23.5	72.0	771.5	629.2	451.4	3.1	215.1	281.9	240	19.2	6.9	470.6	11.7	15.2	1415	24.2	65.1	696.7	74.8	203.4	266.7	1167.2	33.3	28.0
40	29.0	1415	25.7	73.3	819.3	703.8	549.5	13.6	227.4	294.3	182	20.9	6.2	541.1	10.9	14.1	1232	26.3	67.1	748.8	70.5	216.4	280.2	1289.8	32.2	24.5
45	30.3	1232	27.7	74.2	856.7	761.2	627.9	35.3	237.3	304.2	143	22.5	5.7	607.3	10.2	13.1	1089	28.3	68.5	790.5	66.3	227.1	291.1	1397.8	31.1	21.6
50	31.4	1089	29.5	74.6	886.1	805.7	690.2	68.1	245.4	312.2	115	24.0	5.2	669.5	9.6	12.2	974	30.1	69.4	823.9	62.2	235.8	300.0	1493.4	29.9	19.1
55	32.4	974	31.3	74.8	909.0	840.4	739.6	109.4	252.0	318.6	94	25.3	4.8	728.0	9.0	11.3	880	31.8	70.0	850.6	58.5	243.0	307.2	1578.6	28.7	17.0
60	33.2	880	32.9	74.8	926.8	867.5	778.9	155.5	257.5	323.8																

Table 11. Yield table for low density and SI = 10 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	5.2	3366	5.5	8.0	23.2	0.0	0.0	0.0	15.6	50.3	1196	4.6	2.0	5.8	5.8	2.3	6.9	2170	5.9	6.0	17.5	13.4	43.4	23.2	2.3	
15	7.4	2170	8.1	11.1	42.3	0.0	0.0	0.0	25.2	61.2	581	6.6	2.0	7.8	13.6	2.6	6.1	1590	8.5	9.1	34.5	22.5	55.1	48.1	3.2	5.0
20	9.3	1590	10.4	13.6	62.0	2.7	0.0	0.0	34.1	71.2	341	8.6	2.0	9.0	22.6	2.8	5.7	1248	10.9	11.6	53.0	31.3	65.5	75.5	3.8	5.5
25	11.0	1248	12.6	15.7	81.0	15.6	1.1	0.0	42.3	80.1	224	10.3	1.9	9.8	32.4	2.9	5.3	1025	13.1	13.8	71.2	39.4	74.8	103.6	4.1	5.6
30	12.4	1025	14.7	17.3	98.7	36.4	7.2	0.0	49.7	88.0	158	12.0	1.8	10.2	42.5	2.9	4.9	867	15.1	15.6	88.5	46.8	83.1	131.1	4.4	5.5
35	13.6	867	16.6	18.7	114.9	59.3	20.2	0.0	56.3	95.0	117	13.5	1.7	10.3	52.9	2.8	4.7	751	17.0	17.0	104.6	53.4	90.3	157.4	4.5	5.3
40	14.7	751	18.4	19.9	129.6	81.0	37.6	0.0	62.1	101.2	90	14.9	1.6	10.3	63.2	2.8	4.4	661	18.8	18.3	119.2	59.3	96.8	182.4	4.6	5.0
45	15.7	661	20.0	20.8	142.8	100.5	56.7	0.0	67.3	106.6	71	16.2	1.5	10.2	73.4	2.7	4.2	590	20.4	19.3	132.5	64.6	102.4	206.0	4.6	4.7
50	16.6	590	21.6	21.6	154.6	117.7	75.6	0.1	72.0	111.4	58	17.5	1.4	10.1	83.5	2.6	4.0	532	22.0	20.2	144.5	69.3	107.5	228.0	4.6	4.4
55	17.4	532	23.1	22.2	165.2	132.8	93.2	0.5	76.1	115.7	48	18.7	1.3	9.8	93.3	2.5	3.8	484	23.5	20.9	155.3	73.6	111.9	248.6	4.5	4.1
60	18.1	484	24.5	22.8	174.6	146.1	109.2	1.4	79.8	119.5																

Table 12. Yield table for low density and SI = 14 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	7.7	3366	7.1	13.3	52.5	0.0	0.0	0.0	28.8	67.8	1196	5.9	3.3	13.1	13.1	4.2	9.4	2170	7.7	10.0	39.4	24.6	58.4	52.5	5.2	
15	10.7	2170	10.3	17.9	91.0	3.3	0.0	0.0	44.6	85.5	581	8.5	3.3	16.7	29.8	4.7	8.7	1590	10.8	14.7	74.3	39.9	76.8	104.1	6.9	10.3
20	13.1	1590	13.1	21.4	128.0	29.8	2.8	0.0	58.7	100.8	341	10.7	3.1	18.6	48.4	4.9	8.1	1248	13.7	18.3	109.4	53.9	92.6	157.8	7.9	10.7
25	15.2	1248	15.7	24.1	161.5	72.8	19.9	0.0	71.0	113.8	224	12.8	2.9	19.5	67.9	4.8	7.6	1025	16.2	21.2	142.0	66.1	106.2	209.9	8.4	10.4
30	16.9	1025	18.0	26.2	191.0	116.1	51.7	0.0	81.4	124.9	158	14.7	2.7	19.7	87.6	4.7	7.1	867	18.6	23.5	171.3	76.7	117.8	258.9	8.6	9.8
35	18.4	867	20.2	27.9	216.6	154.3	88.8	0.0	90.4	134.4	117	16.4	2.5	19.5	107.1	4.6	6.6	751	20.7	25.4	197.1	85.9	127.7	304.2	8.7	9.1
40	19.7	751	22.2	29.1	238.8	186.6	124.8	0.3	98.2	142.4	90	18.1	2.3	19.0	126.1	4.4	6.2	661	22.7	26.8	219.7	93.8	136.1	345.9	8.6	8.3
45	20.8	661	24.1	30.1	257.9	213.7	157.3	1.6	104.8	149.3	71	19.5	2.1	18.5	144.6	4.2	5.9	590	24.6	28.0	239.4	100.6	143.4	384.0	8.5	7.6
50	21.8	590	25.9	30.9	274.4	236.4	185.6	5.0	110.6	155.1	58	20.9	2.0	17.8	162.4	4.0	5.5	532	26.3	28.9	256.5	106.6	149.6	419.0	8.4	7.0
55	22.7	532	27.5	31.6	288.5	255.7	210.0	11.0	115.5	160.2	48	22.3	1.9	17.2	179.6	3.8	5.2	484	28.0	29.7	271.4	111.7	155.0	451.0	8.2	6.4
60	23.4	484	29.0	32.1	300.8	272.0	230.9	19.9	119.9	164.6																

Table 13. Yield table for low density and SI = 18 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	10.3	3366	8.6	19.6	97.2	0.2	0.0	0.0	45.6	88.8	1196	7.2	4.8	24.2	24.2	6.6	12.5	2170	9.3	14.8	73.0	39.0	76.4	97.2	9.7	
15	14.0	2170	12.3	25.7	161.9	26.4	1.4	0.0	68.7	114.0	581	10.1	4.7	29.7	53.9	7.2	11.7	1590	13.0	21.0	132.1	61.5	102.3	186.1	12.4	17.8
20	17.0	1590	15.5	30.1	220.1	96.6	25.2	0.0	88.2	134.9	341	12.7	4.3	32.1	86.0	7.3	10.9	1248	16.2	25.8	188.1	80.9	123.9	274.1	13.7	17.6
25	19.4	1248	18.4	33.3	270.2	170.0	80.0	0.0	104.3	152.0	224	15.1	4.0	32.6	118.6	7.1	10.2	1025	19.1	29.3	237.5	97.2	141.8	356.2	14.2	16.4
30	21.4	1025	21.1	35.7	312.2	232.2	143.3	0.1	117.7	166.0	158	17.2	3.6	32.2	150.8	6.8	9.5	867	21.7	32.1	280.0	110.9	156.5	430.8	14.4	14.9
35	23.0	867	23.4	37.5	347.3	282.6	201.9	1.3	128.8	177.5	117	19.1	3.3	31.2	182.0	6.5	8.8	751	24.1	34.1	316.1	122.3	168.7	498.1	14.2	13.5
40	24.4	751	25.6	38.8	376.5	323.2	252.0	6.1	138.0	187.1	90	20.8	3.1	30.0	212.1	6.1	8.2	661	26.2	35.7	346.5	131.9	178.8	558.6	14.0	12.1
45	25.6	661	27.7	39.8	400.9	356.2	293.8	16.5	145.8	195.0	71	22.5	2.8	28.7	240.8	5.8	7.7	590	28.2	36.9	372.1	140.0	187.3	612.9	13.6	10.9
50	26.7	590	29.6	40.5	421.1	383.1	328.3	32.7	152.4	201.7	58	24.0	2.6	27.4	268.2	5.5	7.2	532	30.1	37.9	393.7	146.9	194.5	661.9	13.2	9.8
55	27.6	532	31.3	41.0	438.0	405.2	356.9	53.5	157.9	207.3	48	25.4	2.4	26.1	294.3	5.2	6.8	484	31.9	38.6	411.9	152.7	200.5	706.2	12.8	8.9
60	28.4	484	33.0	41.4	452.1	423.5	380.7	77.3	162.7	212.0																

Table 14. Yield table for low density and SI = 22 m

Input variables		Stand before thinning									Stand removed							Stand after thinning						Total stand		
t	H_0	N	d_g	G	V	V_{15}	V_{20}	V_{40}	W_w	W_t	N_e	d_{ge}	G_e	V_e	V_{ac}	W_{we}	W_{te}	N_{at}	d_{gat}	G_{at}	V_{at}	W_{wat}	W_{tat}	V_t	MAI	PAI
10	13.1	3366	10.1	26.8	159.8	4.6	0.0	0.0	66.2	113.4	1196	8.4	6.6	39.8	39.8	9.6	16.0	2170	10.9	20.2	120.0	56.6	97.4	159.8	16.0	
15	17.5	2170	14.2	34.3	256.8	84.2	13.7	0.0	97.0	146.7	581	11.7	6.2	47.2	86.9	10.2	15.2	1590	15.0	28.1	209.6	86.8	131.5	296.5	19.8	27.3
20	20.8	1590	17.8	39.5	339.5	201.4	86.1	0.0	121.9	173.2	341	14.6	5.7	49.5	136.4	10.1	14.1	1248	18.6	33.8	290.1	111.9	159.1	426.4	21.3	26.0
25	23.5	1248	21.0	43.1	407.4	301.7	184.9	0.1	141.9	194.2	224	17.1	5.2	49.2	185.6	9.7	13.1	1025	21.7	38.0	358.2	132.2	181.1	543.8	21.8	23.5
30	25.7	1025	23.8	45.7	462.2	380.0	276.2	2.3	157.9	210.8	158	19.4	4.7	47.6	233.2	9.1	12.1	867	24.5	41.0	414.6	148.7	198.8	647.8	21.6	20.8
35	27.5	867	26.4	47.4	506.4	440.8	351.7	12.0	170.8	224.2	117	21.5	4.2	45.5	278.7	8.6	11.2	751	27.1	43.2	460.9	162.2	213.0	739.6	21.1	18.4
40	29.0	751	28.7	48.7	542.0	488.4	412.2	32.7	181.3	235.0	90	23.3	3.8	43.2	322.0	8.1	10.4	661	29.4	44.9	498.7	173.2	224.6	820.7	20.5	16.2
45	30.3	661	30.9	49.6	570.7	526.0	460.6	63.3	190.0	243.8	71	25.1	3.5	40.9	362.9	7.6	9.7	590	31.6	46.1	529.8	182.4	234.1	892.6	19.8	14.4
50	31.4	590	32.9	50.2	593.9	556.0	499.4	100.3	197.1	251.0	58	26.7	3.2	38.6	401.5	7.1	9.0	532	33.5	47.0	555.2	190.0	241.9	956.7	19.1	12.8
55	32.4	532	34.8	50.6	612.6	580.0	530.6	140.0	203.0	256.9	48	28.2	3.0	36.5	438.0	6.7	8.5	484	35.4	47.6	576.1	196.3	248.4	1014.1	18.4	11.5
60	33.2	484	36.6	50.9	627.8	599.4	555.8	179.9	208.0	261.8																

Fig. 1

Fig. 2

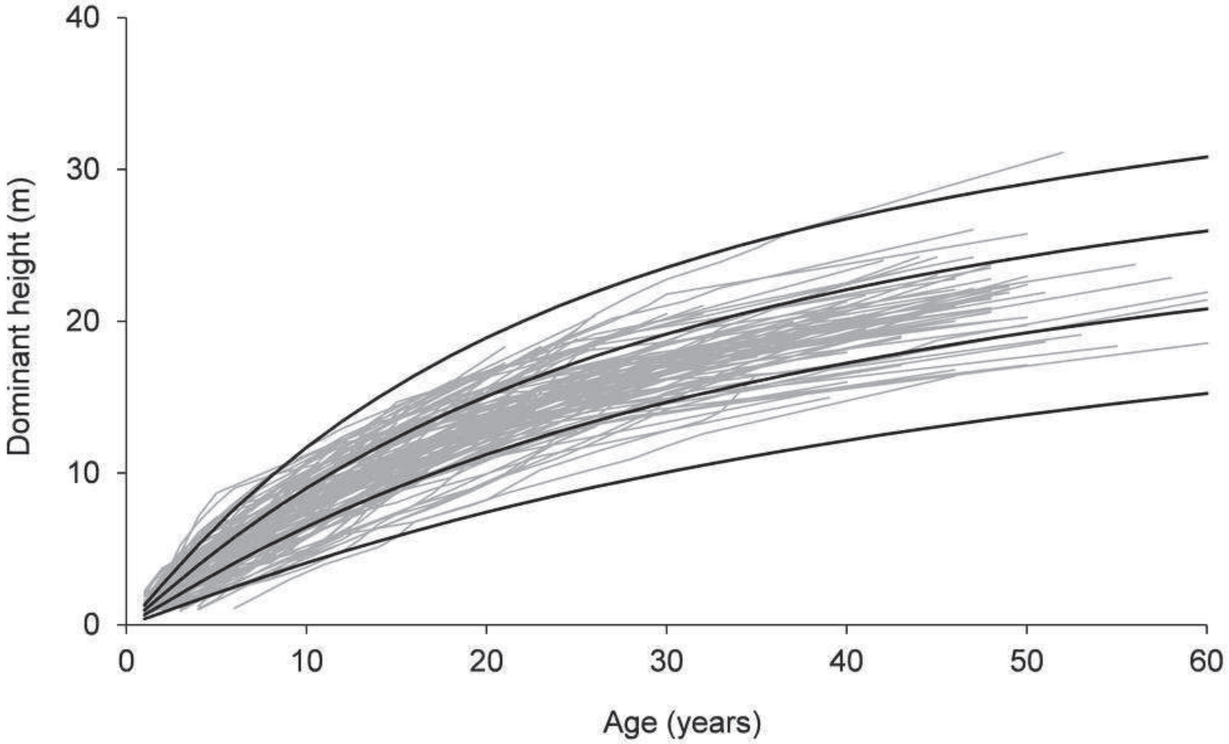


Fig. 3

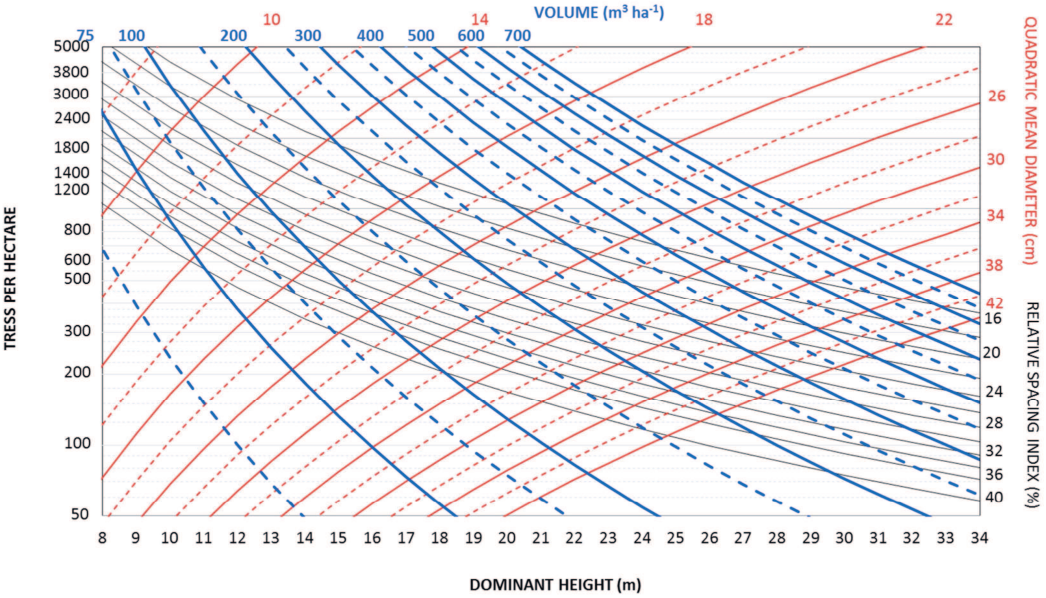

VOLUME (m³ ha⁻¹)
75
100
200
300
400
500
600
700
10
14
18
22
26
30
34
38
42
QUADRATIC MEAN DIAMETER (cm)
16
20
24
28
32
36
40
RELATIVE SPACING INDEX (%)
TRESS PER HECTARE
5000
3800
3000
2400
1800
1400
1200
800
600
500
300
200
100
50
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
DOMINANT HEIGHT (m)

Fig. 4

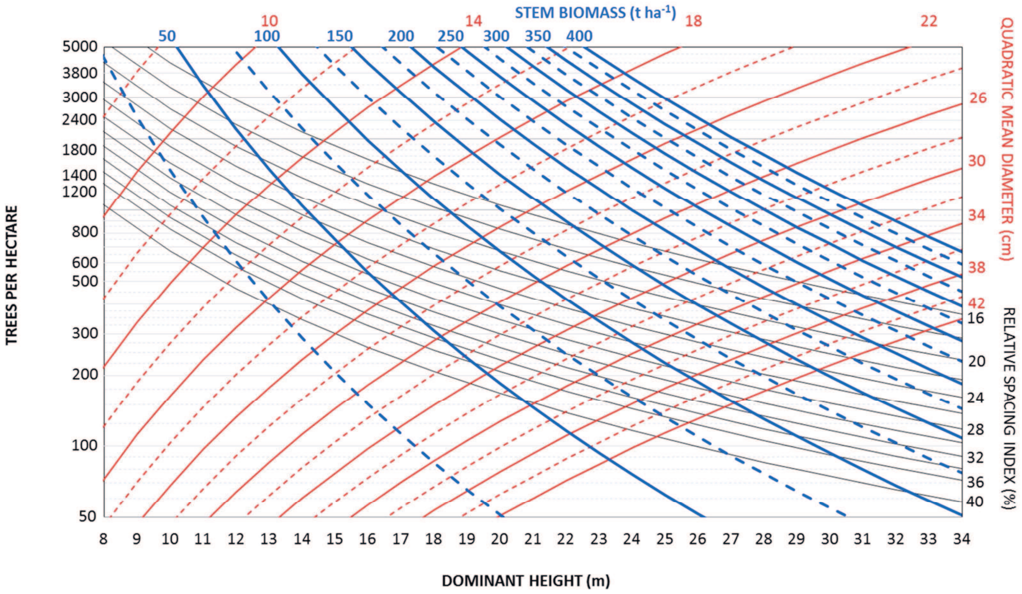
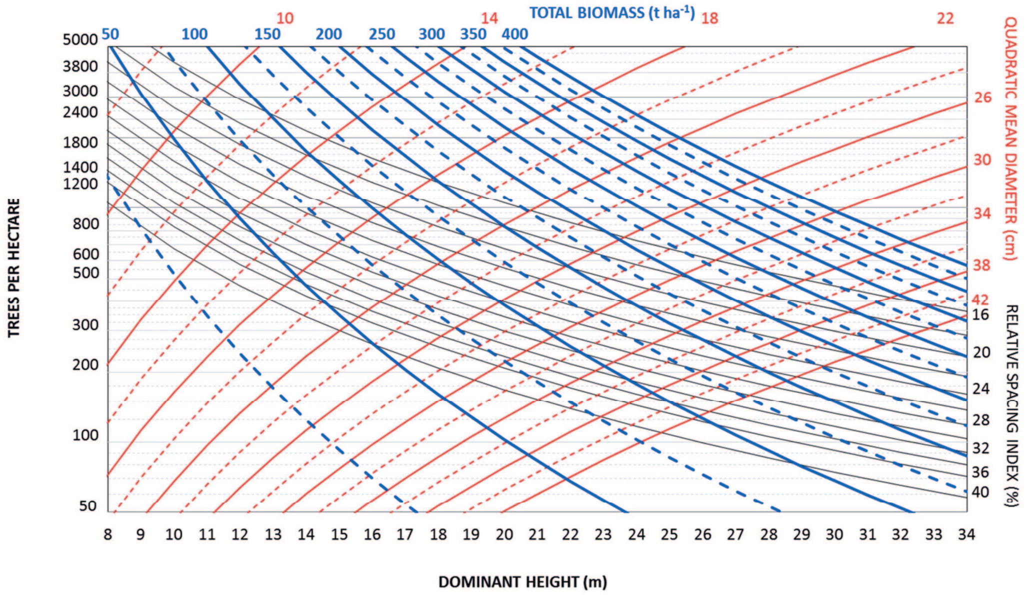

STEM BIOMASS (t ha^{-1})
50
100
150
200
250
300
350
400
10
14
18
22
QUADRATIC MEAN DIAMETER (cm)
26
30
34
38
42
RELATIVE SPACING INDEX (%)
16
20
24
28
32
36
40
TREES PER HECTARE
5000
3800
3000
2400
1800
1400
1200
800
600
500
300
200
100
50
DOMINANT HEIGHT (m)
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34

Fig. 5


TOTAL BIOMASS (t ha^{-1})
50
100
150
200
250
300
350
400
10
14
18
22
QUADRATIC MEAN DIAMETER (cm)
26
30
34
38
42
RELATIVE SPACING INDEX (%)
16
20
24
28
32
36
40
TREES PER HECTARE
5000
3800
3000
2400
1800
1400
1200
800
600
500
300
200
100
50
DOMINANT HEIGHT (m)
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34

Effects of soil nutrients and environmental factors on site productivity in *Castanea sativa* Mill. coppice stands in NW Spain

New Forests (2015) 46:217–233
DOI 10.1007/s11056-014-9456-2

Effects of soil nutrients and environmental factors on site productivity in *Castanea sativa* Mill. coppice stands in NW Spain

María Menéndez-Miguélez · Pedro Álvarez-Álvarez · Juan Majada · Elena Canga

Received: 8 April 2014 / Accepted: 24 September 2014 / Published online: 5 October 2014

Abstract Ecological behaviour and productive capacity of chestnut (*Castanea sativa* Mill.) coppice stands are key factors in predicting forest growth and subsequent management decision, especially in areas where timber production is the primary objective. The effects of soil nutrients and environmental factors on site productivity in chestnut coppice stands in North-West Spain were studied. Site productivity described by site index was related to environmental characteristics, including edaphic, physiographic and climatic variables. The key factors affecting site productivity were evaluated according to two different statistical analyses: the CHAID procedure and parametric regression techniques. The CHAID algorithm applied separately to each type of variable revealed that the most important to explain SI were edaphic (sand and clay percentage, pH, stoniness) and climatic variables (summer and spring precipitation and mean annual temperature) (24 and 47 %, respectively). According to the regression tree and the parametric regression model for all variables, summer precipitation was the most significant variable (51 and 53 %, respectively). The results show the importance of climatic variables for chestnut coppice stands growth and provide further information about the ecology of the species in North-West Spain. The use of specimens from sites representing a wide range of habitats/growing conditions of this species means that both the results and methodology described here are

---

M. Menéndez-Miguélez (✉) · J. Majada · E. Canga
Forest and Wood Technology Research Centre (CETEMAS), Finca Experimental "La Mata" s/n,
Grado, Asturias, Spain
e-mail: mmenendez@cetemas.es

Present Address:
M. Menéndez-Miguélez
Forest and Wood Technology Research Centre (CETEMAS), Finca Experimental "La Mata" s/n,
Grado, Asturias, Spain

P. Álvarez-Álvarez
Research Group in Atlantic Forests (GIS-Forest), Department of Organisms and Systems Biology,
Escuela Politécnica de Mieres (E.P.M.), University of Oviedo, Campus Universitario de Mieres,
C/Gonzalo Gutiérrez Quirós, 33600 Mieres, Spain

of great relevance for improving the management of this species throughout its European range.

Keywords Chestnut coppice · Site index · Environmental factors · CHAID procedure · Parametric regression

Introduction

Sweet chestnut (*Castanea sativa* Mill.) forests have been recognized as habitats of interest in the European Natura 2000 network, and are considered characteristic cultural landscapes of the Mediterranean and Atlantic regions (Díaz Varela et al. 2009). In Spain, chestnut stands are distributed over an area of 272,400 ha, of which 154,500 ha are covered by pure chestnut stands, i.e. in which chestnut is the dominant tree species (chestnut tree cover rate, CTR $\geq$ 60 %). The main area of chestnut coppice in Spain is in the North-West, and accounts for 100,000 ha of the total chestnut stands area (coppice stands, high forest and cultivated orchards) of 160,638.5 ha in North-West Spain (DGCN 2013) (Fig. 1).

Despite the fact that fruit production has traditionally driven management in the North-West, timber production is considered the main objective in most exploitations nowadays (Álvarez-Álvarez et al. 2010). The total volume (with bark) of chestnut stands (high forest and coppice stands together) harvested in Spain during 2011 was 58,090 m^3 (MARM 2011), with more than 42.46 % of this total volume being formed by trees from coppice stands in North-West Spain.

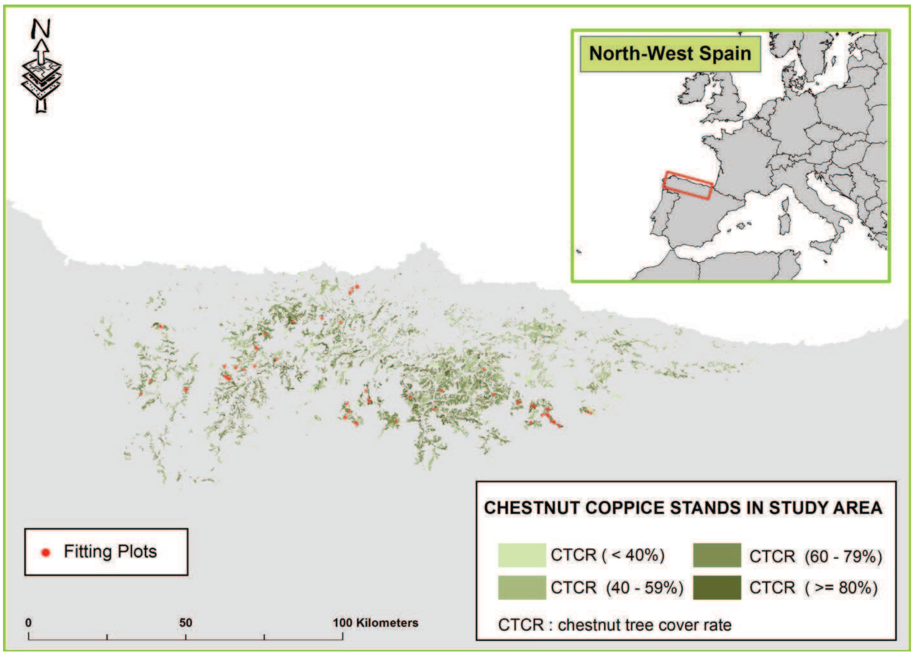


Fig. 1 Map showing cover rates for chestnut coppice stands in the study area. Fitting plots are indicated by *red dots*. (Color figure online)

Forest resource managers have always been interested in developing methods of site quality estimation with regard to species selection in afforestation, and also to being able to predict the volume growth rate in order to obtain the best returns for management efforts (Ringius et al. 1997). The most accurate and commonly used productivity assessment methods for even-aged stands are based on the height development of the upper canopy (Burkhart and Tomé 2012; Weiskittel et al. 2011). Typically, site quality for a certain species is described by *site index*, the predicted dominant or top height at a given reference age. This site quality indicator is commonly used because it is easy to interpret, is of great significance in terms of productivity, and is of practical use in applying forest growth models correctly.

Two concepts can be used to define the quality of a forest site for growing trees: site quality and site productivity. The first is related to the inherent ability of a site to provide resources that support growth (potential productivity) and can be defined in terms of timber management as "the timber production potential of a site for a particular species" (Clutter et al. 1983). The second refers to the potential growth that a site can support following its modification (expected productivity). In this study, both site quality and site productivity were estimated using the same indirect measure (site index).

Many studies have been carried out to estimate the stand site index for different species using site factors as explanatory variables. Some of them took into account only climatic variables (Lebourgeois 2007), others such as Monserud et al. (1990) and Rubio and Sánchez-Palomares (2006) used soil and topographic and topographic and climatic variables, respectively. Nevertheless, attempts to predict site quality from a small number of variables have usually proven unsuccessful (e.g., Rayner 1992), except where one factor is of overriding importance in explaining inter-site or inter-annual variation in growth (e.g., Snowdon and Waring 1991). The combination of information regarding climatic, soil and foliar nutrients and physiographic characteristics, such as in this study, has provided more accurate results (Afif-Khouri et al. 2011; Álvarez-Álvarez et al. 2011; Romanyà and Vallejo 2004).

The main aim of the present study was to explore the feasibility of using soil nutrients and environmental (climatic and physiographic) properties as indicators of site quality in chestnut coppice stands in North-West Spain. The results of the study should help to ascertain the growth potential of this type of stand in order to take it into account in deciding the most appropriate management practices for established stands.

Materials and methods

Data collection

The data used in this study were collected in 70 circular permanent plots (15 m radius) established between 2010 and 2011 by the Forest and Wood Technology Research Centre (CETEMAS) in chestnut coppice stands located throughout the range of this species in North-West Spain. Plots were selected to represent the different age ranges, stand densities and sites of this species.

All plots were labelled and diameter at breast height (d, cm) and total height (h, m) of trees were measured. Additional information including age, stool identification, physiographical factors, vegetation and stand health was also recorded-see Menéndez-Miguélez et al. (2013) for more details. Dominant height (H_0, m) for each plot was calculated as the average height of the 100 thickest trees per hectare, and site index (SI, defined as the

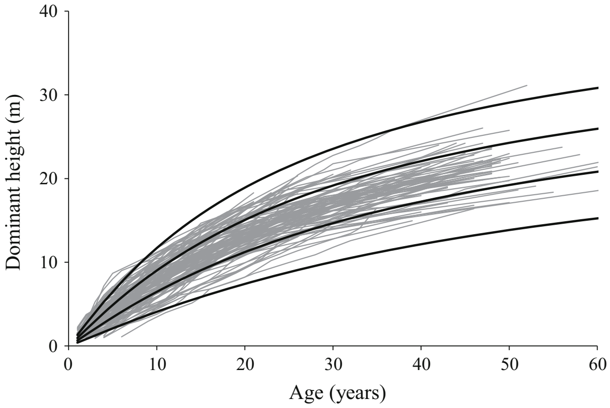


Fig. 2 Dominant height growth curves for SI values of 8, 12, 16 and 20 m at a reference age of 22 years, overlaid on the trajectories of the observed heights over time for dynamic equation developed for North-West Spain

dominant height of the stand, in meters, at a reference age of 22 years), was obtained from a site quality system (Fig. 2) developed applying the generalized algebraic difference approach (GADA). The system selected is based on the function proposed by Cieszewski (2002), from which it is possible to generate polymorphic curves with multiple asymptotes, and was selected from 4 models analysed as it was the best at describing the dominant height growth in chestnut coppice stands in North-West Spain. The dummy variables method (Cieszewski et al. 2000), in which autocorrelation is corrected using a continuous autoregressive structure was used to estimate the model parameters. The dynamic equation (Eq. 1) selected for site index estimation with two site specific parameters was:

$$\mathrm{SI} = \frac{(17.34 + X_0) \cdot X_0 \cdot t^{-1.077}}{803.61} \tag{1}$$

with:

$$X_0 = 0.5 \cdot \left[H_0 - 17.34 + \sqrt{(H_0 - 17.34)^2 + 3210.45 \cdot H_0 \cdot t_0^{-1.077}} \right]$$

where H_0 is the dominant height (m) at age t_0 (years), and SI the estimated height (m) at age t (years).

In each plot, soil depth was determined with a Dutch auger at a minimum of three randomly selected points. Five soil samples were taken with the same auger from depths of between 0 and 20 cm, and combined to make a bulk soil horizon. The samples were air-dried, crumbled, finely crushed and sieved with a 2 mm screen before analysis, in duplicate. Particle size distribution was determined by the pipette method according to Gee and Bauder (1996). The pH, organic matter content, total N, available P, exchangeable cations (K, Mg, Na and Ca) and effective cation exchange capacity (ECEC) (sum of exchangeable cations and exchangeable Al) were determined applying the methodology described by Afif-Khouri et al. (2011).

The models proposed by Sánchez-Palomares et al. (1999) for interpolating climatic variables in Spain, were used here to calculate climate-related variables. These models are functions of altitude, geographical position (UTM X–Y coordinates) and the hydrographical basin or sub-basin to which each site belongs. The climatic variables estimated were: total annual and seasonal precipitation; mean annual temperature; mean, maximum and minimum temperatures in the warmest and coldest months; summer and winter temperature; potential evapotranspiration; surplus moisture and annual moisture deficit; Vernet index and index of annual water reserve. Physiographic variables (slope, aspect and altitude) were recorded in the field inventory.

Summary statistics, including the mean (and standard deviation), minimum and maximum values of the main plot characteristics and values of environmental factors are shown in Table 1.

Statistical analysis

The CHAID (Chi squared Automatic Interaction Detector) method was used in order to determine the interaction between SI and the available qualitative and quantitative variables (climatic, edaphic and physiographic variables). CHAID is an algorithm that splits a data set into segments that differ with respect to the response variable (Kass 1980). The segments are defined by a tree structure of a number of independent variables, the predictors.

The CHAID method is an alternative to CaRT (classification and regression trees) analysis for analysing prediction-type problems on the basis of a set of categorical or continuous predictor variables. The CHAID determines a final hierarchical classification tree (using a different algorithm) in which each node can produce multiple branches, in contrast to CaRT in which all nodes are binary.

When dealing with continuous predictors, the first step in the CHAID algorithm is to create predictor categories by dividing the respective continuous distributions into a number of categories with approximately equal numbers of observations. It subsequently determines the pair of predictor categories that has the least significant difference with respect to the dependent variable. When the dependent variable is continuous, the *F* test is used to determine the statistical significance (Hill and Lewicki 2006). The CHAID merges those categories of a predictor that are homogeneous with respect to the dependent variable, but keeps separate all categories that are heterogeneous. Since more than two categories of a predictor may differ significantly, the CHAID merging process does not necessarily produce dichotomous categories.

The result of the CHAID algorithm is a decision tree structure with a split at each node. Combinations of the predictor variables define the final nodes—called leaves—(Van Diepen and Franses 2006). More information regarding the CHAID method can be found in Van Diepen and Franses (2006).

In the present study, SPSS software (SPSS 2007) was used to carry out the analysis. A significance level of 5 % was used in the *F* test, the maximum number of levels was set at 3, and the minimum number of cases in a node for it to be considered a child node was established as 8 plots. The adequacy of the regression trees was assessed by means of the standard error of the estimate (SEE) statistic.

In addition, stepwise regression was used to derive parametric models for predicting site index. The general formulation of the parametric models is as follows:

$$SI = \beta_0 + \beta_1 \cdot \mathrm{X}_1 + \ldots + \beta_n \cdot \mathrm{X}_n + \varepsilon \tag{2}$$

where SI is the site index (dominant height at a reference age of 22 years), $X_1, \ldots, X_\mathrm{n}$ are the explanatory variables, $\beta_1, \ldots, \beta_\mathrm{n}$ are the unknown parameters, and ε is the error term.

Two different types of parametric models were developed: (1) the best models when considering each of the three types of available variables separately, and (2) the best model

Table 1 Summary of the main characteristics of the chestnut plots under study

Variables	Code	Min.	Max.	Mean	SD
Stand					
Stand age (years)	t	14.00	61.00	39.61	10.85
Dominant height (m)	H_0	12.16	28.17	19.85	3.38
Site index (m at 22 years age)	SI	11.49	25.16	15.17	2.91
Stocking density (stems ha^{-1})	SD	410.27	4753.42	1597.41	979.13
Basal area (m^2 ha^{-1})	G	16.33	86.28	42.36	13.79
Edaphic					
Soil depth (m)	Depth	0.460	1.150	0.704	14.87
Stoniness (%)	Sto	0.00	50.00	20.94	13.27
Clay (%)	Clay	10.11	36.08	20.12	7.51
Sand (%)	Sand	40.48	78.84	63.10	10.02
Silt (%)	Silt	9.34	29.07	16.78	4.76
Organic matter (%)	OM	1.42	4.90	3.03	0.89
pH (water 1:1)	pH	3.73	4.79	4.28	0.26
Total N (%)	N	0.05	0.10	0.08	0.01
C/N ratio	C/N	9.50	57.08	24.69	10.01
Electric conductivity (dSm^{-1})	EC	0.04	0.13	0.06	0.02
Available P Mehlich 3 (mg kg^{-1})	PM3	10.24	29.46	18.92	4.69
Extractable K (cmolc kg^{-1})	K	0.22	0.63	0.40	0.09
Extractable Ca (cmolc kg^{-1})	Ca	0.34	0.98	0.58	0.17
Extractable Mg (cmolc $kg^{-1)}$	Mg	0.21	0.69	0.38	0.12
Extractable Al (cmolc kg^{-1})	Al	3.14	14.92	7.70	2.58
Effective cation exchange capacity (cmolc kg^{-1})	ECEC	5.76	17.76	10.37	2.49
Physiographic					
Slope (%)	Slope	19.40	75.20	50.06	14.55
Elevation (m)	Elev	175.55	880.73	601.90	167.32
Climatic					
Annual total precipitation (mm)	TP	978.00	1,312.00	1,137.35	82.60
Spring precipitation (mm)	SP	240.00	323.00	278.97	20.18
Summer precipitation (mm)	SuP	132.00	179.00	153.76	13.02
Autumn precipitation (mm)	AP	277.00	378.00	321.79	26.84
Winter precipitation (mm)	WP	313.00	432.00	382.85	27.39
Mean annual temperature (°C)	MAT	9.80	12.80	10.96	0.74
Mean temperature of the warmest month (°C)	MTWM	16.23	18.50	17.43	0.48
Mean temperature of the coldest month (°C)	MTCM	3.60	8.10	5.31	1.07
Maximum mean temperature of the warmest month (°C)	MMTWM	22.24	25.00	23.96	0.67
Minimum mean temperature of the coldest month (°C)	MMTCM	−0.50	4.10	1.22	1.11
Evapotranspiration (mm)	ETP	623.00	698.00	653.38	18.06
Annual moisture surplus (mm)	TS	440.00	802.00	627.44	86.14
Annual moisture deficit (mm)	PD	113.00	177.00	143.47	14.77
Annual water reserve index	AWRI	49.70	117.80	83.27	16.39
Mean summer temperature (°C)	MST	15.24	17.60	16.54	0.52

Table 1 continued

Variables	Code	Min.	Max.	Mean	SD
Mean winter temperature (°C)	MWT	4.10	8.30	5.74	1.01
Vernet index	VI	−4.04	−2.41	−3.01	0.43

The main characteristics of the aspect variable are: north (24.64 % of plots): northeast (27.54 %); northwest (27.54 %); east (10.14 %); south (1.45 %); southeast (4.35 %); southwest (4.35 %) and west (0 %)

including all the available variables as potential regressors. The significance level for entering and retaining variables in the model was set at 0.01.

The criteria used to evaluate the adequacy of both types of parametric models was based on the statistical analysis of the goodness-of-fit statistics R^2_{adj} (adjusted coefficient of determination) and SEE (standard error of the estimate), also known as the RMSE (root mean squared error).

Results

Regression trees

Soil characteristics

With regard to soil parameters, the CHAID procedure revealed that sand content is the main soil-related variable (P value = 0.017) that limits height growth of the chestnut coppice stands in North-West Spain (Fig. 3). In this case, two groups were found to be statistically significant: less sandy soils (≤57.34 % sand content), which implies a mean SI of the stand of 13.72 m, and sandy soils (>57.34 % sand content), for which the highest mean SI (16.14 m) was obtained. This means a site index increment of 2.42 m.

The soil regression tree was able to explain 23.97 % of the total variability (R^2_{adj}) and the SEE was 1.981 m (Fig. 3).

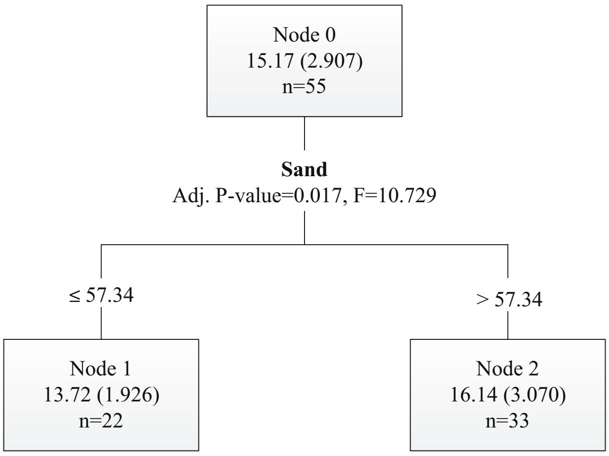


Fig. 3 Regression tree in which CHAID algorithm is used for soil nutrient variables. Significant variables: sand content (%). *Note* the number in the boxes represent the predicted mean and standard deviation (*between brackets*) of SI for each branch; n is the number of plots in each branch; Adj. P value is the adjusted P value of the analysis; F is the value for the F test of independence

Physiographic and climatic conditions

Summer precipitation (SuP) is the variable that plays the most important role in the height growth of chestnut coppice stands in the area evaluated (Fig. 4); two significant groups were established on this basis (P value = 0.0001): one for low summer precipitations (≤151.00 mm) with a mean SI of 16.75 m for the plots, and the other for stands with summer precipitations above 151.00 mm, for which the site index was lower (13.53 m). This classification meant an important difference of 3.22 m between both groups (Node 1 and 2, Fig. 4).

At the second level, spring precipitation (SP) was the most decisive variable (P value = 0.040) in explaining SI for drier summer zones (≤151.00 mm), with SPs of below or above 262.00 mm resulting in a SI of 14.65 m and 17.92 m, respectively.

The physiographic and climatic regression tree explained close to 47.34 % of total variability and the SEE was 1.264 m (Fig. 4). No physiographic variable was statistically significant with a 95 % level of confidence.

All available variables

The regression tree including all the different types of environmental factors (Fig. 5) provides an overall picture of the relative importance of each variable. Both the first and second splitter variables were identical to those obtained in the separate analyses of

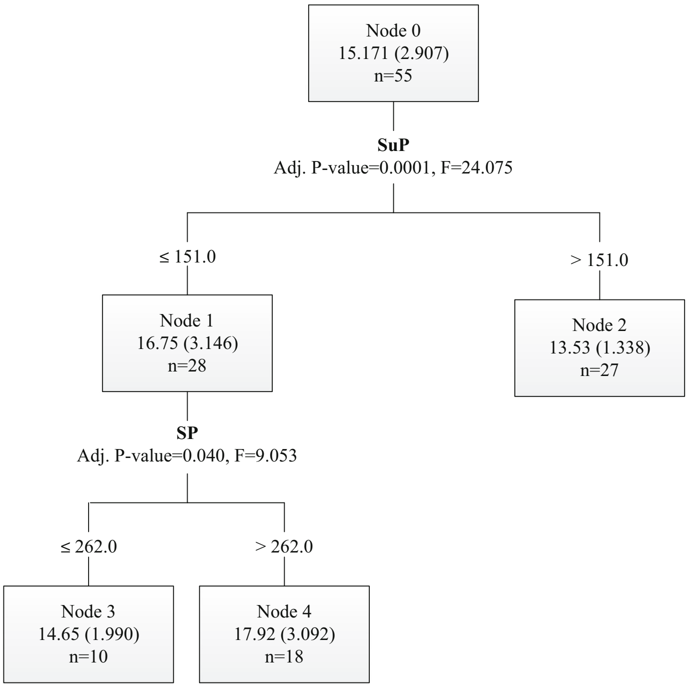


Fig. 4 Regression tree in which the CHAID algorithm is used for physiographic and climatic variables. Significant variables: summer precipitation (mm), spring precipitation (mm). *Note* the number in the boxes represent the predicted mean and standard deviation (*between brackets*) of SI for each branch; n is the number of plots in each branch; Adj. P value is the adjusted P value of the analysis; F is the value for the F test of independence

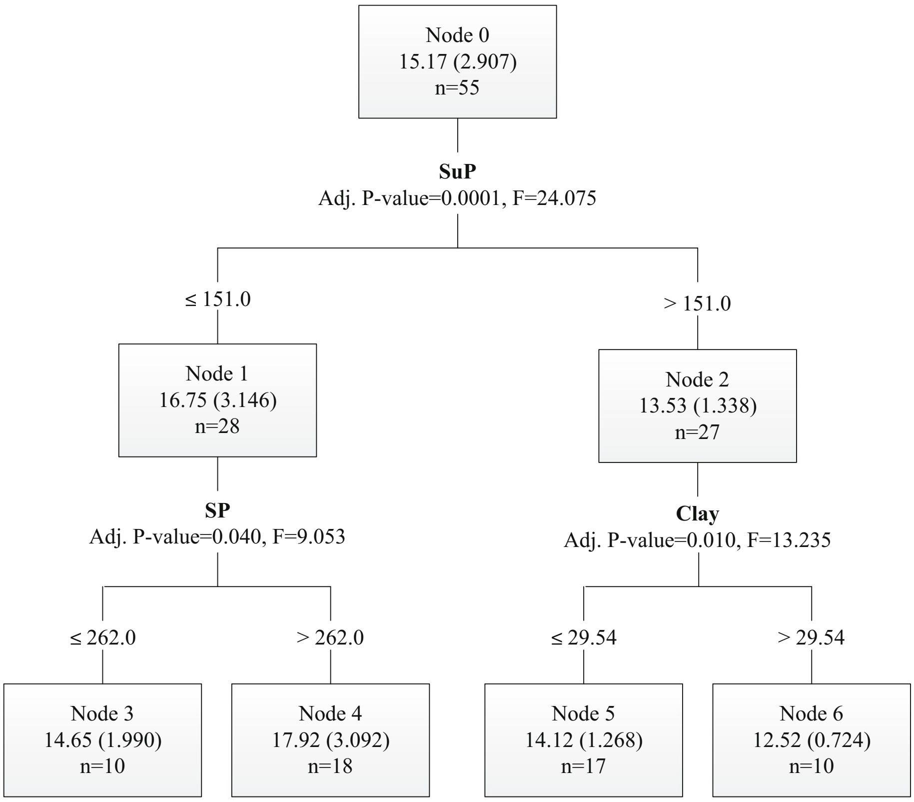


Fig. 5 Regression tree in which the CHAID algorithm is used for all the variables available. Significant variables: summer precipitation (mm), spring precipitation (mm), clay content (%). *Note* the number in the boxes represent the predicted mean and standard deviation (*between brackets*) of SI for each branch; n is the number of plots in each branch; Adj. *P* value is the adjusted *P* value of the analysis; *F* is the value for the *F* test of independence

climatic-related variables: summer (SuP) and SP. The only difference was the inclusion of a third split level, defined by the clay percentage in soils with values of summer precipitations over 151.00 mm (Node 2, Fig. 5), where there were significant differences in site index, which was higher in coppice stands with a clay percentage less than or equal to 29.54 %.

As expected, this model explained the highest percentage of variability in SI (50.81 %) and the standard error was 1.264 m. The use of climatic and edaphic variables together resulted in a 2 % increment in the explanatory power of the non-parametric model. This can obviously be explained by the reduced influence of soil variables on the growth of chestnut coppice stands as a consequence of the root system already being completely established.

Parametric regression models

Parametric regression models were fitted separately for each group of variables (edaphic, physiographic and climatic variables), and for all variables together (the "best" parametric

Table 2 Parametric models for estimation of SI in chestnut coppice stands in NW Spain

Model	Figure	Node	Fitted equation	R^2_{adj}	SEE (m)
Climatic	3	0	$SI = 68.518 - 0.189 \cdot SuP - 2.204 \cdot MAT$	0.43	2.18
Edaphic	4	0	$SI = 3.201 \cdot Clay - 0.240 \cdot pH - 0.079 \cdot Sto$	0.41	2.28
All variables available	5	0	$SI = 74.211 - 0.211 \cdot SuP - 2.402 \cdot MAT$	0.52	2.05
		1	$SI = -7.034 + 0.065 \cdot WP$	0.33	2.64
		2	$SI = 8.769 + 0.085 \cdot Sand$	0.26	1.15

All independent variables are significant at $P < 0.05$ and all the models are significant at $P < 0.001$. All variable units are the same as in Table 1

model). The fitted equations and the values of the goodness-of-fit statistics are shown in Table 2.

The variables selected by the stepwise regression were the same as those which constitute the first level of branches of the CHAID. Variables related to soil accounted for a lower percentage of total variability than those related to climate.

Two further models were fitted for the second level of branches in the all variables together tree. The first of these explained SI for locations with summer precipitations lower or equal to 151.00 mm, and which therefore depend on winter precipitation, which explains over 33 % of total variability (All variables available model—Fig. 5, node 1) (Table 2). The second accounted for a lower percentage of total variability (25.60 %) and explained SI for places with summer precipitations higher than 151.00 mm using sand content as the only independent variable of the model (All variables available model—Fig. 5, node 2) (Table 2).

As would be expected, the model that explained the highest percentage of variability in SI (52.50 %) was obtained by combining the different variables. Summer precipitation and mean annual temperature were predictors in the "best" parametric model (All variables available model—Fig. 5, node 0) (Table 2), while soil variables were not found to be significant.

Discussion

Shoot growth in coppice stands differs greatly from that in high forest (Bourgeois 1992). In the former, the root system of the stool is already fully established and developed, therefore resources are only required to increase the height and thickness of the tree (Bourgeois 1992). Furthermore, the existing root system and carbohydrate reserves of the stool could be of benefit in facilitating fast initial growth of coppice shoots, according to Kauppi and Kiviniitty (1990) and Rinne et al. (1994). In contrast, tree growth in high forest initially needs a strong and consistent root system to be established, which subsequently allows the absorption of nutrients to facilitate increase in height and thickness (Bourgeois 1992). This simple concept is clearly reflected in the results obtained in this study since the joint assessment of climatic and edaphic variables shows that the former were able to explain by themselves approximately 50 % of total variability for site index (47.34 % in the non-parametric model and 52.50 % in the parametric), while soil variables explained far less variability (only 3.47 % in the first case).

Afif-Khouri et al. (2011) evaluated the influence of variables such as climate and soil on SI, and the results were very different to those obtained in this study. However, the two sets of results are not directly comparable because Afif-Khouri et al. (2011) used a guide curve to explain SI—the top height growth model developed by Cabrera and Ochoa (1997)—and in the present study the GADA methodology (Cieszewski and Bailey 2000) was used to generate polymorphic curves, with data coming from permanent plots and stem analysis. The suitability of one or the other of these methods depends on the species under study (Hahn and Carmean 1982; Payandeh 1977). Nevertheless, it is generally assumed that height growth pattern is not the same in all SI classes (Carmean 1970; Goelz and Burk 1992; Splechtna 2001) hence in this study polymorphic curves were used. In addition, it was observed from consideration of the graphics that the SI curves developed in this study showed the individual growth trend of chestnut in coppice stands in North-West Spain better than those used in Afif-Khouri et al. (2011).

Regression trees

Soil characteristics

In relation to soil parameters, the CHAID analysis showed that sand percentage was the most important variable for estimating SI (Fig. 3). Various authors (e.g., Bourgeois 1992; Nageleisen 1994; Rameau et al. 1993) also demonstrated the importance of sand in chestnut growth, highlighting that high percentages of sand in soils means too much porosity and hence difficulties in water supply. That said, in the study area there were no problems related to water supply as a consequence of it having high precipitation through the year, even taking into account that the soil here is less permeable than other typical chestnut coppice soils in the Eurosiberian region (Rubio and Gandullo 1994).

According to Bourgeois (1992), chestnut is known for its ability to grow on naturally acidic soils that are poor in exchangeable elements. This growth capacity may be the consequence of an ability to draw mineral elements from reserves in the soil, as Brethes and Nys (1975) previously suggested for resinous trees.

Climatic characteristics

The CHAID and parametric regression analyses both revealed that summer precipitation is indirectly related to height growth. This is not surprising, since the level of precipitations at the end of the spring and summer are very important to chestnut coppice because of physiological processes like pollination (Berrocal et al. 1998). This importance could be even more relevant in the future as a consequence of climate change, which is affecting the Iberian Peninsula with mean annual temperature increments of 3–4 °C and yearly precipitations dropping by up to 20 % (Christensen et al. 2007; IPCC 2001). Some authors (Anderson et al. 2004; Wilhelm et al. 1998) suggest that these increasing temperatures can also give more advantages to *Cryphonectria parasitica* (chestnut blight) and reduce the systematically acquired resistance of the host trees; while moisture is a key factor for the establishment, spread and longevity of *Phytophthora cinnamomi* (ink disease) diseases (Hardham 2005).

Rubio et al. (1997) have previously concluded that summer precipitation is linearly related to some individual silvicultural variables, such as height, basal area or Hart index. This is important in Mediterranean areas, such as they used, maximum summer precipitation was 95.4 mm in the study area of Rubio et al.—because low levels of summer precipitations are a limiting factor for chestnut growth in these areas. However, this is not the case in Atlantic areas, such as ours, where precipitation is not a limiting factor through the year—minimum summer precipitation in the current study area was 132 mm (Table 1). Obtaining the same key variable for both areas (our own and that of Rubio et al.) adds weight to the importance of summer precipitations in relation to site index.

It is well known that adult chestnut resists severe drought without difficulty, however juveniles are far more sensitive to water stress. This is why chestnut coppice grows best when water availability is regular (CEMAGREF 1987; Pichard 1994; Sevrin 1994).

All variables available

It is generally accepted that there is wide chestnut plasticity in relation to precipitations. This is the consequence of plasticity in its autoecology, illustrated by its acceptance of a wide range of precipitation levels—from 700 to 1,500 mm (Bourgeois 1992; Pichard 1994; Sevrin 1994). In Spain, minimum precipitation per year is always over 600 mm (López 1991), a fact confirmed in this study where the minimum value of annual total precipitation was 978 mm (Table 1).

Even taking into account this plasticity, it is still very important for chestnut coppice growth not to have more than two consecutive months of drought (Bourgeois 1992), because the length of the drought period has also been identified as a principal climatic limitation for chestnut growth in some regions (Gandullo et al. 2004; Rubio et al. 2002a).

With regard to the relationship between all variables together and SI, summer precipitation (SuP) was found to be highly significant for explaining site index in North-West Spain. Rubio et al. (1997) have previously noted the relation between the location of coppice stands, especially those for timber production, and the distribution of precipitation, mainly during the summer.

The relation between both variables (summer precipitation and SI) in Rubio et al. (1997) was positive and in this study was negative, as Fig. 5 shows (SI is reduced by 3 m for summer precipitations over 151.00 mm). This apparent contradiction is due to the comparison of coppices from two different climatic areas (Mediterranean and Atlantic, respectively), as Gallardo-Lancho (2001) has shown. Whilst it may seem inappropriate to compare areas which are as different as the Mediterranean and the Atlantic areas of Spain, the results of this paper demonstrate that excessive rainfall with no summer drying of the soil, and the effect of good soil permeability are equally important in the two areas. Nevertheless, the explanation of the different relations between summer precipitations and SI is related to differences in the criteria used for characterizing the most productive chestnut coppices, i.e. the SI itself, in the two areas: In Northern Spain (Atlantic area) mean annual temperature, last frost and soil permeability are good criteria for selecting the best chestnut coppice areas, but in southern districts (Mediterranean area) the most useful factors are altitude, summer evapotranspiration, soil moisture storage and length of drought (Gallardo-Lancho 2001).

For soils with lower levels of summer precipitation ($\leq$151.00 mm), SP was the most important variable for estimating SI (Node 1, Fig. 5). The importance of SP is such that SI can vary from 14.65 to 17.92 m, the higher SP is, the higher the SI. Pereira et al. (2011) have also concluded that high levels of SPs are very important for chestnut growth because they provide the appropriate soil humidity conditions to favour budbreak. High rainfalls may have the advantage that they enable the chestnut to withstand physiological drought and to maintain high values of maximum evapotranspiration, such as in Galicia, Navarra and Catalonia (Rubio et al. 2002b). In spring and summer, temperature and precipitation induce plants to limit photosynthetic activity in order to reduce water loss by transpiration (Waring and Running 2007).

Álvarez-Álvarez et al. (2010) proposed the following edge values for optimal chestnut growth conditions for timber production: potential evapotranspiration <650 mm, summer precipitation >130 mm, a precipitation deficit of <200 mm, site elevation below 800 m and a frost-free period of at least 3–4 months.

With regard to soil parameters, soil clay content was the most important variable for estimating SI in soils with the highest levels of summer rainfall (>151.00 mm) (Node 2, Fig. 5). This is consistent with the poor adaptation of chestnuts to clay soils, as a consequence of their impermeability and compression (IDF 1991; Rameau et al. 1993; Nageleisen 1994). This importance of clay content is related to the sensitivity of chestnut roots to aeration (Bourgeois1992; IDF 1991). Since the tree does not grow optimally in soils showing drainage problems, loam rather than fine textured subsoils are preferred (Queijeiro et al. 2000). Furthermore, porous soils are preferable to clay, where the accumulation of water could also facilitate the proliferation of chestnut ink disease (caused by *Phytophtora cinnamomi* Rabds. or *Phytophthora cambivora* Buissman) (Martínes et al. 1999).

Parametric regression models

According to the parametric regression models obtained from the different types of variables (Models: *Climatic* and *Edaphic*, Table 2), climatic variables (represented by summer precipitation and mean annual temperature) account for most of the variation in SI. In fact, these two variables were selected by the stepwise procedure including all the available variables, and explained 52.50 % of total variability (Model *All variables available*, Fig. 5, Node 0) (Table 2).

Some authors have found better performance of SI prediction with other species, e.g., Carter and Klinka (1990) and Fontes et al. (2003) for Douglas fir, and Chen et al. (1998), for Trembling aspen. However, when comparing this type of results between species, the following two aspects should be considered: (1) chestnut coppice stands are highly complex to model as a consequence of them growing many shoots from the same stool which share nutrients, water, space, etc. (Bourgeois 1992), and (2) in the present study, only robust statistical models with just one or two predictor variables were selected.

Despite the worse performance for SI prediction compared to studies of other species, the parametric regression models obtained in this study performed better than those in Afif-Khouri et al. (2011), who also worked with chestnut coppice stands. Differences in results between the two studies ranged from 1 % for the edaphic variables model and 10 % for the all variables model, to over 31 % of the total variability explained by the climatic variables model. These differences are directly related to the SI curves developed, with the curves estimated in this study being better at explaining the relationship of dominant height for a certain reference age (SI) for chestnut coppice stands in North-West Spain.

In spite of not being the most explanatory variables in relation to the productivity of chestnut coppice stands according to the results obtained in this study, the soil variables selected in the model (clay content, pH and stoniness) are key factors in chestnut growth. Massive structure in soils, such as clay soils, causes permanent water blockages and accumulations which are very favourable conditions for the establishment and development of *Phytophthora cinnamomi* (ink disease) (Bourgeois 1992). The combination of excess water and its accumulation could also become a limiting factor for chestnut growth, it is preferable a constant volume of water in the first 40 cm of soil (Bourgeois 1992, Lemaire 2008). The acidity of the soil could also negatively influence for chestnut growth, because the higher the level of acidity in the soil the lower the richness of available minerals is (Lemaire 2008).

Conclusions

Any environmental factor which goes beyond its acceptable range for any vascular plant means a decrease in productivity for the species evaluated. Taking this into account, the relationship between productivity (explained by site index) and soil nutrient and environmental factors (climatic and physiographic) was evaluated in chestnut coppice stands in North-West Spain, in order to ascertain the most suitable growth conditions for this type of stand.

Two different statistical analyses were carried out for this purpose: the non-parametric CHAID procedure and parametric regression analysis. The CHAID procedure was found to be a powerful alternative tool compared to other methods, such as discriminant rules or principal components analysis, for determining the key factors that affect stand growth.

It is worth remarking that the variables selected in the regression tree for all variables available from the CHAID algorithm were the same as those obtained in the stepwise parametric regression, for each of the three types of variables: edaphic, physiographic and climatic. This concordance makes the process of selecting the variables that have the greatest influence on site index more robust.

According to the parametric regression models, two climatic characteristics (summer precipitation and mean annual temperature) were found to be the most important factors in explaining the productivity of chestnut coppice stands in North-West Spain. These types of variables are frequently easier and quicker to obtain than dasometric ones, and are sometimes even already known for certain geographic locations. These factors make the regression models developed here more easily applicable, and therefore more useful, in real forestry scenarios.

The best site qualities were observed in plots with less summer precipitation and lower mean annual temperatures. Although the percentage of variability in SI explained by these variables is 52.50 %, it must be taken into account that genetic factors are likely to account for a substantial percentage of the unexplained variability in SI. Chestnut coppice stands already have established root systems, meaning that there is an additional intrinsic component (the stool) which accounts for a percentage of unexplained variability as a consequence of it providing nutrients for many different shoots.

The results obtained in the present study provide further knowledge related to the ecology of chestnut coppice stands in North-West Spain. The knowledge of site productivity (SI) is of great interest when considering different forest management strategies especially when timber production is the primary objective, because it can provide a priori the productive capacity of the stands. Depending on wether site productivity is higher or lower, different management plans should be considered in order to optimize stand yield. Stands of higher quality provide more possibilities in relation to their management: for example, reduction of rotation times or more intensive clear-cuttings. On the contrary, stands of lower quality require rotations to be lengthened and the final products obtained are unable to meet the criteria of high quality wood.

This information is essential too for the management of a threatened Natura 2000 habitat, especially considering the current state of abandonment that many coppice stands are experiencing across Europe. Stakeholders and Public Administrations could use this information to plan investments and works to be carried out so as to obtain the best performance according to different site qualities.

In addition, the behaviour of the species in light of climatic and edaphic variations in its ecological niche could be analysed in the future and could be a key factor since the current importance of these edaphic and climatic variables is only likely to increase under predicted climatic change scenarios.

Acknowledgments The authors thank Forest Services (Government of the Principality of Asturias), and the private owners who allowed the establishment of the permanent plots necessary for the development of the study. This study was supported by the Spanish Ministry of Science and Innovation (MICIN) and the Plan for Science, Technology and Innovation of the Principality of Asturias (PCTI) as part of the research project "Forest and industrial evaluation of Spanish chestnut" (VALOCAS).

References

Afif-Khouri E, Álvarez-Álvarez P, Fernández-López MJ, Oliveira-Prendes JA, Cámara-Obregón A (2011) Influence of climate, edaphic factors and tree nutrition on site index of chestnut coppice stands in north-west Spain. Forestry 84(4):385–396. doi:10.1093/forestry/cpr025

Álvarez-Álvarez P, Díaz-Varela E, Cámara-Obregón A, Afif-Khouri E (2010) Relating growth and nutrition to site factors in Young chestnut plantations established on agricultural and forest land in northern Spain. Agrofor Syst 79:291–301. doi:10.1007/s10457-010-9313-z

Álvarez-Álvarez P, Afif-Khouri E, Cámara-Obregón A, Castedo-Dorado F, Barrio-Anta M (2011) Effects of foliar nutrients and environmental factors on site productivity in *Pinus pinaster* Ait. stands in Asturias (NW Spain). Ann For Sci 68:497–509. doi:10.1007/s13595-011-0047-5

Anderson PK, Cunningham AA, Patel NG, Morales FJ, Epstein PR, Daszak P (2004) Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. Trends Ecol Evol 19(10):535–544

Berrocal M, Gallardo JF, Cardeñoso JM (1998) El castaño. Mundi-Prensa, Madrid

Bourgeois C (1992) Le châtaignier, un arbre, un bois. Institut pour le développement forestier, Paris

Brethes A, Nys C (1975) Effects des résineux sur la fertilité des sols. Difficulté des recherches et premiers résultats. Soil Sci 1:3–18

Burkhart HE, Tomé M (2012) Modelling forest trees and stands. Springer, Berlin

Cabrera BM, Ochoa F (1997) Tablas de producción de castaño (*Castanea sativa* Mill.) tratado en monte bajo, en Asturias. In: Puertas F, Rivas M (eds) II Congreso Forestal Español-Irati 97. Pamplona, Spain, pp 131–136

Carmean WH (1970) Tree growth patterns in relation to soil and site index. In: Tree growth and forest soils. Oregon State University, Corvallis

Carter RE, Klinka K (1990) Relationship between growing season soil water-deficit, mineralizable soil nitrogen and site index in Coastal Douglas fir. For Ecol Manag 30:301–311. doi:10.1016/0378-1127(90)90144-Z

CEMAGREF (1987) Guide technique du forestier méditerranéen français

Chen HYH, Klinka K, Kabzems RD (1998) Site index, site quality, and foliar nutrients of trembling aspen: relationships and predictions. Can J For Res 28:1743–1755. doi:10.1139/x98-154

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, pp 847–940

Cieszewski CJ (2002) Comparing fixed-and variable-base-age site equations having single versus multiple asymptotes. For Sci 48:7–23

Cieszewski CJ, Bailey RL (2000) Generalized algebraic difference approach: a new methodology for derivation of biologically based dynamic site equations. For Sci 46:116–126

Cieszewski CJ, Harrison M, Martin SW (2000) Practical methods for estimating non-biased parameters in self-referencing growth and yield models. University of Georgia, Athens. PMRC-TR 2000-7

Clutter J, Fortson J, Pienaar L, Brister H, Bayley R (1983) Timber management: a quantitative approach. Wiley, New York

DGCN (2013) III Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España

Díaz Varela RA, Calvo Iglesias MS, Díaz Varela ER, Ramil Rego P, Crecente Maseda R (2009) *Castanea sativa* forests: a threatened cultural landscape in Galicia NW Spain. In: Krzywinski K, O'Connell M, Küster H (eds) Cultural landscapes of Europe. Fields of demeter haunts of pan. Aschembeck Media UG, Bremen, pp 94–95

Fontes L, Tomé M, Thompson F, Yeomans A, Sales Luis J, Savill P (2003) Modelling the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal. Forestry 76:491–507. doi:10.1093/forestry/76.5.491

Gallardo-Lancho JF (2001) Distribution of chestnut (*Castanea sativa* Mill.) forests in Spain: possible ecological criteria for quality and management (focusing on timer coppices). For Snow Landsc Res 76(3):477–481

Gandullo JGM, Blanco-Andray A, Sánchez-Palomares O, Rubio-Sánchez A, Elena-Roselló R, Gómez-Sanz V (2004) Las estaciones ecológicas de los castañares españoles. Monografías INIA: Serie Forestal No 7, Madrid, Spain

Gee GW, Bauder JW (1996) Particle size analysis. In: Methods of soil analysis, part 1, 2nd edn. American Society of Agronomy, Madison, pp 383–411

Goelz JCG, Burk TE (1992) Development of a well-behaved site index equation: jack pine in north central Ontario. Can J For Res 22:776–784. doi:10.1139/x92-106

Hahn JT, Carmean WH (1982) Lake States site index curves formulated. USDA For. Serv Gen Tech Rep NC-88

Hardham AR (2005) *Phytophtora cinnamomi*. Mol Plant Pathol 6(6):589–604. doi:10.1111/j.1364-3703.2005.00308.x

Hill T, Lewicki P (2006) Statistics: methods and applications: a comprehensive reference for science, industry, and data mining. Stat Soft Inc

IDF (1991) Quelques nouvelles. Pour vos plantations de châtaigniers. Forêt Enterp 78(6):2

IPCC (2001) In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Climate change 2001: the scientific basis. Contribution to Working Group I in the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kass G (1980) An exploratory technique for investigating large quantities of categorical data. Appl Stat 29:119–127. doi:10.2307/2986296

Kauppi A, Kiviniitty M (1990) Leaf morphology and photosynthetic rate in birch seedlings and stump sprouts. Can J For Res 20:952–960. doi:10.1139/x90-128

Lebourgeois F (2007) Climatic signal in annual growth variation of silver fir (*Abies alba* Mill.) and spruce (*Picea abies* Karst.) from the French Permanent Plot Network (RENECOFOR). Ann For Sci 64:243–333. doi:10.1051/forest:2007010

Lemaire J (2008) Autécologie du châtaignier: un fougueux qui craint la sécheresse! Forêt Enterp 179:18–24

López J (1991) Dossier: Le châtaignier en Europe; Espagne: De la Galice à la Catalogne, une situation diversifiée. Forêt Enterp 76(4):28–32

MARM (2011) Avance del Anuario de Estadística Forestal. Área de Medio Ambiente, Madrid, España

Martínes LM, Oliveira MT, Abreu CG (1999) Soils and climatic characteristics of chestnut stands that differ on the presence of ink disease. In: Salesses G (ed) Proceedings of 2nd international chestnut symposium. Acta Horticulturae, Bordeaux, pp 447–449

Menéndez-Miguélez M, Canga E, Barrio-Anta M, Majada J, Álvarez-Álvarez P (2013) A three level system for estimating the biomass of *Castanea sativa* Mill. coppice stands in north-west Spain. For Ecol Manag 291:417–426. doi:10.1016/j.foreco.2012.11.040

Monserud RA, Moody U, Breuer DW (1990) A soil-site study for inland Douglas-fir. Can J For Res 20:686–695. doi:10.1139/x90-092

Nageleisen LM (1994) Le dépérissement actuel de feuillus divers: Hêtre, Merisier, Alisier torminal, Érable sycomore, Peuplier, Châtaignier, Charme, Aulne glutineux. Revue Forestière Française 5:54–562

Payandeh B (1977) Metric site index formulae for major Canadian timber species. Bimon Res Notes 33(5):37–39

Pereira MG, Caramelo L, Gouveia C, Gomes-Laranjo J, Magalhães M (2011) Assessment of weather-related risk on chestnut productivity. Nat Hazards Earth Syst Sci 11:2729–2739. doi:10.5194/nhess-11-2729-2011

Pichard G (1994) La regeneration naturelle assistée du châtaignier en Bretagne. Une method désormaisé prouvée. Forêt de France 355:27–29

Queijeiro JM, Díaz-Raviña M, de la Montana J (2000) Edaphic characterization of chestnut tree orchards in Monterrey (Southeast Galicia, Spain). Ecol Mediterr 26(1–2):163–167

Rameau JC, Mansion D, Dume G (1993) Flore Forestière Française 2 Montagnes, IDF

Rayner ME (1992) Evaluation of site classifications for modelling timber yield of regrowth karri (*Eucalyptus diversicolor* F. Muell.). For Ecol Manag 54:315–336. doi:10.1016/0378-1127(92)90020-A

Ringius GS, Sims RA, Meades SJ (1997) Indicator plant species in Canadian forests. Can For Serv, Ottawa

Rinne P, Saarelainen A, Junttila O (1994) Growth cessation and bud dormancy in relation to ABA level in seedlings and coppice shoots of *Betula pubescens* as affected by a short photoperiod, water stress and chilling. Physiol Plant 90:451–458. doi:10.1111/j.1399-3054.1994.tb08801.x

Romanyà J, Vallejo VR (2004) Productivity of *Pinus radiata* plantation in Spain in response to climate and soil. For Ecol Manag 195:177–189. doi:10.1016/j.foreco.2004.02.045

Rubio A, Gandullo JM (1994) Modelos predictivos de la estructura selvícola en castañares extremeños (España). Ecología 8:137–150

Rubio A, Sánchez-Palomares O (2006) Physiographic and climatic potential areas for *Fagus sylvatica* based on habitat suitability indicator models. Forestry 79:439–451. doi:10.1093/forestry/cpl025

Rubio A, Escudero A, Gandullo JM (1997) Sweet chestnut silviculture in an ecological extreme of its range in the west of Spain (Extremadura). Ann Sci For 54:667–680. doi:10.1051/forest:19970707

Rubio A, Elena R, Sánchez-Palomares O, Blanco A, Sánchez F, Gómez V (2002a) Soil evaluation for *Castanea sativa* afforestation in Northeastern Spain. New For 23:131–141. doi:10.1023/A:1015624014868

Rubio A, Sánchez-Palomares O, Gómez V, Graña D, Elena R, Blanco A (2002b) Autoecología de los castañares de Castilla (España). Investigación Agraria Sistemas y Recursos Forestales 11(2):373–393

Sánchez-Palomares O, Sánchez Serrano F, Carretero Carrero MP (1999) Modelos y cartografía de estimaciones climáticas termo pluviométricas para la España peninsular. INIA, Ministerio de Agricultura, Pesca y Alimentación, Madrid

Sevrin E (1994) Améliorer les taillis de châtaignier. Fôret Enterp 97(4):13–14

Snowdon P, Waring HD (1991) Effects of irrigation and artificial drought in the growth and health of *Pinus radiata* near Canberra, ACT. Aust For 54:174–186. doi:10.1080/00049158.1991.10674574

Splechtna BE (2001) Height growth and site index models for pacific silver fir in southwestern British Columbia. J Ecosyst Manag 1(1):1–14

SPSS (2007) SPSS for Windows, Rel. 16 (1993–2007). SPSS Inc., Chicago

Van Diepen M, Franses HP (2006) Evaluating Chi squared automatic interaction detection. Inf Syst 31:814–831. doi:10.1016/j.is.2005.03.002

Waring RH, Running SW (2007) Forest ecosystems: analysis at multiple scales, 3rd edn. Academic Press, San Diego

Weiskittel AR, Hann DW, John A, Kershaw J, Vanclay JK (2011) Forest growth and yield modelling. Wiley, New York

Wilhelm E, Arthofer W, Schafleitner R, Krebs B (1998) *Bacillus subtilis* an endophyte of chestnut (*Castanea sativa*) as antagonist against chestnut blight (*Cryphonectria parasitica*). Plant Cell Tiss Org 52(1–2):105–108. doi:10.1023/A:1005917906769

Informe del factor de impacto

6. Informe del factor de impacto

El Informe del factor de impacto según Journal Citation Report 2013 sería el siguiente:

- ✓ **Menéndez-Miguélez M**, Canga E, Barrio-Anta M, Majada J, Álvarez-Álvarez P. 2013. A three level system for estimating the biomass of *Castanea sativa* Mill. coppice stands in North-West Spain. Forest Ecology and Management 291: 417-426. doi: 10.1016/j.foreco.2012.11.040. Journal Impact Factor 2013: 2.667.

- ✓ **Menéndez-Miguélez M**, Canga E, Álvarez-Álvarez P, Majada J. 2014. Stem taper function for sweet chestnut (*Castanea sativa* Mill.) in northwest Spain. Annals of Forest Science. Vol. 7, Issue 7: 761-770. doi: 10.1007/s13595-014-0372-6. Journal Impact Factor 2013: 1.536.

- ✓ **Menéndez-Miguélez M**, Álvarez-Álvarez P, Majada J, Canga E. 2015. Basic tools for silvicultural management of *Castanea sativa* Mill. coppice stands in northwestern Spain. iForest. Submitted. Journal Impact Factor 2013: 1.150.

- ✓ **Menéndez-Miguélez, M**, Álvarez-Álvarez P, Majada J, Canga E, 2015. Effects of soil nutrients and environmental factor son site productivity in *Castanea sativa* Mill. coppice stands in NW Spain. New Forests. 46: 217-233. doi: 10.1007/s11056-014-9456-2. Journal Impact Factor 2013: 1.783.

Anexo - Resumen en español

7. Resumen en español

7.1 Introducción

El castaño (*Castanea sativa* Mill.) es la única especie nativa del género *Castanea* en Europa. Se extiende a lo largo de 15 países en la Europa central y mediterránea, cubriendo un total de 2,5 millones de ha (Bourgeois *et al*., 2004; Conedera *et al*., 2004; Konstantinidis *et al*., 2008). Los bosques de castaño han sido reconocidos como hábitat de interés en la Red Natura 2000. Esta calificación garantiza la continuidad de este tipo de hábitats naturales, reduce su degradación y favorece la biodiversidad, a la vez que tiene en cuenta todos los factores sociales, económicos, culturales y regionales que la población demanda en relación con esta especie (CEE Directive 92/43, 1992).

Se estima que el castaño cubre en España en torno a 272.400 ha, de las cuales 154.500 ha corresponden a masas puras, es decir, masas en las que el castaño es la especie principal (cobertura de copas de castaño, CTR ≥60%). Se trata de la especie forestal más importante en el nororeste de España y cubre unas 100.000 ha, la mayoría de monte bajo (DGCN, 2013), concentrando de esta manera más del 95% de la superficie potencial de monte bajo de castaño de España.

La gestión tradicional del castaño planteaba la obtención de madera a partir de prácticas selvícolas en montes bajos con pequeñas rotaciones (12 a 25 años), lo que hacía que a menudo la madera obtenida tuviera pequeño calibre y bajo valor comercial, como consecuencia del pequeño tamaño de los pies al final del turno y de la falta de claras intermedias (Mannetti *et al*., 2001; Vogt *et al*., 2006; Seci *et al*., 2013). La ausencia de claras es uno de los factores fundamentales que limitan el crecimiento en grosor de los árboles. Sin embargo, diversos estudios realizados en países como Francia (Lemaire, 2009) e Italia (Amorini y Manetti, 2002) han propuesto nuevos esquemas de gestión basados en rotaciones más largas y planes de claras con los que aumentar el valor comercial de la madera producida.

Para mantener la estabilidad y perpetuidad de las masas de castaño es necesario aplicar las oportunas intervenciones selvícolas, de manera que se optimice la capacidad productiva y se establezca el equilibrio ecológico. Pero no es sólo el hecho de mantener la estabilidad de estas masas, si no la necesidad de crear nuevas herramientas, modelos y metodologías de gestión que permitan poder empezar a actuar en estos bosques (Cabrera, 1997). La propia Administración reconoce el actual abandono y degradación de las masas asturianas de castaño, así como la importancia de establecer iniciativas de investigación, concienciación y divulgación para fomentar el conocimiento de esta importante especie y la necesidad de realizar estudios de la misma que permitan en un futuro disponer de técnicas de gestión adecuadas a las diferentes estructuras y formaciones de castaño.

7.2 Planteamiento

A nivel mundial los conocimientos sobre castaño abarcan un amplio rango de materias: sanidad, nutrición, conservación y mejora genética, ecología de la especie, selvicultura, modelización, etc. La gestión forestal es uno de los principales aspectos a tener en cuenta y en base a ello se han realizado estudios en diversos países como Francia, Suiza o Italia.

Sin embargo, las masas forestales son algo más que un ciclo de nutrientes, una variación genética o un modelo que explique el crecimiento diametral, por ello la mejor manera de conocer el conjunto del bosque es englobar cada uno de estos aspectos en un estudio que permita conocer exhaustivamente las masas de castaño ante las que nos encontramos, es decir, crear una herramienta que permita gestionar el monte partiendo de todos los conocimientos que se tienen de él, tal y como se ha hecho previamente en Francia.

Todo ello unido con la importancia del castaño en el noroeste de España, hace que sea más necesario si cabe la generación de modelos de predicción de la evolución futura de la masa combinados con un amplio estudio de la fenología y ecología de estas masas, tal y como se plantea en esta tesis, para obtener el mayor rendimiento posible en cada una de las masas forestales.

7.3 Objetivos

El objetivo general de esta tesis fue desarrollar herramientas para la estimación del crecimiento y producción de la masas de monte bajo de castaño en el noroeste de España, facilitando de esta manera una gestión adecuada.

Los objetivos específicos fueron:

- ✓ Modelizar la biomasa arbórea de diferentes fracciones (madera, corteza, ramas y biomasa total) según tres niveles de studio: árbol individual, cepa y masa.
- ✓ Desarrollar un sistema de volumen compatible compuesto por una function de perfil, una ecuación de volumen total y una ecuación de volumen comercial.
- ✓ Modelizar un sistema de calidad de estación, densidad de masa, volume total y commercial y diámetro medio cuadrático como herramientas básicas de la gestión forestall.
- ✓ Desarrollar herramientas de masa, tanto tablas de producción como diagramas de manejo de densidad.
- ✓ Analizar la calidad de una zona en base a las relaciones existentes entre el índice de sitio y características ambientales, incluyendo características edáficas, climáticas y fisiográficas.

7.4 Resultados generales

Los resultados principales obtenidos en esta tesis son los siguientes:

7.4.1 Modelización de biomasa

Se evaluó la biomasa de las masas de monte bajo de castaño en el noroeste de España según el nivel de detalle de la información disponible: árbol individual, cepa y masa. Se desarrollaron además cuatro sistemas para la estimación de biomasa. En dos de ellos se utilizaron variables de árbol individual: variables de árbol en pie y variables de árbol individual. Mientras que en los otros dos se utilizaron variables de cepa y de masa, respectivamente.

Cada componente de biomasa fue ajustada individualmente con la metodología NSUR y posteriormente se aseguró la aditividad de las diferentes componentes mediante el ajuste simultáneo. En las componentes en que se observó presencia de heterocedasticidad, se corrigió mediante ajuste ponderado.

Los diferentes sistemas obtenidos fueron capaces de explicar entre el 60 y el 90% de la variabilidad total de la muestra empleada, dependiendo del nivel y la componente de biomasa evaluados. La mayoría de las ecuaciones desarrolladas fueron validadas con una muestra de datos independiente, confirmando la buena capacidad de predicción de las mismas.

7.4.2 Sistema de volumen compatible

Se probaron cinco funciones de perfil para predecir el diámetro a cualquier altura a lo largo del fuste. Todas ellas resultaron significativas al 5% de nivel de confianza, excepto la función de Bi (2000) en la que no se consiguió la convergencia.

Todos los modelos presentaron buen comportamiento, explicando más del 95% de la variabilidad total. Se corrigió la autocorrelación de los residuos mediante una estructura autorregresiva de segundo orden, ya que la de primer orden no fue suficiente.

Finalmente se seleccionó el modelo de Fang *et al*. (2000) como el más adecuado para la descripción del perfil de los árboles de monte bajo de castaño en el noroeste de España, siendo además un modelo muy útil desde el punto de vista práctico porque es un modelo compatible.

7.4.3 Ecuaciones básicas y otras herramientas de gestión

Se evaluaron cuatro modelos para el desarrollo de las curvas de índice de sitio para monte bajo de castaño en el noroeste de España, aplicando la metodología GADA (generalización de ecuaciones en diferencias algebraicas). La presencia de autocorrelación en los residuos se corrigió mediante la modelización del término del error con una estructura autorregresiva. Se seleccionó el modelo de Cieszewski (2002) que explicó un 99% de la variabilidad total de la masa. La edad de referencia seleccionada como la más adecuada para la predicción de la altura dominante a otras edades fue 22 años.

Se desarrollaron dos ecuaciones de densidad con una clasificación previa de los datos en dos grupos (alta y baja densidad), explicando los modelos seleccionados más del 65% de la variabilidad total.

Se ajustaron dos ecuaciones diferentes para la predicción del diámetro medio cuadrático de la masa. Ambas pueden ser utilizadas directamente o implementadas en las tablas de producción, la primera de ellas, o en los diagramas de manejo de densidad, la segunda. Ambas ecuaciones explicaron más del 80% de la variabilidad total de la muestra.

Se desarrollaron una ecuación de volumen comercial y una ecuación de volumen total para ser utilizadas directamente o implementadas en las tablas de producción o en los diagramas de manejo de densidad, respectivamente.

Se ajustaron también dos grupos de ecuaciones de biomasa para utilizar en las tablas de producción y en los diagramas de manejo de densidad. El primer grupo de ellas se corresponde con las desarrolladas para el nivel de masa en la publicación de *Modelización de biomasa*, mientras que el segundo fue ajustado dependiendo únicamente de altura dominante y densidad de la masa como variables independientes.

Las ecuaciones previamente ajustadas se utilizaron para elaborar dos herramientas de gestión: unas tablas de producción y unos diagramas de manejo de densidad. En el caso de las tablas de producción, se desarrollaron un total de dos tablas para cada índice de calidad de estación previamente definido (10, 14, 18 y

22 m a la edad de referencia de 22 años), uno para cada clase de densidad (alta y baja densidad).

7.4.4 Efectos de los factores ambientales en el índice de sitio

Se evaluó la relación de la productividad (explicada a través del índice de sitio, SI) con el suelo y otros factores ambientales (fisiográficos y climáticos) mediante análisis de regresión paramétrica y el procedimiento no paramétrico CHAID (árboles de regresión).

El algoritmo CHAID aplicado de manera separada a cada tipo de variable determinó que las variables edáficas (porcentaje de arena y arcilla, pH y pedregosidad) y climáticas (precipitación de verano y primavera, temperatura media anual) son las que mejor explican la variación del SI (24 y 47% respecitvamente).

Los modelos de regresión paramétrica y los árboles de regresión aplicados para todas las variables juntas mostraron que la precipitación de verano era la mejor variable explicativa del SI (51 y 53% respectivamente).

7.5 Conclusiones generales

Las principales conclusiones obtenidas en esta tesis son las siguientes:

7.5.1 Modelización de biomasa

- ✓ Se ha desarrollado una herramienta precisa para la estimación de la biomasa en las masas de monte bajo de castaño en el noroeste de España según el nivel de detalle de los datos disponibles – árbol individual, cepa y masa.
- ✓ El primer nivel permite calcular distintos componentes biomasa a nivel de árbol individual, tanto para árbol en pie como árbol apeado. El segundo y tercer nivel permiten la estimación de diferentes componentes de biomasa a nivel de cepa y de masa, respectivamente.
- ✓ Los diferentes niveles de biomasa desarrollados explican entre el 60 y 90% de la variabilidad total, según el nivel y componente evaluados.

- ✓ La utilización de una muestra de datos independiente en el proceso de validación permitió reflejar la calidad de las predicciones, así como verificar la fiabilidad de los modelos.
- ✓ El conocimiento de las existencias de biomasa en este tipo de masas puede utilizarse para estudios sobre secuestro de carbono, cantidad de combustible, condiciones de propagación del fuego, etc.

7.5.2 Sistema de volumen compatible

- ✓ Los cinco modelos analizados presentaron buen comportamiento en la estimación de diámetros a lo largo del fuste y describieron adecuadamente el perfil de los árboles de monte bajo del noroeste de España, excepto en el caso de la función de exponente variable propuesta por Bi (2000) donde no se logró su convergencia.
- ✓ Los estadísticos de bondad de ajuste y la capacidad de predicción del diámetro y altura a lo largo del fuste revelaron que el sistema compatible de estimación de volumen propuesto por Fang *et al.* (2000) es el que mejor explica el perfil de los árboles de monte bajo.
- ✓ El sistema seleccionado presenta la ventaja de ser un sistema compatible compuesto por una función de perfil, una ecuación de volumen total y una ecuación de volumen comercial.
- ✓ La validación utilizando una muestra independiente de datos reflejó la calidad de las predicciones y confirmó la capacidad del modelo seleccionado para describir el perfil de los árboles de monte bajo en el noroeste de España.
- ✓ La falta de funciones de perfil que describan el perfil de los árboles de monte bajo en el resto del país o en otros diferentes, permite que el sistema desarrollado pueda utilizarse como primera aproximación hasta que se desarrollen nuevas funciones de perfil que permita estimaciones más precisas para cada zona específica.

7.5.3 Ecuaciones básicas y otras herramientas de gestión

- ✓ Las herramientas básicas desarrolladas en este capítulo permiten resolver el problema de la ausencia de estudios de crecimiento y producción en monte bajo de castaño.
- ✓ La ecuación dinámica de índice de sitio propuesta por Cieszewski (2002) fue el que presentó mayor precisión en la explicación del índice de sitio y en las estimaciones del crecimiento en altura. La edad de referencia seleccionada como la más adecuada en la predicción de altura a otras edades fue los 22 años.
- ✓ La evolución de la densidad de masa en monte bajo es una de las variables más importantes y difíciles de estimar como consecuencia de la gran cantidad de brotes que crecen simultáneamente en la misma cepa. Este hecho, junto con la ausencia de gestión y la heterogeneidad de las masas de monte bajo del noroeste de España hizo imposible poder desarrollar una única ecuación que explicara la evolución de esta variable. Este problema se resolvió calsificando los datos en dos grupos: alta y baja densidad.
- ✓ El conocimiento del estado y desarrollo de las masas de monte bajo se completó con ecuaciones para la predicción del diámetro medio cuadrático, volumen total y comercial y varios componentes de biomasa.
- ✓ Estas herramientas pueden utilizarse directamente o implementarse en tablas de producción o diagramas de manejo de densidad.
- ✓ Se realizaron dos herramientas de gestión diferentes para diseñar y evaluar futuras opciones de manejo: la primera de ellas – las tablas de producción – son más clásicas y tradiciones, mientras que las segundas – los diagramas de manejo de densidad – son más visuales y actuales. Ambas herramientas permiten conocer el volumen total y comercial, la biomasa de fuste, la biomasa de copa y la biomasa total o los stocks de carbono.
- ✓ Se desarrollaron dos tablas de producción, una para cada clase de densidad (alta y baja), para cada una de las curvas de calidad de estación

previamente establecidas (10, 14, 18 y 22 m a la edad de referencia de 22 años).

- ✓ Estas herramientas de gestión precisas permitirán proponer diferentes tipos de escenarios de gestión o regímenes de claras y suponen el punto de partida para análisis más detallados del crecimiento, como los modelos dinámicos, cuando se disponga de más información.

7.5.4 Efectos de los factores ambientales en el índice de sitio

- ✓ El análisis desarrollado reflejó la importancia de las características climáticas en la predicción de la productividad de las masas de monte bajo de castaño en el noroeste de España.
- ✓ Los resultados obtenidos en este capítulo indican que las mejores calidades de estación se observaron en parcelas con reducidas precipitaciones en verano y temperaturas medias anuales bajas.
- ✓ Las variables dasométricas a menudo son más difíciles y lentas de obtener que las climáticas. Además, las características climáticas muchas veces ya se conocen en determinadas áreas geográficas. Ambos aspectos hacen que los modelos de regresión desarrollados sean incluso más útiles e importantes si cabe para los escenarios forestales reales.
- ✓ En un futuro escenario de cambios climáticos impredecibles, la importancia de las variables edáficas y climáticas en la productividad del sitio son básicas para planificar inversiones y trabajos con los que obtener el mejor rendimiento según las diferentes calidades de estación.

7.6 Referencias

Amorini E, Manetti MC. 2002. Selvicoltura nei cedui di castagno. Sostenibilità della gestione e produzione legnosea di qualità. In: Ciancio O, Nocentini S: Il bosco ceduo in Italia. A.I.S.F., Firenze: 219-248.

Bi H 2000. Trigonometric variable-form taper equations for australian eucalypts. Forest Science 46 (3): 397-409.

Bourgeois C, Sevrin É, Lemaire J. 2004. Les guides du sylviculteur. Le châtaignier un arbre, un bois. Deuxième édition. Institut pour le Développement Forestier.

Cabrera M. 1997. El monte bajo de castaño en Asturias: alternativas selvícolas. Tesis doctoral. Escuela Superior de Ingenieros de Montes. Universidad Politécnica de Madrid.

CEE. 1992. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. The Council of the European Communities, OJ L, 21 May 1992.

Cieszewski CJ. 2002. Comparing fixed-and variable-base-age site equations having single versus multiple asymptotes. Forest Science 48: 7–23.

Conedera M, Krebs P, Tinner W, Pradella M, Torriani D. 2004. The cultivation of *Castanea sativa* (Mill.) in Europe, form its origin to its diffusion on a continental scale. Vegetation History and Archaeobotany 13: 161-179. doi: 10.1007/s00334.004.0038.7.

DGCN. 2013. III Mapa Forestal de España. MFE50. 1:50000. Ministerio de Medio Ambiente, Madrid, España.

Fang Z, Borders BE, Bailey RL. 2000. Compatible volume-taper models for Loblolly and Slash pine based on a system with segmented-stem form factors. Forest Science 46 (1): 1–12.

Konstantinidis P, Tsiourlis G, Xofis P, Buckley GP. 2008. Taxonomy and ecology of *Castanea sativa* Mill. forest in Greece. Plant Ecology 195: 235-256.

Lemaire J. 2009. Produttività dei cedui e trattamenti selvicolturali. In: Dossier Castagno: Selvicoltura e Cipollatura. Sherwood 151: 13-16.

Manetti MC, Amorini E, Becagli C, Conedera M, Giudici F. 2001. Productive potential of chestnut (*Castanea sativa* Mill.) stands in Europe. Forest Snow and Landscape Research 76 (3): 471-476.

Seci A, Seenappa SN, Lushaj BM, Lushaj AB, Lushaj AB, Sina K, Dega E, Myteberi I, Toromani E, Tabaku V, Mine V, Boja A, Brahimi J, Lushaj BS. 2013. Conversion of an old, abandoned chestnut forest into simple coppice and coppice forest into orchards through the wise using of the agroforestry practices and estimated energy potential. Journal of Environmental Science, Computer Science and Engineering & Technology. 2 (2): 249-261.

Vogt J, Fonti P, Conedera M, Schröder B. 2006. Temporal and spatial dynamic of stool uprooting in abandoned chestnut coppice forests. Forest Ecology and Management 235: 88-95. doi: 10.1016/foreco.2006.08.008.