Dasometric characterization, study of productivity and territorial analysis of radiata pine (*Pinus radiata* D. Don) in El Bierzo (León)

Academic dissertation

Eva Sevillano Marco

Departamento de Ciencias Agrarias. Escuela Superior y Técnica de Ingeniería Agraria

Universidad de León

Supervised by:

Dr Alfonso Fernández-Manso, Universidad de León, España

Dra Carmen Quintano Pastor, Universidad de Valladolid, España

Ponferrada, 2009

This thesis is based on the following chapters, which are referred to in the text by their numerals:

1. Development of a dynamic growth model for *Pinus radiata* D. Don plantations in El Bierzo
2. Silvicultural alternatives for *Pinus radiata* D. Don plantations: applications of the growth model developed in El Bierzo
3. Influence of ecological parameters on site index of *Pinus radiata* D. Don plantations in El Bierzo
4. Aboveground biomass modelling and carbon pools estimation of *Pinus radiata* D. Don stands combining inventory and RS data in Northwestern Spain
5. Management guidelines for *Pinus radiata* D. Don stands in El Bierzo: general review of radiata pine experiences and practical analysis of a Nelder trial in New Zealand

With the special collaboration of:

Dr. Fernando Castedo-Dorado
Departamento de Ingeniería y Ciencias Agrarias, Escuela Superior y Técnica de Ingeniería Agraria, Universidad de León. Ponferrada (León), Spain

Dr. Andreas Schulte
Wald-Zentrum Institut für Landschaftsökologie, Westfälische Wilhelms- Universität Münster. Münster, Germany

Dr. Yosio Edemir Shimabukuro
INPE- Instituto Nacional de Pesquisas Espaciais. São José dos Campos – SP, Brasil

Dr. Jenny Grace
Forest Science and Management, SCION. Rotorua, New Zealand

Funding for this research was provided by the **Junta de Castilla y León**

Manaaki Whenua, Manaaki Tangata, Haere whakamua

Care for the land, care for the people, go forward

To my family, especially Adelia, and friends.

E iti noa ana, na te aroha

Though my present be small, my love goes with it

Acknowledgements

I would like to express my gratitude to Alfonso, Carmen and Fernando for supervising me through my PhD thesis, providing an excellent working environment and plenty of advice all along the way. Support from my supervisors has enabled the presentation of some of the results of constituting chapters in national conferences.

Thanks to all the students of the ESTIA-Ponferrada of the University of León who had been involved in the establishment of the permanent sample plots network of radiata pine in El Bierzo and all the preliminary studies. This dissertation is a synthesis of all our efforts. In particular, I will always be heartily grateful to Beatriz, Encina and Javier, who assisted me in the field survey and in many other more personal aspects. I also appreciate the collaboration of other PhD candidates at the Agroscience Department, Juan and Pablo. I am also deeply thankful for my co-authors, especially Javier and Marcela. Thanks, Marcela, for all your help and friendship at the Wald-Zentrum and all around Germany.

Dr Andreas Schulte at the Wald-Zentrum (Münster-Germany) and Dr Jenny Grace at Scion (Rotorua-New Zealand), for successful co-operation, the good atmosphere and facilities at both Forestry Research Centres. At Scion, Jenny provided constructive criticism, personal assistance being so far away from home and gave me the chance of living the kiwi perspective, which I pleasurely shared with Alicia. I would like to see you all again, your beautifully radiata-forested country and your southern stars. I also acknowledge the supplier of the CBERS satellite data, Dr Yosio Shimabukuro, at INPE-Brasil. PhD candidate at Berkely University (California-USA) Elena and Andrew Brudenell proof-read all my manuscripts for English.

I would like to acknowledge all other teachers, students and staff that assisted me in diverse aspects, from administrative issues to research queries, advice or refreshing discussions, and so on. It has been an unforgettable experience. I want to thank you all for your positive and helpful attitude. It is great to know you all.

Finally, I want to thank all my friends and family for their encouragement, even though you might never read these lines nor the following text. I do not forget my grandparents, who left us in the interim of this work (it is very likely I become a “Médica”, abu), and I am grateful for the birth of my nieces, Lorena and María, who were born in this period and have cheered up us all. Congratulations, Susana and Bernardo, for your lovely children. I can not thank enough my mother for her warm support and understanding. Now it is good time to send some greetings to my friends, I owe you much. Jordi, thank you for your faithful company, your visits to Ponferrada and Germany (I know you would have also come as far as New Zealand, had you been able to) and for organizing our spectacular and rewarding holidays. Thanks to all of you for listening, your understanding, and above all, for the good moments we have shared. We will soon toast together to the coming experiences and to the celebration of this happy ending!

Eva

Contenidos

RESUMEN (*castellano*) 10
RESUMEN.................... 13
INTRODUCCIÓN.................... 15
OBJETIVOS.................... 18
ESQUEMA GENERAL DE LA TESIS 19
ZONA DE ESTUDIO 23
FUENTES DE DATOS 25
1 Datos de campo 25
2 Datos RS 30
3 Datos SIG complementarios.................... 31

CAPÍTULO 1. Desarrollo de un modelo de crecimiento dinámico para plantaciones de *Pinus radiata* D. Don en El Bierzo 33
1 Introducción 33
  1.1 Modelos de crecimiento forestal 33
2 Métodos 35
  2.1 Estructura, desarrollo y ajuste del modelo 35
    2.1.1 Estructura del modelo.................... 35
    2.1.2 Desarrollo y ajuste de las funciones de transición para las variables de estado . 35
    2.1.3 Sistema de desagregación 39
  2.2. Selección de la mejor ecuación de cada módulo 41
  2.3 Evaluación global del modelo de masa.................... 42
3 Resultados 42
  3.1 Funciones de transición de las variables de estado.................... 42
  3.2 Sistema de desagregación.................... 45
  3.3 Evaluación global de modelo de masa.................... 47
4 Discusión.................... 48
5 Conclusiones 50

CAPÍTULO 2. Alternativas selvícolas para plantaciones *Pinus radiata* D. Don: aplicaciones del modelo de crecimiento desarrollado en El Bierzo 52
1 Introducción 52
2 Métodos 54
3 Resultados 56
4 Discusión.................... 60
5 Conclusiones 62

CAPÍTULO 3. Influencia de los parámetros ecológicos en el índice de sitio de plantaciones de *Pinus radiata* D. Don en El Bierzo 63
1 Introducción 63
2 Métodos 66
2.1 Parémetros ecológicos y descripción del hábitat 66
2.1.1 Cartografía de factores ambientales: áreas potenciales para el establecimiento de pino radiata 67
2.2 Exploración descriptiva y test de correlaciones de Pearson 68
2.3 Análisis de estadística multivariante 68
2.3.1 ACP 69
2.3.2 Análisis discriminante (AD) 69
2.4 Construcción de modelos 70
2.5 Evaluación y test de hipótesis 70
3 Resultados 71
3.1 Parámetros ecológicos y descripción del hábitat 71
3.1.1 Cartografía de áreas de potencialidad 72
3.2 Descripción de parámetros ecológicos y correlaciones 76
3.2.1 Exploración de los datos 76
3.2.2 Matriz de correlación 77
3.3 Técnicas multivariantes 79
3.3.1 ACP 79
3.3.2 AD 79
3.4 Modelización del *SI* 79
3.5 Evaluación 81
4 Discusión 84
5 Conclusiones 90

CAPÍTULO 4. Modelización de la biomasa aérea y estimación de reservas de carbono de rodales de *Pinus radiata* D. Don combinando datos de inventario y TD en el noroeste peninsular 91
1 Introducción 91
2 Métodos 94
2.1 Procesamiento de datos de campo 96
2.2 Procesamiento de imágenes y datos satelitales derivados 97
2.2.1 Preprocesamiento de la imagen ASTER 98
2.2.2 Preprocesamiento de la imagen CBERS 99
2.3 Análisis estadístico 101
2.4 Análisis espacial 102
3 Resultados 103
3.1 Resultados del preprocesamiento de imágenes 103

3.2 Correlaciones entre datos de RS y variables dasométricas 104
3.2.1 Imagen ASTER 104
3.2.2 Imagen CBERS 104
3.3 Modelos estadísticos y estimación de variables dasométricas 104
3.3.1 Imagen ASTER 105
3.3.2 Imagen CBERS 107
3.4 Análisi espacial empleado datos de ASTER 110
3.5 Validación y comparación de resultados 112
4 Discusión 112
5 Conclusiones 118

CAPÍTULO 5. Recomendaciones de gestión para plantaciones de *Pinus radiata* D. Don en El Bierzo: revisión general de experiencias con pino radiata y análisis práctico de una parcela Nelder en Nueva Zelanda 120
1 Introducción 120
1.1 Requisitos ecológicos: estaciones 120
1.2 Genética 121
1.3 Manejo 122
1.4 RS 123
2 Métodos 124
2.1 Inventario de campo de una parcela Nelder 124
2.2 Análisis estadísticos 127
3 Resultados 127
3.1 Inventario de campo de una parcela Nelder 127
3.2 Pautas de crecimiento y propiedades de la madera 128
3.3 Hábito de las ramas 131
3.4 Forma del tronco 132
4 Discusión 133
5 Conclusiones 136

CONCLUSIONES (*castellano*) 138
FUTURAS LÍNEAS DE INVESTIGACIÓN (*castellano*) 140
CONCLUSIONES 142
FUTURAS LÍNEAS DE INVESTIGACIÓN 144
BIBLIOGRAFÍA 146
TABLAS Y FIGURAS 173
ACRÓNIMOS 175

Contents

RESUMEN 10
ABSTRACT 13
INTRODUCTION 15
OBJECTIVES 18
OUTLINE OF THE THESIS 19
AREA OF STUDY 23
DATA SOURCES 25
1 Field data 25
2 RS data 30
3 Ancillary GIS data 31

CHAPTER 1. Development of a dynamic growth model for *Pinus radiata* D. Don plantations in El Bierzo 33
1 Introduction 33
  1.1 Forest growth models 33
2 Methods 35
  2.1 Model structure, model development and model fitting 35
    2.1.1 Model structure 35
    2.1.2 Development and fitting of transition functions for state variables 35
    2.1.3 Disaggregation system 39
  2.2. Selection of the best equation in each module 41
  2.3 Overall evaluation of the whole-stand model 42
3 Results 42
  3.1 Transition function for state variables 42
  3.2 Disaggregation system 45
  3.3 Overall evaluation of the whole-stand model 47
4 Discussion 48
5 Conclusions 50

CHAPTER 2. Silvicultural alternatives for *Pinus radiata* D. Don plantations: applications of the growth model developed in El Bierzo 52
1 Introduction 52
2 Methods 54
3 Results 56
4 Discussion 60
5 Conclusions 62

CHAPTER 3. Influence of ecological parameters on site index of *Pinus radiata* D. Don plantations in El Bierzo 63
1 Introduction 63
2 Methods 66
2.1 Ecological parameters and habitat description 66
2.1.1 Environmental factors mapping: potential areas for radiata pine establishment . 67
2.2 Descriptive exploration of data and Pearson’s correlation test 68
2.3 Multivariate statistical analyses 68
2.3.1 PCA 69
2.3.2 Discriminant analysis (DA) 69
2.4 Model construction 70
2.5 Evaluation and assumptions testing 70
3 Results 71
3.1 Ecological parameters and habitat description 71
3.1.1 Cartography of areas of suitability 72
3.2 Description of ecological parameters and correlations 76
3.2.1 Data exploration 76
3.2.2 Correlation matrix 77
3.3 Multivariate techniques 79
3.3.1 PCA 79
3.3.2 DA 79
3.4 SI modelling 79
3.5 Evaluation 81
4 Discussion 84
5 Conclusions 90

CHAPTER 4. Aboveground biomass modelling and carbon pools estimation of *Pinus radiata* D. Don stands combining inventory and RS data in Northwestern Spain 91
1 Introduction 91
2 Methods 94
2.1 Field data processing 96
2.2 Image processing and satellite-derived data 97
2.2.1 ASTER image preprocessing 98
2.2.2 CBERS image preprocessing 99
2.3 Statistical analysis 101
2.4 Geospatial analysis 102
3 Results 103
3.1 Image preprocessing results 103
3.2 Correlations between RS data and stand variables 104
3.2.1 ASTER image 104

3.2.2 CBERS image ... *104*
3.3 Statistical models and stand variables estimation ... 104
3.3.1 ASTER image ... *105*
3.3.2 CBERS image ... *107*
3.4 Spatial analysis using ASTER data ... 110
3.5 Validation and comparison of results ... 112
4 Discussion ... 112
5 Conclusions ... 118

CHAPTER 5. Management guidelines for *Pinus radiata* D. Don stands in El Bierzo: general review of radiata pine experiences and analysis of a Nelder trial in New Zealand ... 120
1 Introduction ... 120
1.1 Ecological requirements: sites ... 120
1.2 Genetics ... 121
1.3 Management ... 122
1.4 RS ... 123
2 Methods ... 124
2.1 Field inventory of a Nelder trial ... 124
2.2 Statistical analysis ... 127
3 Results ... 127
3.1 Field inventory of a Nelder Trial ... 127
3.2 Growth patterns and wood properties ... 128
3.3 Branching patterns ... 131
3.4 Stem form ... 132
4 Discussion ... 133
5 Conclusions ... 136

CONCLUSIONES ... 138
FUTURAS LÍNEAS DE INVESTIGACIÓN ... 140
CONCLUSIONS ... 142
FUTURE RESEARCH LINES ... 144
REFERENCES ... 146
TABLES AND FIGURES ... 173
ACRONYMS ... 175

RESUMEN

La especie forestal *Pinus radiata* D. Don fue introducida en los años setenta en El Bierzo (NO España, León). En esta tesis, enmarcada en la problemática socioeconómica de esta comarca, propia de las zonas rurales de interior, se abordan los principales aspectos a considerar en la implementación de usos forestales. Los objetivos específicos se centran en el análisis de la productividad de la especie desde el punto de vista dasométrico y ecológico, la caracterización de las masas mediante el empleo de técnicas de teledetección y la revisión de la investigación forestal en otras regiones con importante presencia de la especie. Las conclusiones derivadas de los análisis de datos permiten una reflexión crítica sobre futuras líneas de investigación y las prioridades comarcales en un marco de sostenibilidad.

El primer paso consistió en la compilación de datos de dos inventarios forestales (2003 y 2006) de la red de parcelas de muestreo permanentes (PSP) establecida por la Universidad de León en 2003 en El Bierzo. El procesamiento de los datos dendrométricos permite la cuantificación de las variables de estado y otras variables dasométricas, así como el desarrollo de un modelo de crecimiento dinámico de masa para plantaciones de *Pinus radiata* D. Don en El Bierzo. La hipótesis de partida del modelo es que las condiciones de la masa en un momento dado del tiempo vienen definidas por tres variables de estado (área basimétrica, número de pies por hectárea y altura dominante). El modelo incluye tres funciones de transición derivadas a partir de la técnica de diferencias algebraicas generalizadas que permite la proyección de las variables de estado a un momento futuro dado. Una vez conocidas las variables de estado, puede estimarse el número de pies en cada clase diamétrica con una función de distribución, mediante la recuperación de los parámetros de la función de Weibull usando el método de los momentos. Finalmente, una función generalizada de altura-diámetro y una función de perfil de tronco permiten la estimación del volumen total o comercializable. Además, la estimación del crecimiento de la masa utilizando el modelo de crecimiento dinámico ajustado simulando varios regímenes silvícolas en dos calidades de estación diferentes ha proporcionado predicciones locales para las masas de radiata en El Bierzo (León). La comparación de resultados permite el bosquejo de valiosas recomendaciones para el establecimiento de la especie en la región y a la vez ha confirmado que las estimaciones generadas por el modelo en conjunto representan adecuadamente los efectos tanto de la densidad de la masa como de la calidad de estación. El modelo permite el cálculo del índice de sitio (*SI*) como una variable continua, abordando mediante un método directo el estudio de la productividad.

Independientemente, se ha empleado una metodología indirecta para analizar la productividad de la especie en la zona de estudio: se han examinado relaciones entre variables ambientales y el *SI*, seleccionado como indicador de productividad en plantaciones de *Pinus radiata* D. Don de El Bierzo. Las variables ambientales observadas se clasifican en datos fisiográficos, edáficos, climáticos y edafoclimáticos. Análisis descriptivos estadísticos han permitido la definición del hábitat óptimo y marginal de los correspondientes parámetros ecológicos. La cuantificación de las relaciones entre variables ambientales y productividad ha implicado el uso de las siguientes técnicas de estadística multivariante: correlación, análisis de componentes principales y funciones discriminantes. Entre los modelos ajustados mediante análisis de regresión múltiple, la precipitación otoñal y la profundidad del horizonte superficial han resultado los parámetros de mayor influencia sobre la productividad. La aplicación de técnicas de análisis espacial ha posibilitado la extrapolación en un mapa de superficies de potencialidad para la especie. El resultado permite la predicción del crecimiento de las masas (*SI*) en áreas donde la especie no ha sido previamente establecida y sugiere la

importancia de la selección de la estación y de los tratamientos de fertilización en los programas de reforestación.

Por otro lado, en la planificación forestal, la introducción de plantaciones debe considerar otros puntos de vista aparte de la producción maderera. Por ejemplo, las plantaciones pueden tener como objeto metas medioambientales y/o sociales (conservación de suelos, producción de biomasa, empleo, etc.). En el contexto del cambio climático global, la producción de biomasa es un recurso cada vez más demandado. El estudio de la cuantificación de la biomasa y almacenamiento de carbono en las masas de radiata de la zona de estudio se abordó empleando como herramientas de investigación las técnicas de teledetección. El planteamiento de este estudio permite al mismo tiempo analizar la potencialidad de estas técnicas en la investigación medioambiental a escala regional. Las técnicas de teledetección proporcionan información sobre parámetros biofísicos de las masas forestales. Se han utilizado escenas del Chinese-Brazilian Earth Resources Satellite (CBERS) y Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) acopladas a datos georreferenciados complementarios de Sistemas de Información Geográfica (SIG) y datos de inventario de campo para determinar el potencial de los datos de teledetección para la evaluación de área basimétrica, volumen y biomasa aérea en superficies amplias de plantaciones de pino radiata en una región del Noroeste español de la provincia de León. Se han utilizado los datos procesados de terreno de las parcelas permanentes, las bandas de la imagen (infrarrojo visible VNIR, infrarrojo de onda corta SWIR) e índices de vegetación espectrales (SVIs) derivados de la imagen ÁSTER así como índices de vegetación, bandas espectrales e imágenes fracción obtenidas a partir del análisis de mezclas espectrales de los datos del sensor Charge-Coupled Device (CCD) CBERS. Las imágenes fracción, al representar aspectos físicos de las cubiertas de la superficie, muestran las propiedades biofísicas más fácilmente que las bandas discretas originales. Los análisis estadísticos incluyen matriz de correlación, modelos de regresión e inspección de residuos. La banda del infrarrojo cercano (NIR) y la imagen fracción de sombra han mostrado coeficientes de correlación significativos con todas las variables dasométricas consideradas. Los estudios preliminares son satisfactorios y refuerzan la convicción de la utilidad de la teledetección en la caracterización de los sistemas forestales. Modelos predictivos lineales y no lineales han sido acordemente seleccionados y empleados para abordar la distribución espacial de las variables dasométricas en las masas de radiata delimitadas por el Mapa Forestal Nacional (MFN) por primera vez en la zona de estudio. La integración de las mediciones en superficie en fuentes de datos de amplia resolución espacial es un paso esencial para lograr una gestión forestal y la estimación de la biomasa aérea y las reservas de carbono de forma sostenible y coste-efectiva.

Finalmente, los resultados locales fueron sometidos a una reflexión crítica. En términos relativos, el pino radiata ha sido recientemente introducido en El Bierzo, por lo que la experiencia con la especie es limitada. En cambio, es una conífera de primer orden en plantaciones forestales a nivel mundial, especialmente en Nueva Zelanda. En la fase final, se han estudiado los principales aspectos relativos a la planificación forestal y selvicultura de *Pinus radiata* D. Don desde la perspectiva neozelandesa, centrando el enfoque en la aplicación a las condiciones locales en El Bierzo. La investigación de alto nivel y la amplia experiencia práctica con la especie de este país, en horizontes temporales amplios, apuntan a que la rentabilidad de las plantaciones, especialmente al tratarse de una especie exótica, requiere información sobre cómo las propiedades de la madera y las tasas de crecimiento pueden manipularse con tratamientos culturales y programas de mejora genética. Por ello, se han examinado los efectos interactivos de la densidad de plantación y el genotipo sobre la dureza y el crecimiento (altura y diámetro) mediante la revisión de la experiencia forestal con *Pinus radiata* D. Don y mediciones obtenidas a partir de una muestra de pies de pino radiata de una parcela tipo Nelder en Nueva Zelanda. Esta tesis doctoral es una síntesis de todos estos pasos e integra todos los estudios relacionados con pino radiata en el área de estudio.

ABSTRACT

The species *Pinus radiata* D. Don was introduced during the seventies in El Bierzo (NW Spain). This thesis considers the major concerns of the introduction of forestry uses within the socioeconomic challenges of the region of study, representative of inland rural areas of the country. Specific objectives focus on productivity assessment of the species both from stand and ecological approaches, stand characterisation using RS techniques and forestry research review of other regions with important presence of the species. The conclusions derived from the data analyses allow for a critical reflection about future research lines and priorities in the region within a sustainability frame.

The first step was data collection from two field inventories (2003 and 2006) of a permanent sample plot (PSP) network established by the University of León in 2003. Data processing enabled the quantification of state variables and other stand variables as well as de development of a dynamic growth model for *Pinus radiata* D. Don plantations in El Bierzo (Spain). In the model, stand conditions at any point in time are defined by three state variables (stand basal area, number of trees per hectare and dominant height). The model includes three transition functions derived by the generalized algebraic difference approach to enable projection of the state variables at any particular time. Once they are known, the number of trees in each diameter class is estimated with a distribution function, by recovery of the parameters of the Weibull function by use of the moments method. Finally, a generalized height-diameter function and a taper function allow estimation of total or merchantable stand volume. In addition, simulation of stand growth using the dynamic growth model developed under several silvicultural regimes and two different sites provides local predictions for radiata stands in El Bierzo. The comparison of results enables sketching valuable guidelines for the establishment of the species in the region and at the same time confirms that the estimates provided by the overall model adequately represent the effects of both stand density and site quality. The model enables calculation of site index (*SI*) as a continuous variable, and directly approaches productivity assessment.

Nonetheless, and indirect approach was also undertaken: relationships among environmental variables and *SI*, selected as indicator of productivity, were examined in *Pinus radiata* D. Don plantations of El Bierzo. Environmental variables measured were classified into physiographic, edaphic, climatic and edaphoclimatic data. Descriptive statistical analyses enabled optimal and marginal habitat definition of the corresponding ecological parameters. Quantification of relationships between environmental variables and productivity involved the use of the following multivariate statistical techniques: correlation, principal components, and discriminant rules. Amongst the models fitted by multiple regression analysis, autumn rainfall and soil depth turned out to have the greatest influence on productivity. Application of spatial analyst techniques enabled extrapolation into a map of potentiality areas for the species. The outcome allows forecasting of stand growth (*SI*) in areas previous to the establishment and suggests the importance of site selection and fertilizer treatments in reforestation programmes.

On the other hand, forestry implementation should consider plantations from perspectives other than wood production. For instance, afforestation can also achieve environmental and/or social targets (e.g. soil conservation, biomass production, employment). In the context of global climatic change, biomass is an increasingly demanded resource. Assessing the quantification of biomass and carbon stocks in radiata stands in the area of study was approached using remote sensing (RS) techniques as a tool. This step would at the same time analyse the potentiality of these techniques in environmental studies at a regional scale. RS

techniques provide information about biophysical parameters of forest stands. A Chinese-Brazilian Earth Resources Satellite (CBERS) and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes coupled with ancillary Geographic Information Systems (GIS) data and field survey were employed to examine the potential of the RS data in stand basal area, volume and aboveground biomass assessment over large areas of radiata pine plantations in Northwestern Spain. Processed field data from permanent plots and image (visible and near infrared radiometer VNIR, short wave infrared radiometer SWIR) bands as well as spectral vegetation indices (SVIs) from the ASTER scene whereas vegetation indices, spectral bands and fraction images obtained by unmixing the Charge-Coupled Device (CCD) CBERS data were used. Unmixed images show biophysics properties more easily than original bands because they represent physics aspects of ground covers. Statistical analysis included correlation matrix, regression models and inspection of residuals. Near infrared (NIR) band and shade fraction image showed significant correlation coefficients with all stand variables considered. Results obtained are satisfactory and reinforce the conviction of usefulness of RS in assessing forestry systems. Predictive linear and non-linear models were accordingly selected and utilized to undertake the spatial distribution of stand variables in radiata stands delimited by the National Forestry Map (MFN) for the first time in the region. Integration of ground measurements with coarse spatial resolution data is an essential step to achieve sustainable cost-effective forest management, aboveground biomass and carbon pools estimation.

Finally, local results were subjected to a critical review. In relative terms, radiata pine has been recently introduced in El Bierzo. Therefore, the local experience with th especies is limited. On the contrary, it is a first-rate conifer in plantations at a global scale and the major planted species in particular in New Zealand. In the final stage, the main subjects related to forestry of *Pinus radiata* D. Don were studied from the New Zealand's perspective, at the same time focussing on local applicability. Research expertisse and a broad field experience with the species in time suggests that the profitability of plantations, especially when dealing with exotic species, requires knowledge of how wood properties and growth can be manipulated by silvicultural management and breeding programs. Thus, the interactive effects of initial stand density and genotype on stiffness and growth (height and diameter) were examined reviewing forestry literature with *Pinus radiata* D.Don, and field measurements obtained from a sample of radiata pine stems of a Nelder trial in New Zealand. This dissertation is a synthesis of all these steps and integrates all the studies related to radiata pine in the area of study.

Whaia te iti Kahurangi-ki te tuohu koe, me he maunga teitei
Pursue excellence-should you stumble, let it be to a lofty mountain

INTRODUCTION

In opposition to the general concern that plantation forests have often been referred to as vast boring monocultures, reducing the biodiversity of a region, the fact that forestry can be an environmentally friendly land use when properly planned and managed, is of special significance for the area of study. El Bierzo is located in the vast region of Castilla y León, where common drawbacks and challenges for rural inland areas are shared in most of the territory.

Keeping in mind that intensive plantation forestry with introduced species has not been practised for a sufficiently long time to properly assess whether it is really being done in a sustainable fashion (**West 2007**), creating forests by shifting land-uses, can simultaneously achieve, in addition to wood production, environmental goals suchlike water and soil conservation, greenhouse gas mitigation, recreational and other economic uses suchlike mycology and hunting profitability, or bioenergy. For instance, the delay in clearfelling and the use of low stand densities could have a positive effect on the diversity of the plant communities in plantations, especially at an advanced stand age (**Kerr 2000, Martín-López 2000**).

Afforestations could be particularly appropriate for the socioeconomic frame under consideration, as an alternative land use. The utilisation of wood products and a wider integration of forestry into society are challenges that should be parallel to the establishment of the species in order to fully accomplish the overall benefits of the responsible management of forests.

Substantial effort and expense are involved in the establishment and management of forest plantations. In the end, the rate of growth of trees in a plantation depends on the species planted, the environmental circumstances of the site on which it is planted and the silvicultural practices which are employed. A global and multidisciplinary perspective lies beneath the research labour undertaken, in which different aspects of forestry are tackled, based on a single species as the linking subject. The particular conditions of the area of study provide the underlying background of a rural framework and sustainable development issues.

Native population of radiata pine occur in mainland in separate populations in California at Año Nuevo, Monterrey, and Cambria, existing also two island populations on Guadalupe Island and Cedros Island (**Shelbourne et al. 1979**). Overall, there are three recognized varieties (**Cool and Zavarin 1992**): *Pinus radiata* var. *radiata*, which is the subject of this thesis, *Pinus radiata* var. binata Lemmon, and *Pinus radiata* var. cedrosensis (Howell).

The natural area of distribution of the species adds to a surface of around 4000 ha (**Ruiz-de la Torre 1979**), most probably receding (**Nowak 1993**). On the contrary, the area of distribution in afforestations as an introduced species is by far larger, well over a thousand fold the native surface (i.e. 4000 000 ha), located mostly in the Southern hemisphere (**Pinjuv et al. 2006**).

Certainly, as stated by **Eldridge (1997)**, *Pinus radiata* (D.Don) is the main planted species in South Africa (300 000 ha), Australia (750 000 ha), New Zealand (1800 000 ha) and Chile (1 400 000 ha). In another scale, in the Northern hemisphere, besides its natural area of distribution, several trials in France and Portugal among others, and a reduced plantation area in Calabria (Italy), it is well represented in Spain (approximately 300 000 ha), in particular in the Basque Country (160 000 ha) and Galicia (92 000 ha).

In fact, currently, Spain is the only Northern hemisphere country where radiata stands occupy a relevant area and a radiata wood transformation industry has developed (**Dans-del Valle et al. 1999**). In Castilla y León, the main centres are in El Bierzo (León) and Valle de Mena (Burgos), with populations of respectively 15 000 ha and 1500 ha, where the climate is suitable.

Because of the small area of natural stands, and because of the limited number of areas where it can grow locally, it is a minor species in the wild. It grows only in temperate regions with a maritime climate. This is because radiata pine is killed by the occasional severe frost which can occur in temperate regions with a continental climate, and because radiata does not function well in tropical regions (except at very high altitudes).

Where the climate is satisfactory, radiata is very tolerant of site (e.g. sand to clay, acid to alkaline, high fertility to low fertility, and sea level to 1000 m) (**Sutton 1999**).

Scott (1961) points to a growth of 9-20 m^3 ha^{-1} $year^{-1}$, whilst under breeding programs it can yield to 25-30 m^3 ha^{-1} $year^{-1}$ (**Burdon and Moore 1997**) and even higher (**Zwolinski and Bayley 2001**). In our country, common yields are 13-15 m^3 ha^{-1} $year^{-1}$. Upmost records state, at the age of 20, up to 2 m growth per year which imply a volume increment of 20-25 m^3 ha^{-1} $year^{-1}$ (**Asenjo et al. 2005**). Furthermore, it is able to sustain its very high growth rate over several decades (**Sutton 1999**).

Although not a high-quality structural timber, radiata pine wood is adequate for most purposes. In fact it is ideal as packaging material, at its best as a clearwood with excellent finishing properties, and easy and effectively treated with wood preservatives of almost any kind (**Sutton 1999**). Moreover, the species has shown considerable response to genetic improvement (e.g. stem straightness, branching patterns, growth rates, wood properties, disease resistance) and silviculture regimes (**Kumar et al. 2008**).

Success of the establishment of the species in the area of study can be aided by related research in specific and crucial aspects. To name a few, good decision making, timely management, and profitability, require the use of a technical modelling system that forecasts the outcome of numerous physical actions and decisions that need to be made early in tree crop’s life, that can have major influences on yield, costs, and revenue.

Even though economic benefits, cashflows and wood markets have not been accordingly analysed, and given the fact that environmental and social services provided by forests are not as yet priced with a proper weight in the economic market, profitability of plantations is clearly the most important factor that nowadays would drive the introduction of the species and the favourable vision of growers, land owners and general population in the area of study.

Tree growth translated into wood products, biomass and carbon pools are, however, tangible goods that radiata stands supply and can be feasibly assessed. The latter are in the process of being introduced in the incipient business of emissions trade and scope of the climatic change mitigation measures.

In accordance to the importance of the species, radiata pine has been thoroughly researched in other countries, and still is, as studies are continually updated and funded by the related industries and government. Amongst them, New Zealand and Chile could be distinctly picked up in, for instance, the following aspects: pioneer in the widespread of the species afforestations (**Shepherd 1990**), growth modelling (**Dzierzon and Mason 2006**), biomass (**Guerra et al. 2005, Snowdon 1985, Madgwick 1985, 1983**), environmental impacts of forestry (**Payn and Clinton 2005, Watt et al. 2005, Dyck and Beets 1987**), wood properties (**Cown 2005, Miller 2002**), genetics (**Burdon et al. 2008, Sorensson 2008, 2002**), silviculture regimes (**Whyte 1988, Lavery 1986**), weight on the economy and markets, shelterbelts, and agroforestry systems, to name a few.

Analogously, in our country, a review of the related literature, provide plenty of references, mainly focused on growth modelling and management practices, in particular of the northern coastal regions in the Basque Country (**Chauchard 2001, Cantero et al. 1995, Castilla and Prieto 1992, Aunós 1990, Muñoz 1985, Madrigal and Toval 1975**) and Galicia (**Castedo-Dorado et al. 2007, Castedo-Dorado 2004, Álvarez et al. 2004, López et al. 2003, Sánchez-Rodríguez et al. 2003, Rodríguez et al. 2002, Castedo-Dorado and Álvarez 2000**). This is explained because it is in these regions where the species was first introduced and it was as early as the thirties when the first plots were established for productivity tables development (**Echevarría 1942**).

As regards other subjects, biomass equations have been developed for Galicia (**Balboa-Murias et al. 2006**), Basque Country and Asturias (**Canga 2007**), whereas nutritional status (**Merino et al. 2003**), soil properties (**Sánchez-Rodríguez et al. 2002**) or environmental factors (**Romanyà and Vallejo 2004**) have also been tackled, to our knowledge.

By contrast, due to the comparatively recent introduction of the species, and the socioeconomic conditions in the area of study, there was a general lack of knowledge on the species establishment and management, main growth driving factors, biomass and carbon stocking, etc. that should be locally approached. Besides, it is well known that a proper research almost universally ends in further research needs. Data bases should be updated and extended, and so on. Logically, many areas, that should be in due time accurately researched, remain beyond the scope of the present work.

Unfortunately, at present the practical application of some of the results hitherto obtained and conclusions derived are out of reach due to the current propriety structure and subsequent feasibility of the planning and management in the area of study. However, in the bordering regions, the species is already well established, and wood markets consolidated. This fact should encourage the final object of the enterprise in the area of study and other regions.

Equally, spreading and popularization of scientific knowledge acquired seriously contributes to the final realisation of the conclusions derived. In this respect, several communications and participation in technique seminars are the first steps undertaken (**Fernández-Manso et al. 2001, Álvarez et al. 2004, Castedo-Dorado et al. 2004, Fernández-Manso and Sarmiento-Maíllo 2004, Rodríguez et al. 2004, Castedo-Dorado et al. 2005, Pérez-Crespo et al. 2009, Sevillano-Marco and Fernández-Manso 2009, Sevillano-Marco et al. 2009, 2009a, 2009b**).

OBJECTIVES

The final goal of the thesis was to determine whether radiata pine stands respond adequately to the particular needs of the area of study, as regards forestry uses establishment and consolidation, in a shift of land uses and economic activities from agricultural fields, shrublands or areas devastated by fire, as a solid and sustainable alternative. Nonetheless, this broadminded objective had to be specifically approached from technical areas of knowledge.

Once having revised all the preliminary works related to the species in the area of study and the main characteristics of radiata pine elsewhere, it appeared that to start from, the following questions needed a local answer:

-Is this species adequate to introduce a forestry culture framed in sustainable rural development?

-How does the species perform in terms of productivity (e.g. growth rates, mortality, basal area)? How much wood will the existing stands produce in the near future?

-What would be the most adequate management lines?

-How does the species respond to local ecological conditions?

-How can the study of stand attributes be assessed in a regional scale in a cost-effective way? How much biomass and carbon are stored in radiata pine stands in El Bierzo?

-What are the main characteristics to be controlled by silviculture to optimize the profitability of the species considering quality over quantity of wood produced and other objectives?

-What are the main aspects to be surveyed and improved as regards the spreading of radiata pine afforestations?

Accordingly, this thesis focuses on five targets which are approached in the corresponding chapters:

1) assessment of the productivity of existing radiata stands in El Bierzo, and development of growth model that describes the stands and predicts their evolution

2) application of the growth model developed to test different management alternatives and assist forestry planning

3) assessment of productivity from an ecological perspective to find out the local habitat of the species in the region and determine potential areas for the establishment

4) quantification of biomass and carbon stocks in the surface area occupied by the species in the area of study, and testing the feasibility of remote sensing (RS) techniques as a research tool to approach the study of stand attributes at a regional scale

5) discussion of management guidelines, properly framed, comparing the species status in El Bierzo and the trajectory of the species in New Zealand, the main producer of radiata products worldwide, and where the ultimate related research is being carried out.

OUTLINE OF THE THESIS

In view of the results of preliminary studies and the proposed objectives, the first step was to locate a reliable source of field data from the stands. With this purpose, a permanent sample plot network in pure radiata pine plantations in El Bierzo was established by the University of León in 2003. The plots were located throughout the area of distribution of the species in the region, subjectively selected to adequately cover the existing range of ages, stand densities and sites.

The productivity of radiata pine stands evaluation is undertaken from both forest variables characterizing the existing plantations (Chapter 1), and environmental factors driving the stands yields (Chapter 3). The latter approach enables forecasting of areas for the establishment of new plantations, defining the species optimal and marginal habitats, and potentiality mapping by a classification of lands based on their suitability as regards environmental factors influencing radiata growth.

Field inventories carried out in 2003 and 2006 enabled the characterisation of the stands in the area of study by quantification of forest variables (e.g. dominant height and diameter, mean height, site index, basal area) and the development of a dynamic whole-stand growth model (**Sevillano-Marco et al. 2009**).

The growth model developed (Chapter 1) for the area of study was used to simulate several silviculture alternatives of the stands in El Bierzo (Chapter 2). The final goal was to provide some basic guidelines for the successful management of the species, based on the experiences and key findings about the species from a longer-term experience point of view and the specific forecasts that the practical application of the local model provide.

Site index *(SI)* and quality curves can also be distinguished as key outcomes in the first stage of this project (Chapter 1). The subsequent step was to find out the relationship between this attribute, that precisely represents the growth of the species, and the environmental factors that necessarily affect local growth. Indeed, tree growth, form and wood properties are impacted to some degree by random environmental influences and site effects.

Whereas a growth model enables prediction of the evolution of already established stands, this approach aims at forecasting, even if roughly, the potentiality of lands as regards growth of the species prior to the real establishment. Deeper knowledge of the local ecology of the species (**Pérez-Crespo et al. 2009**), and definition of optimal and marginal habitats, are also achieved (Chapter 3).

Available data sources and collaboration within the research group of the Engineery and Rural Planning (IPR) of the Agroscience Department in the Campus of Ponferrada and the Institut für Landschaftsökologie of the Westfälische Wilhelms Universität in Münster (Germany) led way to the consideration of introducing RS as a valuable research tool in the assessment of radiata pine attributes. Ultimately, the success of this trial would allow quick and continuous updating of inventory data together with forest attributes estimation at a regional scale, which would significantly reduce costs, favouring optimization of future research strategies (Chapter 4).

Two independent studies (Chapter 4) over two different satellite scenes were aimed at the assessment of radiata pine stands variables directly measured (i.e. basal area and volume) from the field inventory carried out in 2003, the closest to the dates of acquisition of both images, and the biomass inferred using the corresponding equations developed for the species in Galicia (**Balboa-Murias et al. 2006**). Highlights of the resemblances and dissimilarities from the comparison of both works reinforce the obtained conclusions.

In parallel, it was considered very interesting to review first-hand information and reflect over the experience with the species from the excellent research compilation and practical trials provided by the SCION Research Centre in Rotorua (New Zealand). All this effort has proved to be highly valuable and has shed light more or less implicitly on the overall document as well as on the individual chapters. Likewise, it generated a proper chapter in itself (chapter 5). In the aforementioned chapter, we investigated the results obtained from the analysis of an extra field data set collected in a Nelder trial from Rotorua. This plot is a sample of the paradigmatic example of a set of experiments carried out in New Zealand that analyses the effect of stocking and seed sources on growth and stem form. Currently, the focus of growth models and production objectives in this country has largely left behind the only target of optimizing volume yields.

A closer look reveals that wood properties are affected by growth rates. A balance between practices enhancing fast growth and at the same time assuring high-quality products must be carefully surveyed.

A basic diagram of the development of this thesis, data bases used, tools and analysis carried out is shown in **Figure 1.**. In the corresponding chapters, a more detailed scheme of specific procedures is shown.

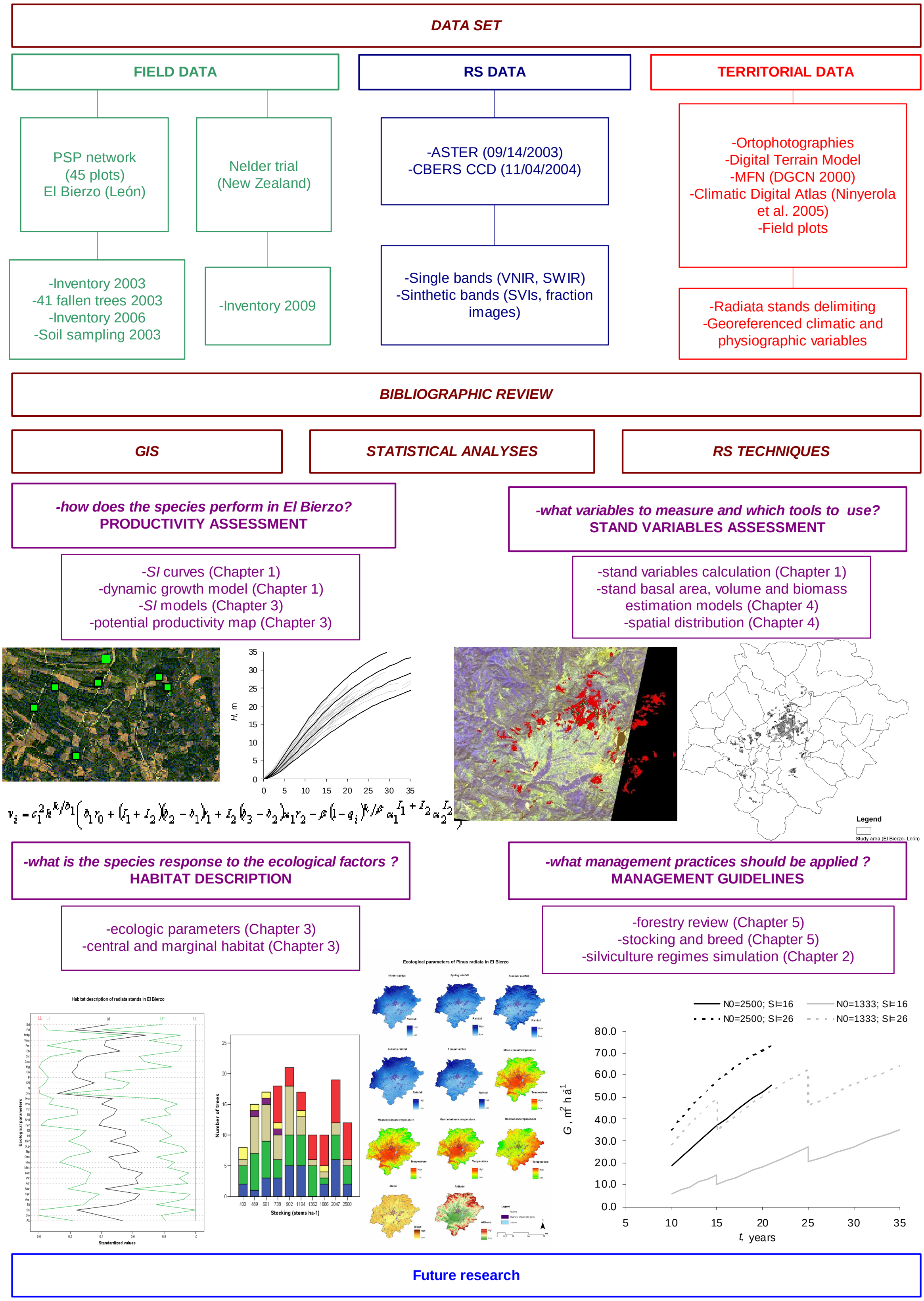

Figure 1. Overall scheme, employed data sources and diagram of methodological processes involved in the study of *Pinus radiata* D. Don in El Bierzo

AREA OF STUDY

This study was carried out in the region of El Bierzo (NW Spain). This region is located in the northwestern corner of the autonomous community of Castilla y León, in the province of León (see **Figure 2.**). The area is an inland transitional area of about 2900 km^2 between the hilly topography towards the northern coastline and the open plain highlands of the inland plateau.

Heights vary gradually from about 2000 m in the encircling mountain chain to 500 m above sea level towards the central plain. This general distribution is broken up by transversal valleys.

The distribution of the parental rock directly affects soil characteristics and dynamics. Together with a milder climate, this makes the soils in the central depression deeper, very fertile and highly productive.

The mountains surrounding the area contribute to relatively constant climatic conditions, thereby creating local microclimates. Frosts are frequent from early November until late April, which certainly affects the growth of radiata pine. The yearly rainfall ranges from 600 to 1600 mm, higher in highlands and from west to east. Rainfall is seasonal and irregular, with three dry months (with less than 100 mm). Fog, mist and haze are favoured by the abrupt and irregular topography, keeping mean humidity levels constant throughout the year and providing an extra water supply during the dry season.

Height and climatic conditions in the area (unique convergence of mild temperatures and high precipitations in the Iberian Peninsula) make it the NW European limit of the transitional stripe between Eurosiberian and Mediterranean environments (**García 1995**), thus enhancing the ecological diversity and research interest of the area.

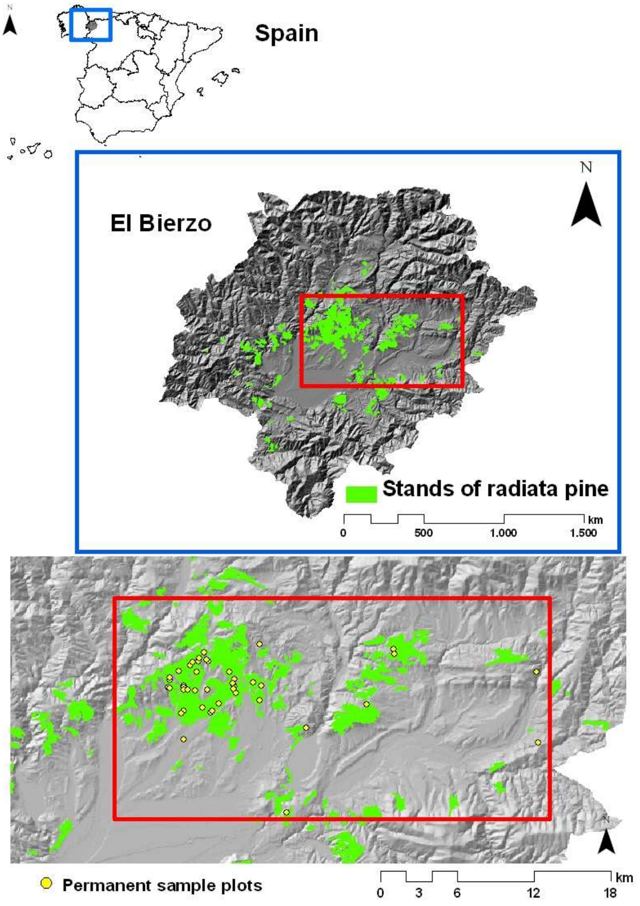

Figure 2. Area of study (El Bierzo, León, Spain)

Two bioclimatic diagrams representative of the range of heights, temperatures and rainfall in El Bierzo are given in **Figure 3a.** and **Figure 3b.**.

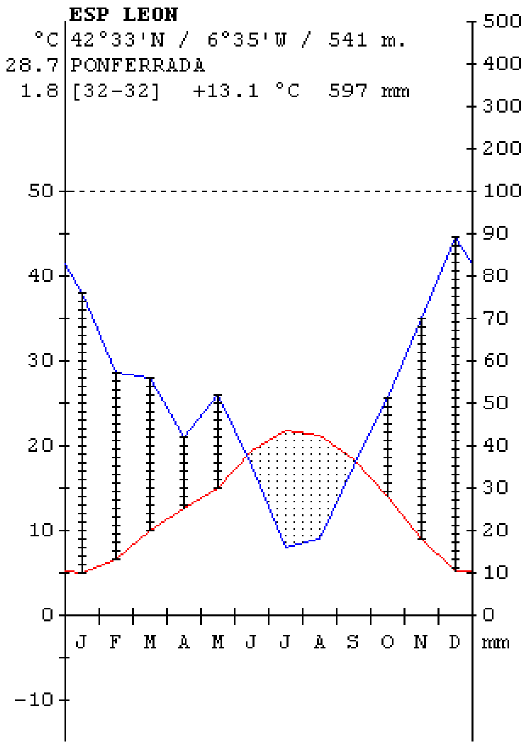

Figure 3a. Bioclimatic diagram representative of the central plain in El Bierzo (Location Ponferrada) (On the X axis: J=January, F=February, M=March, A=April, M=May, J=June, J=July, A=August, S=September, O=October, N=November, D=December)

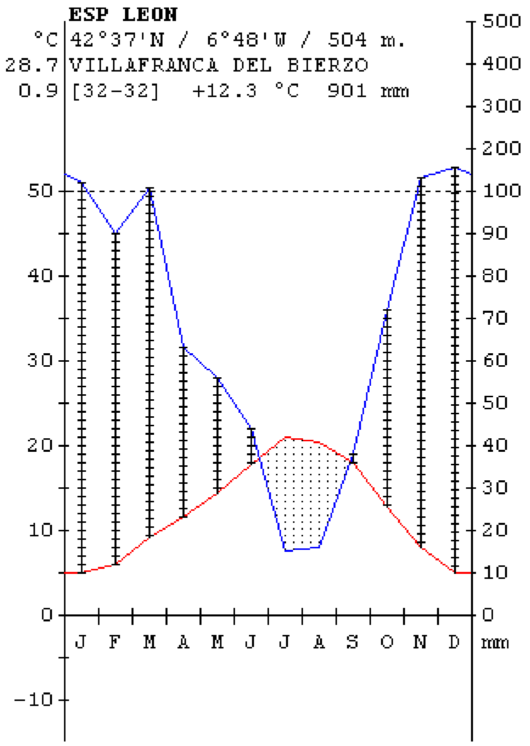

Figure 3b. Bioclimatic diagram representative of the transitional highlands in El Bierzo (Location Villafranca del Bierzo)

(On the X axis: J=January, F=February, M=March, A=April, M=May, J=June, J=July, A=August, S=September, O=October, N=November, D=December)

DATA SOURCES

The data used can be classified as field data obtained in the forest inventories and field environmental survey, RS data recorded by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Chinese-Brazilian Earth Resources Satellite (CBERS) Charge-Coupled Device (CCD) sensors and ancillary Geographic Information System (GIS) data, obtained from different sources.

1 Field data

The field dataset used was obtained from three different sources. Initially, during the early winter of 2003, a network of 45 permanent sample plots (PSP) was established by the University of León in pure radiata pine plantations in the area of study. The plots were located throughout the area of distribution of the species in the area of study, subjectively selected to cover adequately the existing range of ages, stand densities and sites. The plots were rectangular, and sized between 200 and 900 m^2 (mean size, 361.4 m^2), depending on stand density, to achieve a minimum of 50 trees per plot. Limits avoided stand border effects. A numbered label was nailed to the bark of every tree.

The measurements included the diameter at breast height (1.3 m above ground level) of each tree, which was measured twice (measurements made at right angles to each other) to the nearest 0.1 cm with callipers. The arithmetic mean of the two measurements was then calculated. Total height was measured to the nearest 0.1 m with a digital hypsometer (Vertex III) in a 30-trees randomized sample including the dominant trees. The number of dominant trees per plot was considered as the proportion of the 100 thickest trees per hectare (**Assmann 1970**), thereby depending on plot size. Descriptive variables of each tree were also recorded (e.g. if they were alive or dead, or affected by disease).

A subset of 32 of the remaining initially established plots was re-measured in the winter of 2006. These plots were selected for the dynamic components of the model. The interval between the measurements was considered sufficient to absorb the short-term effects of abnormal climatic extremes (**Gadow and Hui 1999**).

The first source of data was the two inventories carried out in 2003 and 2006. The stand variables calculated for each plot and inventory were: age (t, years), stand basal area (G), number of trees per hectare (N), square mean diameter (d_g), dominant height (H) defined by Assmann's rule (**Assmann 1970**) as the 100 thickest trees per hectare, and dominant diameter (D_0) was defined as the mean diameter of the dominant trees. The stand age was estimated by counting rings from samples extracted with a Pressler borer from the base (stump-level) of three trees per plot and by direct knowledge of the age of plantation.

Mean, maximum, minimum values and the respective standard deviations for each of the main stand variables measured in both inventories are shown in **Table 1.**.

Table 1. Summarised data corresponding to the sample of plots used for model development

	1^{st} inventory (45 plots)				2^{nd} inventory (32 plots)			
Variable	Mean	Min	Max	SD	Mean	Min	Max	SD
t (years)	16.4	7	33	6.2	19.7	10	36	6.5
G (m^2ha^{-1})	32.6	7.4	58.1	12.6	41.2	16.2	64.5	12.2
N (stems ha^{-1})	1702.7	400	2950	625.5	1600.9	400	2791.7	585.3
d_g (cm)	16.1	7.7	29.2	4.7	18.9	12.1	32.7	4.9
H (m)	16.8	6.6	26.5	5.5	19.8	10.3	28.8	5.5
D_0 (cm)	22.2	9.9	38.5	6.2	25.9	15.8	42.5	6.2

t = stand age; G = stand basal area; N = number of stems per hectare; d_g = quadratic mean diameter; H =dominant height; D_0 = dominant diameter. Min=minimum; Max=maximum; SD = standard deviation

In addition, one or two dominant trees were destructively sampled at 23 locations. These trees were selected as the first two dominant trees found outside the plots but in the same plantations within ± 5 % of the mean diameter at 1.3m above ground level and mean height of the dominant trees. The trees were felled to leave stumps of average height of 0.1 m; total bole length was measured to the nearest 0.1 m. The logs were cut at 1 or 2 m intervals. At each cross-sectional point, a representative mean diameter was measured and the number of rings was counted, and then converted to age above stump height.

As cross-section lengths do not match the periodic height growth, Carmean's method (**1972**) was used to adjust height-age data from stem analysis to account for this bias. Log volumes were calculated with Smalian's formula, and the top of the tree was considered as a cone. Tree volume above stump height was aggregated from the corresponding log volumes and the volume of the top of the tree.

Thus, the second source of data corresponds to the 41 felled trees, and allowed development of dominant height growth curves and total and merchantable volume equations (Chapter 1).

Summary statistics, including mean, maximum, minimum and standard deviation of each of the main trees variables are shown in **Table 2.**.

Table 2. Summarised data corresponding to the sample of 41 fallen trees used for model development

Variable	Mean	Minimum	Maximum	SD
d (cm)	20.7	10.5	34.4	5.3
h (m)	16.7	6.7	27.3	5.4
v (m^3)	0.312	0.033	0.947	0.220
t (years)	17.2	8	33	6.2
Observations per tree	12.8	9	17	2.1

d = diameter at breast height over bark; h = total tree height; v = total tree volume over bark above stump level; t = age; SD = standard deviation

As a component of the environmental field data base (Chapter 3), a subset of 20 of the permanent plots was randomly selected for soil sampling, considering sufficient spacing between plots thus assuring adequate covering of range of conditions for the species in the region. Edaphic variables calculation is related to this sample.

Soil samples were taken from a 2 m long-1m wide test pit. The digging point was selected near the plot centre, well within the stand to avoid edge effects, in an undisturbed surface. Soil depth was determined by hammering a steel nail into the soil until reaching either the bedrock level, compacted regolith or a maximum of 1.25 m instead. Soil profile was analyzed, identifying horizons and extracting subsamples of each horizon for the corresponding laboratory analyses (**Gandullo et al. 1991**).

All analyses were undertaken on air-dried mineral soil of the fine-earth fraction (<2 mm). These included: gravel and fine gravel percent (> 2 mm particles), thin particles percent (< 2 mm), textural analysis of thin earth (<2 mm) using the USDA triangle (**USDA 1975**) (e.i. sand > 50 μm particles, loess/mud/slime 2-50 μm particles, clay < 2 μm particles), organic oxidable carbon (oxidize) percent (**Walkley 1946**), soil pH (total and exchange acidity), total nitrogen percent following Kjeldahl methodology (**Bremner 1965**), assimilable phosphorus ppm following Olsen method and exchangeable cations (Ca^{2+} and Mg^{2+}) by atomic absorption spectrometry (**US Salinity Laboratory Staff 1954**).

For each horizon, the following variables were calculated: C/N relationship, cementation coefficient capacity (Ccc) as a function of organic matter, clay and fine-earth percents (**Gandullo 1985**), and silt impermeability coefficient (Sic) as a function of slime and fine earth percents (**Nicolás and Gandullo 1966**), permeability (Per) evaluated in five classes (**Gandullo 1985**), equivalent humidity (**Sánchez-Palomares and Blanco 1985**) in weight percent compared to fine earth fraction, water retention capacity (Wrc) as a function of slope, equivalent humidity (Eh), gravel percent and permeability between the corresponding horizon and the immediate horizon below (**Gandullo 1985**).

Physiographic factors measured in the sample plots included slope (expressed in %), aspect (determined by compass considering eight main wind directions of the compass rose), altitude (m above sea level measured with Global Positioning System –GPS-), superficial stoniness (% of rocks or gravel in plot surface classified in five intervals: less of 5%, between 5-25 %, 25-50%, 50-75%, more than 75%), superficial drainage (deficit, normal, excess following the classification of **Gandullo et al. 1991** considering plot surface), erosion (three qualitative classes following **Gandullo et al. 1991**) and a complementary description (e.g. valley, hillside).

The environmental data set includes also GIS climatic and topographic data that will be depicted in Chapter 3. Finally, three edaphoclimatic factors calculated (maximum real evapotranspiration, physiologic draught, calculated soil drainage) following **Sánchez-Palomares et al. (1999)** were also included in the study (Chapter 3). **Table 3.** shows the main descriptive statistics of the ecological parameters calculated from this data.

Finally, an extra field data source from an experimental radiata plot in New Zealand served to add information to the growth rates of the species as regards wood properties, stem form and branching patterns.

The Long Mile Nelder trial (RO2046) was planted in 1984 in Rotorua (New Zealand). The Nelder (**Nelder 1962**) is a circular shaped trial consisting of concentric 10 rings, each ring containing 60 spokes. An aerial look would give a picture like a bicycle wheel with 60 spokes and 10 rings **(Figure 4.**).

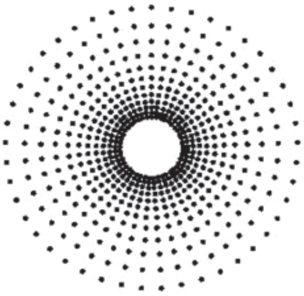

Figure 4. Plan of the Nelder stocking design experiment used. Trees are planted at each spot

The circles are at the following nominal stockings (stems ha^{-1}) from the centre out: 2500, 2047, 1666, 1362, 1104, 902, 738, 601, 489, and 400 stems ha^{-1}.

There are 5 different types of tree stocks: climbing select (unimproved), ‘870’ seedlings, ‘870’ cuttings, ‘268’ seedlings and ‘268’ cuttings (which will be referred to as respectively 268 and 870, c for cuttings and s for seedlings hereafter). Each of the 5 tree stock types were allocated to 2 circles, under the following restricted randomisation: each tree stock was to be in each semicircle of the trial, randomly allocated with the restriction that no tree stock was to be adjacent to the same tree stock. As regards management, the whole trial was subjected to an access pruning to two m when the branches had died, and has been left unthinned since. Only lately dangerously collapsing stems have been removed. Inventory data (following the standard field survey methods of New Zealand) of a sample of 177 stems constituted the data set to be analysed in Chapter 5.

Table 3. Descriptive statistics of ecological parameters

Physiographic parameters	Acronym	Mean	Maximum	Minimum	SD	CV(%)
Altitude (m)	Alt	743.59	921.0	549.0	101.53	13.65
Slope (%)	Slo	12.83	30.0	0	10.63	82.85
Superficial stoniness (1-5 categories)	Ss	1.24	2	1	0.43	34.68
Thermotopographic index	Tti	1.11	1.67	0.55	0.23	20.72
Climatic parameters	Acronym	Mean	Maxim	Minim	SD	CV(%)
Annual rainfall (mm)	Anr	875.71	1012.40	716.0	81.27	9.28
Spring rainfall (mm)	Spr	206.0	231.0	168.50	16.96	8.23
Summer rainfall (mm)	Smr	96.48	116.40	80.40	9.69	10.04
Autumn rainfall (mm)	Atr	242.61	270.30	207.0	18.0	7.42
Winter rainfall (mm)	Wr	326.65	369.50	279.10	26.37	8.07
Growing season rainfall (mm)	Gr	355.17	400.60	299.0	28.88	8.13
Mean annual temperature (ºC)	Mat	11.47	12.30	10.40	0.68	5.93
Mean maximum temperatures warmest month (ºC)	Max	27.07	28.4	25.6	0.67	2.48
Mean minimum temperatures coldest month (ºC)	Min	0.56	1.3	-0.2	0.41	73.21
Oscillation (ºC) = Max-Min	Osc	26.51	27.4	25.8	0.37	1.4
Sum of potential evapotranspiration (mm)	Etp	699.48	642.24	674.17	19.45	2.78
Water surplus (mm)	Sup	554.61	359.20	462.29	57.15	10.3
Water shortage (mm)	Def	300.10	222.92	264.16	25.37	8.45
Hydric index (mm)	Hi	65.20	26.35	45.39	11.71	17.96
Draught length (months)	Dl	2.30	1.40	1.94	0.32	13.91
Edaphic parameters	Acronym	Mean	Maximum	Minimum	SD	CV(%)
Upper horizons depth (cm)	D	67.9	115	28	23.2	34.17
Fine earth fraction (%)	Fef	51.33	86.51	28.46	17.39	33.88
Sand (%)	Snd	38.28	71.17	14.74	13.12	34.27
Silt (%)	Sli	33.33	52.30	15.95	8.51	25.53
Clay (%)	Cly	28.94	45.10	12.87	7.74	26.74
Cementation capacity coefficient	Ccc	0.66	1.75	0.25	0.40	60.61
Silt impermeability coefficient	Sic	0.18	0.44	0.05	0.09	50
Equivalent humidity (weight % related to Fef)	Eh	26.58	37.51	14.87	5.53	20.81
Permeability	Per	2.32	3.56	1.40	0.72	31.03
Water retention capacity (mm/m)	Wrc	229.37	477.64	37.58	93.27	40.66
Organic matter (%)	Om	3.26	18.48	0.45	3.86	118.4
Total acidity (pH)	Pha	4.88	5.44	4.48	0.28	5.74
Exchange acidity (pH)	Phe	3.86	4.09	3.66	0.11	2.85
Superficial nitrogen (%)	N	0.13	0.35	0.05	0.07	53.85
C/N relationship	CN	17.89	36.96	6.78	6.73	37.62
Phosphorus (mg/kg)	P	6.50	23.34	0.16	5.03	77.38
Calcium (cmol(+)/kg)	Ca	0.56	2.24	0.02	0.52	92.86
Magnesium (cmol(+)/kg)	Mg	0.31	1.06	0.04	0.33	106.45
Edaphoclimatic parameters	Acronym	Mean	Maxim	Minim	SD	CV(%)
Maximum real evapotranspiration (mm)	Retp	590.88	631.5	503.7	25.55	4.32
Physiologic draught (mm)	Pd	64.86	164.8	35.3	28.03	43.22
Calculated soil drainage (mm)	Sd	587.59	704.8	494.4	61.26	10.43

SD=standard deviation; CV(%)=coefficient of variation in percentage

2 RS data

The images to be used should be chosen above all regarding the date of the inventory data acquisition, as radiata pine is a fast growing species, in order to assure the veracity of the situation to be described. Other decisive factor, related to image processing capabilities, is weather conditions (mainly cloud cover). Due to scenes availability under such circumstances, two single scenes were finally selected. The focus of this work is on optical satellite RS in the visible spectral region and near infrared region (i.e. approximately in the range of 0.45–0.9 μm).

The RS resources for the study were: (i) an ASTER scene, and (ii) a CBERS CCD scene covering the area of study.

ASTER is a high resolution multispectral imager aboard National Aeronautics and Space Administration NASA´s TERRA platform. It covers a wide spectral region from the visible to the thermal infrared by 14 spectral bands (**Table 4.**). An ASTER level 1B scenes was collected on September 14th, 2003. Level 1B product contains radiometrically calibrated and geometrically coregistered data for all ASTER channels. Radiances are generated at 15 m, 30 m, and 90 m resolutions corresponding to the Visible and Near Infrared Radiometer (VNIR), Short Wave Infrared Radiometer (SWIR), and Thermal Infrared Radiometer (TIR) channels.

Calibrated, at-sensor radiances are given in W/(m ^{2} μm sr). The TIR channels were not used for this study.

In turn, CCD sensor is onboard the CBERS satellite. The scene was collected on November 4th, 2004.

CBERS CCD imagery has five spectral bands including three in the visible (0.45-0.69 μm, bands blue *B1*, green *B2*, and red *B3*) and one near infrared (0.77-0.89 μm, NIR band *B4*); a spatial resolution of 20 m, and a temporal resolution of 26 days nadir view (three days revisit). The images were acquired from the Instituto Nacional de Pesquisas Espaciais (INPE) Data Center. The correspondence of spectral reflectances and spatial resolutions recorded respectively by the ASTER and CBERS CCD sensors is displayed in **Table 4.**.

Table 4. Characteristics of the CBERS CCD and ASTER sensors data recording

Sensor	Subsystem	Notation	Band	Lengthwave range (μm)
ASTER	VNIR	*V1*	Green	0.52-0.60
		V2	Red	0.63-0.69
	(Spatial resolution 15 m)	*V3*	NIR	0.76-0.86
	SWIR	*S1*	Shortwave infrared radiometer	1600-1700
		S2		2145-2185
		S3		2185-2225
		S4		2235-2285
	(Spatial resolution 30 m)	*S5*		2295-2365
		S6		2360-2430
CBERS CCD	VNIR	*B1*	Blue	0.45-0.52
	(Spatial resolution 20 m)	*B2*	Green	0.52-0.59
		B3	Red	0.63-0.69
		B4	NIR	0.77-0.89
		P	Panchromatic	0.51-0.73

VNIR=Visible and Near Infrared Radiometer; SWIR=Short Wave Infrared Radiometer; NIR=Near Infrared

3 Ancillary GIS data

GIS are a potent tool for territorial analysis, allowing geospatial analysis, combination of field data sources, visual inspection of results, mapping of outcomes, etc. In fact, the use of satellite imagery alone is not as powerful or accurate as when it is combined with ancillary GIS field data (**Green et al. 1994**), enhancing data analysis capabilities.

A GPS was used to accurately locate the coordinates of the permanent plot network of radiata pine (Universal Transverse Mercator -UTM- system, European Datum ED50-29N). This resulted in a GIS shapefile (i.e. points layer) (Chapters 3 and 4).

Additionally, high quality ortophotographies (0.25 m spatial resolution) were available. A total of 15 ground control points were selected from these to adequately verify the geometry and co-registrate RS scenes to the ground data. Besides, ortophotographies assisted in the definition of the endmember spectra used during the unmixing process of the RS image (Chapter 4). In this respect, an extra useful source was a digital terrain model DTM (50 m spatial resolution) assisted topographic corrections to the ASTER scene (Chapter 4).

The forest stand, or compartment, is an area of relatively homogeneous forest attributes and it is typically the smallest unit in the forest management (**Koivuniemi and Korhonen 2006**). The stands are handled as polygons in GIS.

This in mind, another digital data source was also used: the National Forestry Map (MFN) (**DGCN 2000**). In particular, a polygon layer of radiata stands was extracted, imposing radiata pine as main species (which assures that above 90% of the stems in the stands are radiata stems). This layer was overlaid to the RS scenes, permanent plots shapefile and ortophotos to contrast spatial resolutions and guarantee consistency of the complete set of georeferenced data. Moreover, this layer turned out to be helpful in indentification of the species in RS scenes (Chapter 4), thus avoiding classification procedures uncertainties which normally affect such applications (**Cihlar 2000**) (e.g. subjectivity and poor reproducibility).

Specific georeferenced layers were used to complete the environmental data set in Chapter 3. The DTM (50 m spatial resolution) integrated topographic parameters in the geospatial analysis performed. Also, climatic data for each plot were extracted from the Digital Atlas of the Iberian Peninsula (**Ninyerola et al. 2005**). This consists in several layers elaborated by the integration of climatic data from meteorology stations into a DTM combining statistical and spatial interpolation techniques in a GIS, thus enabling estimation of monthly temperatures and rainfalls dependent on altitude and geographic location for every pixel. The values of mean monthly temperatures and precipitation amounts provided by the Digital Atlas were obtained for each site from long-term (30–40 years) weather records from the closest weather stations.

All these sources combined, contributed to the global precision of the study, assuring correspondence between digital data, RS data recorded and field surveys, thereby easing steps like image processing.

CHAPTER 1. Development of a dynamic growth model for *Pinus radiata* D. Don plantations in El Bierzo

1 Introduction

Although radiata pine was introduced in the region of El Bierzo relatively recently, it currently occupies an area of approximately 15 000 ha (**Fernández-Manso et al. 2001**). The oldest stands in the region were planted in the 1970s, with seeds initially obtained from nearby areas, such as Galicia.

These stands were originally destined for production of mining timber, and were therefore planted at high densities and managed in short rotations (approximately 15 years); silvicultural practices were rarely carried out. Mining activities have now declined and trends are changing towards extended rotations and enhancement of silviculture practices. These afforestations introduced the species for the first time in a typical inland region of Spain, where Mediterranean and Eurosiberian conditions meet.

Most of the region is a rural marginal area in which forestry is becoming a highly recommended type of land use. Radiata plantations would certainly help to meet the challenges threatening the area (land abandonment, mine restructuring, decline of traditional economy and of population), thus contributing to sustainable development.

1.1 Forest growth models

Forest management decisions are based on information about current and likely future forest conditions. Consequently, it is often necessary to predict the changes in the system with growth and yield models, which estimate forest dynamics over time. Such models have been widely used in forest management because they enable updating of inventories, prediction of future yields, and exploration of management alternatives, thus providing information for decision-making in sustainable forest management (**Falçao and Borges 2005, Vanclay 1994**).

The wide range of forest growth models available differ in complexity and the detail in which they describe the systems under consideration. At one end of the range are the traditional empirical models based on periodic tree measurements, which make no attempt to measure all factors that may affect tree growth, and at the other end the complex process models, based on the mechanisms inherent to growth, which incorporate a large amount of information in the response functions.

Of the two basic types of empirical models (whole-stand and individual-tree models), whole-stand models are generally recommended when dealing with homogeneous, even-aged, pure stands (**Vanclay 1994, García 1993, 1988**), because they can be constructed on the basis of variables often available in forest inventory data, and also represent a good compromise between generality and accuracy of the estimates.

Whole-stand models characterize the state of the stand by means of a small number of aggregate variables, such as basal area, mean diameter, volume per hectare, stems per hectare, average spacing or top height. (**García 1993**). This type of models therefore require few details for growth simulation. On the other hand, they provide rather limited information about the future stand (in some cases only stand volume) (**Vanclay 1994**).

To overcome underlying limitations, whole-stand models can be disaggregated mathematically using a diameter distribution function, which may be combined with a generalized height-diameter equation and with a taper function to estimate commercial volumes. Similar methodologies have been used by **Castedo-Dorado et al. (2007), Diéguez-Aranda et al. (2006), Kotze (2003), Trincado et al. (2003) and Mabvurira et al. (2002)** in the development of forest growth models for plantations.

On the other hand, a recently developed whole-stand model for radiata pine stands is in use in the neighbouring region of Galicia (**Castedo-Dorado et al. 2007**). This model was developed with data from 225 inventories of permanent plots and it was demonstrated to be robust for medium term projections of stand volume. Nevertheless, it produces biased estimates when applied to the local data from the El Bierzo region, as explained in subsequent sections in this study. For this reason, an attempt was made to localize the already fitted model, so that it can be applied to El Bierzo without the need to develop a new model.

Most adaptation procedures fall into one of three categories (**Huang 2002**): the parameter re-estimation method, the proportional adjustment method or the regression adjustment method. According to **Huang (2002)**, the most desirable approach for localizing any model is to refit the individual components (submodels) with local data. Therefore, the structure of the model adopted in this study was the same as that described by **Castedo-Dorado et al. (2007)**. The same submodels were considered (and in most cases the same base equations), and a new set of parameters were re-estimated from the local data.

Objective

The objective of this chapter was to develop a management-oriented whole-stand model for simulating the growth of radiata pine plantations in El Bierzo. The model is constituted by the same interrelated modules as those developed for the Galician model: a site quality system (both for dominant height growth and site index prediction), an equation for reducing tree number, a stand basal area growth function, and a disaggregation system composed of a diameter distribution function, a generalized height-diameter function and a total merchantable volume equation.

2 Methods

2.1 Model structure, model development and model fitting

2.1.1 Model structure

The proposed whole-stand growth model is based on the state-space approach (**Vanclay 1994**), which makes use of state variables to characterize the system at an initial stage, and transition functions to project all or some of the state variables in the future. In addition, it should be possible to estimate other variables of interest from the current values of the state variables through the so-called output functions (**García 2003, 1994**).

The state of a system at any given time may be roughly defined as the information needed to determine the behaviour of the system from that time on; i.e. given the current state, the future does not depend on the past.

According to **García (1994)**, and considering that we are dealing with single-species stands derived from plantations in which different management regimes have been carried out, three state variables (dominant height, number of trees per hectare and stand basal area) are needed to define the stand conditions at any point in time.

To project the future stand state, the model uses three transition functions of the corresponding state variables. Once the state variables are known for a given time, the model is disaggregated mathematically by use of a diameter distribution function, which is combined with a generalized height-diameter equation and with a taper function to estimate total and merchantable stand volumes.

2.1.2 Development and fitting of transition functions for state variables

Transition functions must possess some important properties to provide consistent estimates: (i) consistency, i.e. no change for zero elapsed time; (ii) path-invariance, i.e. the result of projecting the state first from instant t_0 to t_1, and then from t_1 to t_2, must be the same as that of the one-step projection from t_0 to t_2; and (iii) causality, i.e. a change in status can only be influenced by inputs within the relevant time interval (**García 1994**).

Transition functions generated by integration of differential equations (or summation of difference equations when using discrete time) automatically satisfy these conditions. More precisely, we attached to techniques of dynamic equation derivation, known in forestry as the Algebraic Difference Approach (ADA) (**Bailey and Clutter 1974**) or its generalization (generalized algebraic difference approach GADA) (**Cieszewski and Bailey 2000**).

Dynamic equations have the general form (omitting the vector of model parameters) $Y = f\left(t, t_0, Y_0\right)$, where Y is the value of the function at age t, and Y_0 is the reference variable defined as the value of the function at age t_0. The ADA essentially involves replacing a base-model site-specific parameter with its initial-condition solution. The GADA allows expansion of the base equations according to various theories about growth characteristics (e.g. asymptote, growth rate), thereby allowing more than one parameter to be site-specific and allowing the derivation of more flexible dynamic equations (**see Cieszewski 2003, 2002, 2001**).

More details about ADA and GADA derivation can be viewed in **Cieszewski and Bailey (2000)** and **Cieszewski (2002)**. The ADA or GADA can be applied in modelling the growth of any site dependent variable involving the use of unobservable variables substituted by the self-referencing concept (**Northway 1985**) of model definition (**Cieszewski 2004**), such as stand height, number of trees per unit area, stand basal area, stand volume, stand biomass or stand carbon sequestration.

In the present study, dynamic equations with one and two site-specific parameters were tested. For projecting the state variables dominant height and stand basal area, we focused our efforts on the six dynamics equations used by **Barrio et al. (2008, 2006)** for modelling the growth of these variables for maritime pine and poplar plantations. These equations are derived from three well-known growth functions (**Bertalanffy-Richards – Richards 1959, Bertalanffy 1957, 1949, Korf –cited in Lundqvist 1957– and Hossfeld –Hossfeld 1882**–) and have been widely used in modelling stand height and stand basal area growth (e.g. **Diéguez-Aranda et al. 2005, Cieszewski 2002, Tomé et al. 2001, Falcao 1997, Amaro et al. 1997, McDill and Amateis 1992**).

The formulations of the equations analysed (M1-M6) are shown in **Table 1.1**. As general notational convention, a_1, a_2,…, a_n were used to denote parameters in base models, while b_1, b_2,…, b_m were used for global parameters in subsequent GADA formulation.

Table 1.1. Base models and ADA/GADA formulations considered for dominant height and stand basal area growth modelling

Base equation	Parameter related to site	Solution for *X* with initial values (t_0,Y_0)	Dynamic equation	Model
Korf: $Y = a_1 \exp\left(-a_2 t^{-a_3}\right)$	$a_2 = X$	$X_0 = -\ln\left(\frac{Y_0}{a_1}\right) t_0^{\,a_3}$	$Y = b_1 \left(\frac{Y_0}{b_1}\right)^{\left(\frac{t_0}{t_1}\right)^{b_2}}$	(M1)
	$a_1 = \exp(X)$ $a_2 = b_1 + b_2 / X$	$X_0 = \frac{1}{2} t_0^{-b_3} \left(b_1 + t_0^{\,b_3} \ln(Y_0) \pm \sqrt{4 b_2 t_0^{\,b_3} + \left(-b_1 - t_0^{\,b_3} \ln(Y_0)\right)^2} \right)$	$Y = \exp(X_0) \exp\left(-\left(b_1 + b_2 / X_0\right) t^{-b_3}\right)$	(M2)
Hossfeld: $Y = \frac{a_1}{1 + a_2 t^{-a_3}}$	$a_2 = X$	$X_0 = t_0^{-a_3} \left(\frac{a_1}{Y_0} - 1 \right)$	$Y = b_1 / \left(1 - \left(1 - b_1 / Y_0\right)\left(t_0 / t\right)^{b_2}\right)$	(M3)
	$a_1 = b_1 + X$ $a_2 = b_2 / X$	$X_0 = \frac{1}{2}\left(Y_0 - b_1 \pm \sqrt{(Y_0 - b_1)^2 + 4 b_2 Y_0 t_0^{-b_3}}\right)$	$Y = \frac{b_1 + X_0}{1 + b_2 / X_0 \, t^{-b_3}}$	(M4)
Bertalanffy-Richards: $Y = a_1 \left(1 - \exp(-a_2 t)\right)^{a_3}$	$a_2 = X$	$X_0 = -\ln\left(1 - (Y_0 / b_1)^{1/b_2}\right) / t_0$	$Y = b_1 \left(1 - \left(1 - \left(\frac{Y_0}{b_1} \right)^{1/b_2} \right)^{t/t_0} \right)^{b_2}$	(M5)
	$a_1 = \exp(X)$ $a_3 = b_2 + b_3 / X$	$X_0 = \frac{1}{2}(\ln Y_0 - b_2 L_0 + \sqrt{(\ln Y_0 - b_2 L_0) - 4 b_3 L_0})$ $L_0 = \ln(1 - \exp(-b_1 t_0))$	$Y = Y_0 \left(\frac{1 - \exp(-b_1 t)}{1 - \exp(-b_1 t_0)} \right)^{(b_2 + b_3 / X_0)}$	(M6)

In addition, a dynamic equation was developed for predicting the reduction in tree number due to density-dependent mortality, which is mainly caused by competition for light, water and soil nutrients within a stand. Although many functions have been used to model empirical mortality equations, only biologically-based functions derived from differential equations include the set of properties that are essential in a mortality model (**Clutter et al. 1983**): consistency, path invariance and asymptotic limit of stocking approaching zero as old ages are reached.

In the present study, an equation for estimating reduction in tree number was developed on the basis of a differential function in which the relative rate of change in the number of stems is proportional to an exponential function of age:

$$\frac{dN/dt}{N} \equiv \alpha N^{\beta} \delta^{t} \tag{1}$$

where *N* is the number of trees per hectare at age *t* and α, β and δ are the model parameters.

This function was selected by **Álvarez et al. (2004)** and **Castedo-Dorado et al. (2007)** to develop an equation in difference form for estimating reduction in stem number. In the present study, a dynamic equation was developed on the basis of this differential equation by use of the ADA, considering *α* as the site-specific parameter.

The individual trends observed in dominant height, number of trees per hectare and stand basal area data from the plots can be modelled by considering that individuals' responses all follow a similar functional form with parameters that vary among individuals (local parameters) and parameters that are common for all individuals (global parameters).

Following **Cieszewski et al. (2000),** we estimated the random site-specific effects simultaneously with the fixed effects using a base-age invariant (BAI) parameter estimation technique: the dummy variables method. This technique has been used in several other studies in fitting growth functions for these stand variables (e.g. **Barrio et al. 2008, 2006, Castedo-Dorado et al. 2007, Diéguez-Aranda et al. 2005**).

In the general formulation of the dynamic equations, the error terms are assumed to be independent and identically distributed with zero mean. Nevertheless, because of the longitudinal nature of the data sets used for model fitting, correlation between the residuals within the same individual (plot or tree) may be expected.

This problem may be especially important in the development of the dominant height dynamic model on the basis of data from stem analysis, because of the number of measurements corresponding to the same tree. Nevertheless, in the construction of the dynamic equations for reduction in tree number and for basal area growth, which implies the use of data from the first and second inventory of 32 plots, the maximum number of possible time correlations among residuals is practically inexistent, and therefore the problem of autocorrelated errors can be ignored in the fitting process.

To overcome the possible autocorrelation, we modelled the error terms using a continuous time autoregressive error structure (CAR(*x*)), which allows the model to be applied to irregularly spaced, unbalanced data (**Zimmerman and Núñez-Antón 2001, Gregoire et al. 1995**). To evaluate the presence of autocorrelation and the order of the CAR(x) to be used, graphs representing residuals plotted against lag-residuals from previous observations within each tree or plot were examined visually. The dummy variables method and the CAR(*x*) error structure was programmed by use of the SAS/ETS® MODEL procedure (**SAS Institute Inc 2004**), which allows for dynamic updating of the residuals.

2.1.3 Disaggregation system

Diameter distribution

Among the parametric density functions that have been used to describe the diameter distribution of a stand (e.g. Charlier, Normal, Beta, Gamma, Johnson S_B, Weibull), the Weibull function is the most frequently used, because of its flexibility and simplicity (**Merganic and Sterba 2006, Palahí et al. 2006, Cao 2004**). Expression of the Weibull density function is:

$$f(x) = \left(\frac{c}{b}\right)\left(\frac{x-a}{b}\right)^{c-1} e^{-\left(\frac{x-a}{b}\right)^{c}} \qquad (2)$$

where *x* is the random variable, *a* the location parameter defining the origin of the function, *b* the scale parameter and *c* the shape parameter controlling the skewness.

Of the two basic methodologies used to obtain the Weibull parameters (parameter estimation and parameter recovery), we used the parameter recovery approach, because as stated by several authors (e.g. **Parresol 2003, Torres-Rojo et al. 2000, Borders and Patterson 1990, Cao et al. 1982**) it provides better results than parameter estimation, even in long-term projections. To recover the Weibull parameters we used the moments-based parameter recovery method (**Burk and Newberry 1984**) because it directly warrants that the sum of the disaggregated basal area obtained by the Weibull function equals the stand basal area provided by an explicit growth function of this variable, resulting in numeric compatibility (e.g. **Frazier 1981**).

In the moments method, the parameters of the Weibull function are recovered from the first three order moments of the diameter distribution (i.e. the mean, variance and skewness coefficient, respectively). Alternatively, the location parameter (*a*) may be set to zero. The use of this condition restricts the parameters of the Weibull function to two, therefore making it both easier to model and providing similar results to the three-parameter Weibull, at least for even-aged, single-species stands (**Mabvurira et al. 2002, Maltamo et al. 1995**). To recover parameters *b* and *c* the following expressions were used:

$$\mathrm{var} = \frac{\bar{d}^{2}}{\Gamma^{2}\left(1+\frac{1}{c}\right)}\left[\Gamma\left(1+\frac{2}{c}\right) - \Gamma^{2}\left(1+\frac{1}{c}\right)\right] \qquad (3)$$

$$b = \frac{\bar{d}}{\Gamma\left(1 + \frac{1}{c}\right)} \quad (4)$$

where $\bar{d}$ is the arithmetic mean diameter of the observed distribution, var is its variance and Γ the Gamma function.

Once the mean and the variance of the diameter distribution are known, while taking into account that Equation 3 only depends on parameter *c*, the latter can be obtained by iterative procedures. Subsequently, parameter *b* can be calculated directly from Equation 4. As the disaggregation system is developed for inclusion in a whole-stand growth model, only the arithmetic mean diameter requires to be modelled, and the variance is directly obtainable from the arithmetic and the quadratic mean diameter (d_g) by use of the relationship

$$\mathrm{var} = d_g^2 - \bar{d}^2$$

Hence, the arithmetic mean diameter was modelled with Equation 5, which ensures that predictions of $\bar{d}$ are lower than d_g:

$$\bar{d} = d_g - e^{\mathbf{X}\beta} \quad (5)$$

Where $\mathbf{X}$ is a vector of explanatory variables (e.g. dominant height, number of trees per hectare, age) that define the state of the stand at a specific point in time and must be obtained from any of the functions of the stand growth model and β is a vector of parameters to be estimated.

A diagram of the disaggregation system including all the components proposed in the present study is reported by **Diéguez-Aranda et al. (2006)**.

Height estimation for diameter classes

Once the diameter distribution is known, the next step is the estimation of the height of the average tree in each diameter class. Since the height-diameter relationship varies from stand to stand due to heterogeneous site conditions and silviculture state, and is not constant over time even within the same stand (**Assmann 1970**), we used a generalized *h-d* model which takes into account stand variables that introduce the dynamics of each stand into the model (e.g. **Gadow and Hui 1999, Curtis 1967**).

The generalized *h-d* model used in the present study was a modification proposed by **Castedo-Dorado et al. (2006, 2005a)** on the basis of the **Schnute (1981)** function, by forcing it to pass through point (0, 1.3), to prevent negative height estimates for small trees, and to predict the dominant height of the stand (*H*) when the diameter at breast height of the subject tree (*d*) equals the dominant diameter of the stand (D_0).

Parameter estimates were obtained by ordinary least squares, by application of the Gauss-Newton's iterative method of the SAS/STAT® NLIN procedure (**SAS Institute Inc 2004a)**.

Total and merchantable volume estimation

Once the diameter and height of the average tree in each diameter class are estimated, the total tree volume can be calculated directly by use of a volume equation. Since volume prediction to any merchantable limit is usually required, a taper equation can be used. Integration of a taper equation from the ground to any height provides an estimate of the merchantable volume to that height (**Kozak 2004**).

Ideally, a volume estimation system should be compatible, i.e. the volume computed by integration of the taper equation from the ground to the top of the tree should be equal to that calculated by a total volume equation (**Clutter 1980, Demaerschalk 1972**). The total volume equation is preferred when classification of the products by merchantable sizes is not required, thereby simplifying the calculations and making the method more suitable for practical purposes.

A compatible system was fitted with data corresponding to diameter at different heights and total stem volume from 41 destructively sampled trees. To correct the inherent autocorrelation of the hierarchical data used, the error term was expanded by use of an autoregressive continuous model. The presence of autocorrelation and the order of the CAR(x) to be used were examined as explained in Section 2.1.2.

The compatible volume system of **Fang et al. (2000)** was used in this study because it was found to be very suitable for describing the stem profile and predicting stem volume for different species in several stand structures and regions (**Corral et al. 2007, Diéguez-Aranda et al. 2006a**), including *Pinus radiata* (**Castedo-Dorado et al. 2007**). The fittings were carried out by use of the SAS/ETS® MODEL procedure (**SAS Institute Inc 2004**), which allows for dynamic updating of the residuals.

Aggregation of total (*v*) or merchantable (v_i) tree volume times number of trees in each diameter class provides total (*V*) or merchantable stand volume (V_i), respectively.

2.2. Selection of the best equation in each module

Comparison of the estimates of the different models fitted in each module was based on numerical and graphical analyses. Two statistical criteria obtained from the residuals were examined: the coefficient of determination for nonlinear regression (pseudo-R^2), showing the proportion of the total variance of the dependent variable explained by the model (**Ryan 1997**), and the root mean square error (RMSE), which analyses the accuracy of the estimates.

Other important step in evaluating the models was graphical analysis of the residuals and examination of the appearance of the fitted curves overlaid on the trajectories of the dependent variables for each plot. Visual or graphical inspection is an essential point in selecting the most appropriate model because curve profiles may differ drastically, even though fit statistics and residuals are similar (e.g. **Huang et al. 2003**).

2.3 Overall evaluation of the whole-stand model

Although the behaviour of individual sub-models within the model plays an important role in determining the overall outcome, the validity of each individual component does not guarantee the validity of the overall outcome, which is usually considered more important in practice. The overall model outcome must therefore also be evaluated.

The only method that can be regarded as "true" validation involves the use of a new independent data set (**Yang et al. 2004, Kozak and Kozak 2003, Vanclay and Skovsgaard 1997**) However, as new independent data for model validation were not available, only an evaluation of the predictive ability of the overall whole-stand model was carried out.

For that purpose, observed state variables from the first inventory of the 32 plots measured twice were used to estimate total stand volume at the age of the second inventory, including all the components of the whole-stand model. It must be taken into account that total stand volume is the critical output variable of the whole model, since its estimation involves all the functions included and is important in economic assessments.

In order to assess whether the variance of the predictions is within some tolerance limits, the critical error statistic ($E_{crit.}$) was used. The critical error is expressed as a percentage of the observed mean and is computed by re-arranging Freese's χ_n^2 statistic (**Robinson and Froese 2004, Reynolds 1984**):

$$E_{crit.} = \frac{\sqrt{\tau^2 \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 \Big/ \chi^2_{crit.}}}{\bar{y}} \qquad (6)$$

where *n* is the total number of observations in the data set, y_i is the observed value, $\hat{y}_i$ the value predicted from the fitted model, $\bar{y}$ is the average of the observed values, τ is a standard normal deviate at the specified probability level ($\tau = 1.96$ for $\alpha = 0.05$), and $\chi^2_{crit.}$ is obtained for $\alpha = 0.05$ and *n* degrees of freedom.

If the specified allowable error expressed as a percentage of the observed mean is within the limit of the critical error, the χ_n^2 test indicates that the model does not give satisfactory predictions; the contrary result indicates that the predictions are acceptable.

In addition, plots of observed against predicted values of stand volume were inspected. If a model is good, the slope of the regression line between observed and predicted values should pass through the origin at 45º.

3 Results

3.1 Transition function for state variables

Among all the equations tested, model M4, the GADA form derived from the Hossfeld base equation was selected for height growth prediction and site classification (Equation 7)

$$H = \frac{27.45 + X_0}{1 - 1851.5 / X_0 \, t^{-1.522}} \qquad (7)$$

$$X_0 = \tfrac{1}{2}\left(H_0 - 27.45 + \sqrt{(H_0 - 27.45)^2 + 7406 H_0 t_0^{-1.522}} \right)$$

where H_0 and t_0 represent the predictor dominant height (metres) and age (years) respectively, and *H* is the predicted dominant height at age *t*.

This function explained 99.35 % of the total variance of the data, and the value of the RMSE was 0.604 m. This model also showed adequate graphical behaviour, as it produced the most adequate height growth curves (**Figure 1.1a**) with a random pattern of residuals around zero with homogeneous variance and no discernable trend (**Figure 1.1b**).

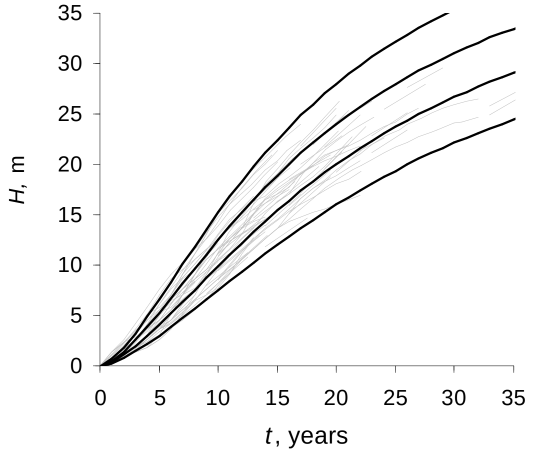

Figure 1.1a Curves for site indices of 16, 20, 24 and 28 m at a reference age of 20 years overlaid on the trajectories of observed values over time (same tree or plot measurements joined by lines)

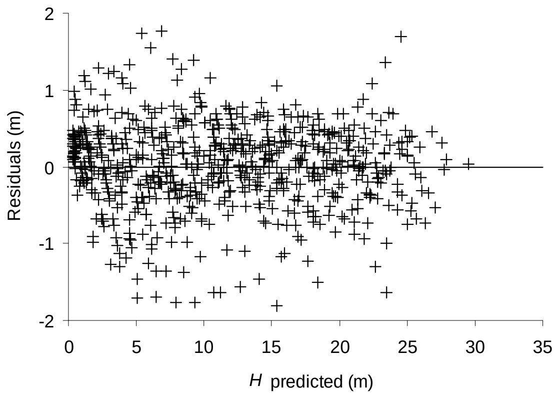

Figure 1.1b Pattern of residuals versus predicted values

As regards the transition function for reduction in tree number, a dynamic equation considering only one parameter to be site specific in the base model (Equation 8) described the data appropriately, providing the best results:

$$N = \left[N_0^{-1.366} + 1.169^{(t - 100)} - 1.169^{(t_0 - 100)} \right]^{\frac{1}{-1.366}} \quad (8)$$

where N_0 and t_0 represent the predictor number of trees per hectare and age (years), and *N* is the predicted number of trees per hectare at age *t*.

Equation 8 explained 99.12 % of the total variance of the data and the RMSE was 57.02 trees/ha. The trajectories of observed and predicted number of trees over time for different initial density conditions are shown in **Figure 1.2a**. The corresponding pattern of residuals is showing **Figure 1.2b**.

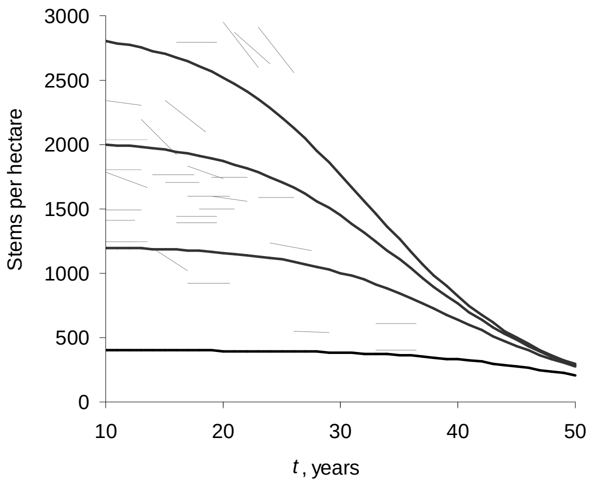

Figure 1.2a Trajectories of observed and predicted stem number over time. Model projections for initial stocking densities of 400, 1200, 2000 and 2800 stems per hectare at 10 years. Same plot measurements joined by lines

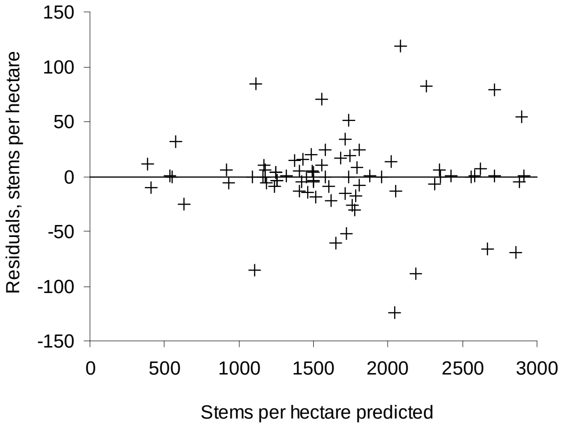

Figure 1.2b Pattern of residuals versus predicted values

Regarding the transition function for stand basal area growth, among all the equations tested, model M5, derived from the Bertalanfy-Richards function solved by parameter a_2 provided the best results for the statistics used for comparison ($R^2 = 0.982$; RMSE = 1.74 $m^2 ha^{-1}$), and provided a random pattern of residuals around zero (**Figure 1.3a** and **Figure 1.3b**). Moreover, the graphical analysis of the stand basal area growth curves overlaid on the trajectories of the observed values over time showed an adequate and biological behaviour. The model is expressed as follows (Equation 9):

$$G = 88.7\left(1-\left(1-\left(\frac{G_0}{88.7}\right)^{1/3.07}\right)^{t/t_0}\right)^{3.07} \qquad (9)$$

where G_0 and t_0 represent the predictor stand basal area ($m^2 ha^{-1}$) and age (years), and *G* is the predicted stand basal area at age *t*.

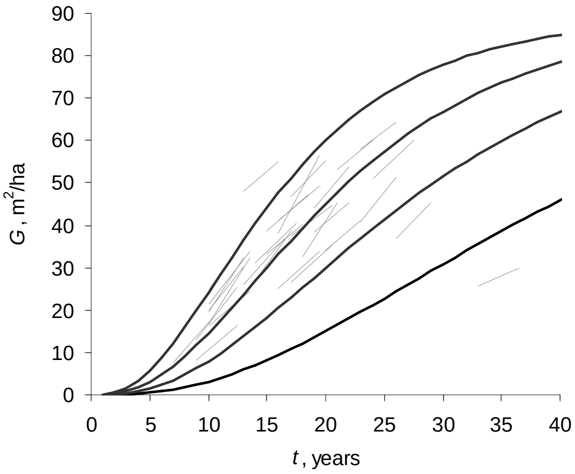

Figure 1.3a Stand basal area growth curves for stand basal areas of 15, 30, 45 and 60 $m^2 ha^{-1}$ at 20 years overlaid on the trajectories of observed values over time. Same plot measurements joined by lines

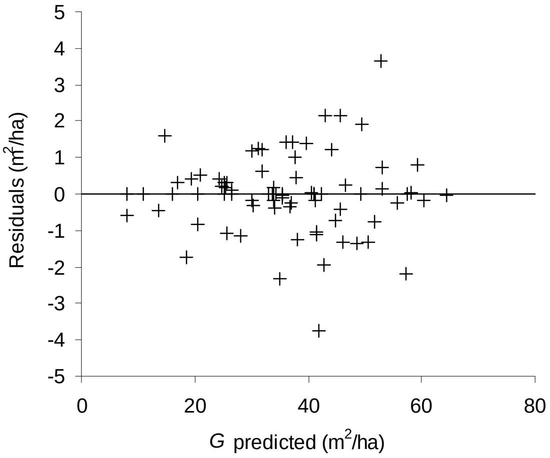

Figure 1.3b Pattern of residuals versus predicted values

Application of the function for projecting stand basal area (*G*) requires an initial value of *G* at a given age, which may be obtained from diameter at breast height data. If this is not available, it must be estimated from other stand variables by use of an initialization equation.

Following the methods of several authors (e.g. **Amateis et al. 1995**), we analysed several linear and nonlinear models with different explanatory stand variables (age, dominant height, site index, number of trees per hectare, relative spacing index, and combinations of these variables). Only data from 25 inventories, corresponding to ages younger than 15 years, were used, assuming that if projections based on ages older than this threshold are required, the initial stand basal area should be obtained directly from inventory data. A linear model with relative spacing index as independent variable behaved best. This model explained 76.4% of the total variance of the data, with a RMSE of 4.70 m^2 ha^{-1}.

The model obtained has the following form (Equation 10):

$$G_0 = 53.97 - 1.318 RS \qquad (10)$$

where G_0 is the predicted stand basal area (m^2 ha^{-1}) at a certain time, and *RS* is the relative spacing index in percentage.

The parameters of the stand basal area initialization function and of the three transition functions for the state variables were significant at a probability level of 0.05.

3.2 Disaggregation system

The equation selected for predicting arithmetic mean diameter and for use in the parameter recovery approach was:

$$\bar{d} = d_g - e^{\left(0.463 - 18.9 \frac{1}{t}\right)} \qquad (11)$$

where $\bar{d}$ is the predicted arithmetic mean diameter (cm), d_g the quadratic mean diameter (cm) and *t* the stand age (years). The goodness of fit statistics were $R^2 = 0.998$ and RMSE = 0.168 cm.

The Kolmogorov-Smirnov test was used to compare the actual diameter distribution at the end of the projection interval with the distribution estimated by the moments method. The null-hypothesis tested was that an estimated distribution corresponds to the real distribution. In accordance with the results of similar studies, a significance level of 20% and a diameter class of one cm were considered. The results of the test showed that only one of the 32 diameter distributions estimated by the moments-based parameter recovery method was rejected.

Once the diameter distribution is known, the following generalized *h-d* relationship derived from the Schnute function was selected to estimate the height of the average tree in each diameter class:

$$h = \left[1.3^{1.9962} + \left(H^{1.9962} - 1.3^{1.9962}\right) \times \frac{1 - e^{-0.0309d}}{1 - e^{-0.0309D_0}}\right]^{\frac{1}{1.9962}} \qquad (12)$$

where *h* is the predicted total height (m) of the subject tree, *d* its diameter at breast height (cm), and D_0 (cm) and *H* (m) are the mean diameter and mean height of the 100 thickest trees per hectare, respectively, of the stand where the subject tree is included.

This model showed a high predictive ability ($R^2 = 0.934$; RMSE = 1.474 m) and is very parsimonious because it only depends on two stand variables.

Finally, for total and merchantable volume diameter class, the compatible system based on the model developed by **Fang et al. (2000)** was fitted. This system is constituted by the following components:

Taper function:

$$d_i = c_1\sqrt{h^{(k-b_1)/b_1}\left(1-q_i\right)^{(k-\beta)/\beta}\alpha_1^{I_1+I_2}\alpha_2^{I_2}} \qquad (13)$$

Where $\begin{cases} I_1 = 1 \text{ if } \; p_1 \le q_i \le p_2;\, 0 \text{ otherwise} \\ I_2 = 1 \text{ if } \; p_2 < q_i \le 1;\, 0 \text{ otherwise} \end{cases}$

p_1 and p_2 are relative heights from ground level where the two inflection points assumed in the model occur

$$\beta = b_1^{1-(I_1+I_2)} b_2^{I_1} b_3^{I_2}$$

$$\alpha_1 = \left(1-p_1\right)^{\frac{(b_2-b_1)k}{b_1 b_2}}$$

$$\alpha_2 = \left(1-p_2\right)^{\frac{(b_3-b_2)k}{b_2 b_3}}$$

$$r_0 = \left(1-h_{st}/h\right)^{k/b_1}$$

$$r_1 = \left(1-p_1\right)^{k/b_1} \qquad r_2 = \left(1-p_2\right)^{k/b_2}$$

$$c_1 = \sqrt{\frac{a_0 d^{a_1} h^{a_2-k/b_1}}{b_1\left(r_0-r_1\right)+b_2\left(r_1-\alpha_1 r_2\right)+b_3\alpha_1 r_2}}$$

Merchantable volume equation:

$$v_i = c_1^2 h^{k/b_1}\left(b_1 r_0 + \left(I_1+I_2\right)\left(b_2-b_1\right)r_1 + I_2\left(b_3-b_2\right)\alpha_1 r_2 - \beta\left(1-q_i\right)^{k/\beta}\alpha_1^{I_1+I_2}\alpha_2^{I_2}\right) \qquad (14)$$

Volume equation:

$$v = a_0 d^{a_1} h^{a_2} \qquad (15)$$

where: d = diameter at breast height over bark (cm); d_i = top diameter at height h_i over bark (cm); h = total tree height (m); h_i = height above the ground to top diameter d_i (m); h_{st} = stump height (m); v = total tree volume over bark (m^3) above stump level; v_i = merchantable volume over bark (m^3), the volume from stump level to a specified top diameter d_i; a_0, a_1, a_2, b_1, b_2, b_3, p_1, p_2 = regression coefficients to be estimated, k = (π/40 000), metric constant to convert from diameter squared in cm^2 to cross-section area in m^2; $q_i = h_i / h$.

A third-order continuous autoregressive error structure was necessary to correct the inherent serial autocorrelation of the experimental stem data. The model provided a very good data fit, explaining 98.9% of the total variance of d_i, and the RMSE = 0.847 cm. The resulting parameter estimates were: $a_0 = 0.000087$; $a_1 = 1.614$; $a_2 = 1.109$; $b_1 = 0.000012$; $b_2 = 0.000025$; $b_3 = 0.000035$; $p_1 = 0.05781$; $p_2 = 0.1940$. All the parameters of the taper function and of all other equations corresponding to the disaggregation system were significant at a probability level of 0.05.

3.3 Overall evaluation of the whole-stand model

Assessment of model accuracy requirements was carried out by comparison between observed volume at the age of the second inventory and the volume estimated from the whole model. For this purpose, observed dominant height, number of trees per hectare and stand basal area from the first inventory of the 32 plots measured twice, served as initial values for the corresponding transition functions (Equations 7, 8 and 9). These functions were used to project the stand state at the age of the second inventory.

Equation 11 was then used to estimate the arithmetic mean diameter, which allowed calculation of the variance of the diameter distribution. Equations 3 and 4 were used to recover the Weibull parameters, thus allowing estimation of the number of trees in each diameter class. Finally, equations 12 and 15 were used to estimate the height and the total volume of the average tree in each diameter class respectively. Aggregation of total tree volume multiplied by the number of trees in each diameter class provided total stand volume.

A plot of observed against predicted values of stand volume obtained following the above procedure for the time interval considered (3 years) is shown in **Figure 1.4**. The linear model fitted for the plot behaved well ($R^2 = 0.983$), however the plot showed that there was a slight tendency towards overestimation of stand volume for the prediction interval. A critical error of 10.79% was obtained in the projection of total stand volume for this time interval.

The plot of the observed stand volume values against the values predicted by the model developed with data from Galician stands (**Castedo-Dorado et al. 2007**) is shown in **Figure 1.5**. Although the percentage variability explained by the linear model fitted for the scatter plot is high ($R^2 = 0.978$), the Galician model clearly underestimates the stand volume. Moreover, the critical error obtained in the projection of stand volume (23.84%) is much higher than that obtained by use of the local model.

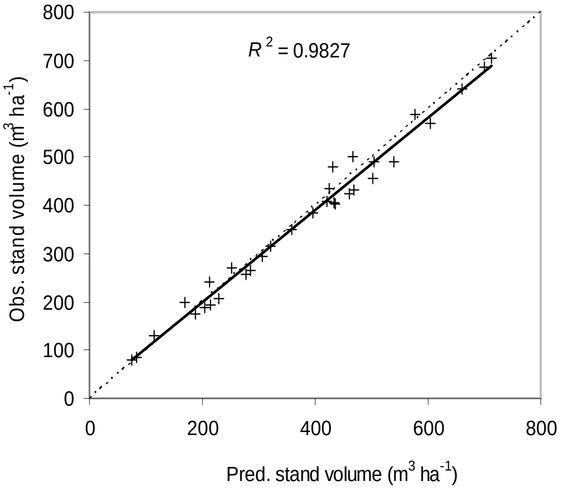

Figure 1.4 Plots of observed stand volume values against model-predicted values, from the model developed in this study. The solid line represents the linear model fitted to the scatter plot of data and the dashed line is the diagonal. R^2 is the coefficient of determination of the linear model

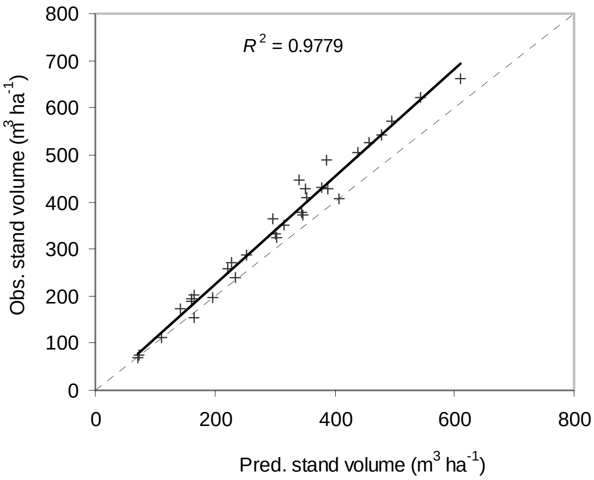

Figure 1.5 Plots of observed stand volume values against model-predicted values, from the Galician model (Castedo-Doradoet al. 2007). The solid line represents the linear model fitted to the scatter plot of data and the dashed line is the diagonal. R^2 is the coefficient of determination of the linear model

4 Discussion

In this study, a dynamic whole-stand growth model for radiata pine plantations in an inland region of Spain (El Bierzo) is presented. The growth model described is comprehensive because it addresses all forest variables commonly incorporated in quantitative descriptions of forest growth.

The method of construction adopted is robust because it is based on only three stand variables: dominant height (*H*), number of trees per hectare (*N*) and stand basal area (*G*). In accordance with García's state space approach to modelling plantations (**García 1988, 1983**), these variables summarize the historical events that affect stand development, and allow predictions from current state and future actions. The behaviour of the system is described by the rate of change of the state variables given by the corresponding transition functions. Besides, other stand variables (e.g. quadratic mean diameter, total or merchantable volume) can be obtained from the current values of the state variables. In addition, the model can efficiently project stand development starting from different spacing conditions (e.g. densities) and considering different thinning schedules.

According to this structure, the whole-stand model only requires five stand-level inputs: age of the stand at the beginning and at the end of the projection interval (t_0 and t), and the initial dominant height (H_0), number of trees per unit of area (N_0) and stand basal area (G_0). Considering that modelling should be restricted to those variables available in forest inventory data (**Burkhart 2003**), we consider our approach to be adequate for the practical management of *Pinus radiata* stands in El Bierzo, where predictor variables required are often measured and data are available at stand level.

The use of the GADA or ADA techniques in the development of the transition functions ensures that base-age and path invariance properties provide consistent predictions. Moreover, the functions were fitted by use of a BAI method that accounts for site-specific and global effects (**Cieszewski et al. 2000)**.

The dominant height growth transition equation provided accurate values of site index from height and age and vice versa, regardless of the levels of site productivity. This transition function is one of the basic submodels in whole-stand growth models and allows assessment of the basic productivity on a stand-specific basis (e.g. **Clutter et al. 1983**). It is applied as follows: given *SI* and its associated base age (20 years in this case), to estimate the dominant height (*H*) of a stand for some desired age (*t*), simply substitute *SI* for H_0 and 20 for t_0 in equation 7. Similarly, to estimate site index at some chosen base age, given stand height and age, substitute *SI* for *H* and 20 years for *t* in the same equation.

Regarding the stand survival function, the methodology used for the projection estimates the reduction in the number of trees from a single mortality function fitted with all the data from plots measured in 2003 and in 2006. Although this interval of measurement collection is relatively short (**Eid and Tuhus 2001**) it is considered representative of the natural mortality process that occurs in the stands, especially taking into account that radiata pine is a fast growing species. The accuracy of the survival function is important for generating realistic projections of the final output variables of the whole model (e.g. total or merchantable volume), especially when light thinnings or no thinnings are carried out (**Avila and Burkhart 1992**), as was the case in most of the studied stands.

As regards the stand basal area projection equation, initial basal area and initial age provided sufficient information about the future trajectory of the basal area of the stand, regardless of initial spacing, thinning history or site quality. This can be explained because stand basal area and age are good enough estimators of quality in stands where silviculture is applied next to forest dynamics with low thinning (**Bravo-Oviedo et al. 2004**). The basal area initialization function developed should only be used to predict this variable in stands similar to those where the experimental data were collected, i.e. unthinned or lightly thinned stands younger than 15 years. The initialization and the projection function are not compatible because of the variation over time in the relative spacing index. This incompatibility is not a major problem, as the initialization function would only be used when no inventory data are available (**Amateis et al. 1995**).

Explanatory variables of the components of the disaggregation system can be easily obtained at any point in time from the three transition functions previously mentioned. The only exception is dominant diameter of the generalized *h-d* relationship, which is a difficult variable to project (**Lappi 1997**), and must be estimated from the diameter distribution.

Total stand volume was selected in the present study as the critical output variable for the whole-stand growth model, although other stand variables can be assessed on the basis of this model. For instance, within the framework of climate change challenges, an increasing interest in studying the amount of biomass and carbon sequestration through forest management is expected and could be adequately tackled using the model. For example, if biomass equations that include the diameter at breast height and the total height as independent variables are developed for this species they can be easily incorporated into the disaggregation system proposed and converted in carbon pools (e.g. **Merino et al. 2005**).

Considering the required accuracy in forest growth modelling at stand-level, where a mean prediction error of the observed mean at 95% confidence intervals within ± 10%-20% is generally realistic and reasonable as a limit for the actual choice of acceptance and rejection levels (**Huang et al. 2003**), it can be stated that, on the basis of the critical error statistic obtained (10.79%), the model developed in this study provides satisfactory predictions.

Taking the same criterion into account, the model developed from the Galician data (**Castedo-Dorado et al. 2007**) cannot be applied directly to the region of El Bierzo, since the critical error statistics obtained in this case (23.84%) is higher than the upper limit usually considered for acceptance of a model. This result is expected *a priori*, since a fitted model is likely to produce errors when used on a local data set different from the data used in its construction (**Huang 2002**). Moreover, these results also justify the need to adapt the Galician model, refitting the individual submodels on the basis of local (El Bierzo) data.

In summary, the overall evaluation of the model developed for El Bierzo demonstrates that it is robust, at least for short term projections of stand volume. This characteristic is especially interesting for planning purposes in fast growing species, as is the case here. As the study is based on stands of ages between 7-36 years, predictions for stands less than 7-years or more than 36 years-old should be used with caution.

5 Conclusions

In conclusion, afforestation with radiata pine appears an adequate alternative considering both the stand growth rates that can be achieved and the socio-economic conditions of the area of study, in which most land would otherwise be abandoned. The high level of forest productivity confirms the results obtained by **Romanyà and Vallejo (2004)**, who found a higher growth rate for this species in Mediterranean environments in Spain when compared to more Eurosiberian conditions.

The growth model developed can be considered as a potential tool for sustainable rural development.

Multidisciplinary research should follow to complete radiata establishment, also considering wider objectives and derived environmental and socioeconomic synergies. Further consequences apply directly to rural development, socioeconomic and land management practices.

CHAPTER 2. Silvicultural alternatives for *Pinus radiata* D. Don plantations: applications of the growth model developed in El Bierzo

1 Introduction

Debate on silvicultural regimes is often trivialised by concentration on a single component (e.g. rotation length or final crop stocking) and a failure to consider profitability in its entirety. Furthermore, regime choice may be driven by factors other than profitability, including feasibility. Regime choice will depend on site factors (such as soil, climate, topography, and presence of weeds), on location (e.g. distance to markets, nature of local processing plants), and on the manager's financial and psychological profile (**Maclaren and Knowles 2005**).

Forest research has provided tools, in the form of models that can help to determine the physical and financial outcome of any combination of inputs, rather than recommending a particular regime. For radiata pine in El Bierzo (NW Spain), an empirical stand growth model is available (**Sevillano-Marco et al. 2009**), which will help highlight some interesting aspects as regards the comparison of management options.

There are many potential applications for the model. As was explained in Chapter 1, it can be applied with data normally available from stand inventories in the region. The model allows simulation of different types of thinnings (systematic, selective from below or semi-systematic). This may be extremely interesting considering the need for implementation and generalization of silviculture practices in the area of study.

In addition, the review of experiences in other regions or countries, where the species is already established and has been largely researched, can provide interesting guidelines, always keeping in mind that the local conditions will carry the most decisive weight on the matter.

For instance, the predominance of direct regimes (i.e. those without a commercial thinning) throughout New Zealand can be explained by the often-difficult topography on new forest sites, and the poor or non-existent markets for stems of small piece-size. Other factors include the observations that, during extraction of thinnings, damage to crop trees can occur and land can be removed from production by the construction of roads and landings (**Maclaren and Knowles 2005**). Indeed, thinning operations introduce a higher risk of wind damage for a few years until the trees compensate for their new stocking and higher risks are as well implied in thinnings after a mean crop height of 20 m (**Ainsworth 1989**).

There is a trade-off between low final stockings, with large tree diameters at an early age, and higher stockings, with greater volume per hectare, better form, smaller branches, and possible superior internal wood quality. Higher stockings can be justified with longer rotation lengths, higher site indices, lower discount rates, and lower prices for clearwood.

Summing up, in New Zealand, generally the species is intensively tended, considering not only stand volume as the main target in yield objectives, but also wood properties which have proved to be determinant of the value and profitability of plantations. Hence, current practice is to plant 600-1000 stems ha^{-1}, depending on regime and terrain, thinning in one or two operations to 250-400 stems ha^{-1} final stocking. Extreme regimes are for agroforestry with as few as 100 stems ha^{-1}, up to four pruning lifts and three waste thinnings, and for pulp production 1500-1600 stems ha^{-1} and no thinning. Though, increasing final stockings are the ultimate trend in recent years, as the reduction in the proportion of juvenile corewood, which is especially important for structural timber, calls for minimum stand densities (**Oliver 1985**). Rotation length is between 25-35 years, definitely longer than the rotation carried out in plantations in El Bierzo (around 20 years).

Silviculture regimes aimed at small-size timber production are generally not applied nowadays in Spain, but were widely used in the 1960s to produce pulpwood (**Aunós 1990**). A comprehensive review of the regimes commonly applied in Spain (especially Galicia and Basque Country) is given by **Rodríguez et al. (2002)**. In short, the alternatives can be classified according to the production objective sought (i.e. pulpwood, saw-timber, elite trees) and management is highly dependent on land property (communal or public forests versus private woodlands). These two factors influencing silviculture (production objective and property) are, in general, not independent. Other variables affecting decision making as regards selection of a regime are siting and wood market prospects. A compromise between all these variables is the basis of the choice of alternatives to be simulated and the flexibility proposed in Galicia (**Rodríguez et al. 2002, Dans-del Valle 1999**).

In general, in Galicia on high quality sites, with deep soils, regular rainfall and adequate climatic conditions (i.e. absence of frosts), an intensive silviculture can be applied: initial stockings between 800-1000 stems ha^{-1}, 2-3 intermediate thinnings and intense pruning lifts at early ages (e.g. 10-12 and 15-18 years of age), short rotation at 25 years of age. On the contrary, on the poorest sites, a more progressive silviculture is required: higher initial densities around 1400 stems ha^{-1}, later thinnings at 10-15 and 20-25 years of age, extended rotations to 35 years of age (**Dans-del Valle et al. 1999**).

In Galicia, the stands conditions are highly similar to the plantations in El Bierzo (predominance of homogeneous even-aged stands with similar growth rates), including property structure and feasibility of management alternatives. Thus, even though a more innovative approach would be the simulation of extreme regimes, the range of existing environments and practices in El Bierzo, together with the methodology in model development, confine the regimes to be simulated with an acceptable certainty in the derived predictions. In this sense, it seems more realistic to simulate alternatives closer to the range of existing conditions (i.e. regimes applied in Galicia).

In particular, in El Bierzo, most of the stands are distributed in small-medium private woodlots (woodlots of around 0.3-0.7 ha and 30-70 ha respectively).There's only one large landowner, a mining enterprise (MSP), with around 400 ha of radiata pine stands. The species is not as yet relevant in communal forestlands, nor is the Forest Service management regularly applied. Thus, radiata pine is mainly planted and tended in private lands. A main feature of radiata pine forestry in the area of study is the lack of updated records of the real surface of existing and recently established plantations and the difficulty to track the evolution of the stands, including silviculture practices standardization. As aforementioned, the stands in the area of study were originally aimed at pulpwood production, planted at high densities, directly tended, and managed in short rotations (approximately 15 years). However, trends are changing towards extended rotations and enhancement of silvicultural practices.

There are two other aspects that should be tackled when assessing management of radiata stands: genetic traits control and pruning operations. As appropriate data sources were not available, neither subjects have been approached in the area of study. In this respect, the fact that traits will be necessarily resulting from genotype and environment interaction (GxE), will be considered implied in the predictions when using the local growth model.

An interesting remark would be that application of other regimes could be equally tested in field trials that would finally enable updating and rescaling of growth modelling in the area.

Objective

The main objective in this chapter is to evaluate the possible dynamic evolution of the radiata pine stands in the target region in NW Spain, El Bierzo under different management regimes. The local growth model developed is used to predict the effects of several silvicultural managements that have been in common use in other regions (i.e. Galicia, New Zealand). The overall discussion from these examples provides valuable guidelines and recommendations for the successful establishment of the species in El Bierzo. On the other hand, the second objective of the study was the evaluation of the growth model developed which in this manner is practically tested by the simulations performed.

2 Methods

Previous research provided a management-oriented whole-stand model for simulating the growth of radiata pine plantations in El Bierzo. The model is constituted by a site quality system (both for dominant height growth and *SI* prediction), an equation for reduction in tree number, a stand basal growth function, and a disaggregation system composed of a diameter distribution function, a generalized height-diameter relationship and a total merchantable volume equation. Further details about the local growth model can be found in **Sevillano-Marco et al. (2009)**.

The available local growth model was used to predict stand evolution under different silviculture alternatives that have been or are in use in other regions.

Alternative management regimes that are applied to the species in other areas of Spain, New Zealand and others (**Rodríguez et al. 2002, Dans-del Valle et al. 1999, Maclaren 1993**) are shown in **Table 2.1**. Note that, as the range of data employed for model development does not cover all possible scenarios, not all of the regimes can be simulated, especially the most extremes. The plant and leave alternatives (i.e. no silviculture applied, referred to as NS in results section) of the regimes shown in **Table 2.1** have also been simulated.

The methodology used to simulate the thinning operations is that proposed by **Alder (1979)**, which was successfully applied in subsequent studies (e.g. **Álvarez et al. 2002**).

Table 2.1 Management regimes for radiata pine: guidelines for local model simulation

t	***N_0***	**Thinnings**		***t***	***N_0***	**Thinnings**	
years	stems ha^{-1}	Exctrated *N*	Extracted %*G*	years	stems ha^{-1}	Exctrated *N*	Extracted %*G*
0	800			0	1500		
5		300*	*	7		300*	*
8		200*	*	14		200*	*
28		clearfelling		22		clearfelling	
0	800			15	1612		
5		400*	*	21		325	21.7%
14		200*	*	28		200	21.6%
32		clearfelling		38		clearfelling	
10	833			10	2126		
12		200		17		750	30 %
18		250		25		375	21.5 %
25		clearfelling		35		clearfelling	
0	1000			10	2126		
7		500*	*	17		750	30%
12		250*	*	25		clearfelling	
28							
10	1142			0	2500		
15		300		15			
25		350		20		clearfelling	
35		clearfelling					
0	1333			0	3000		
15		700	30%	15		750	
25		415	26%	25		350	
35		clearfelling		35		clearfelling	
10	1342			0	3000		
20		325	25%	15		500	
30		clearfelling		25		500	
				30		clearfelling	

t=age; *N_0*=stems ha^{-1} (representing initial stocking in model simulation); *N*=number of stems ha^{-1} extracted in thinning; % *G*=basal area (percentage extracted in thinning); ***** out of data range in model development (unacceptable uncertainty of predictions)

3 Results

As an example, **Figure 2.1** shows the changes in basal area over the whole rotation for two silvicultural alternatives under two different site quality scenarios defined by *SI* of 16 m and 26 m. The first alternative corresponds to the treatments usually applied in the past and occasionally at present in El Bierzo: planting density (N_0) of 2500 stems per hectare (e.g. 2 × 2 m) without commercial thinnings, and rotation age of around 20 years. The second is a more intensive alternative, characterized by a wider initial space of 3 × 2.5 m (e.g. 1333 stems/ha), with two intermediate thinnings and an extended rotation age of 35 years.

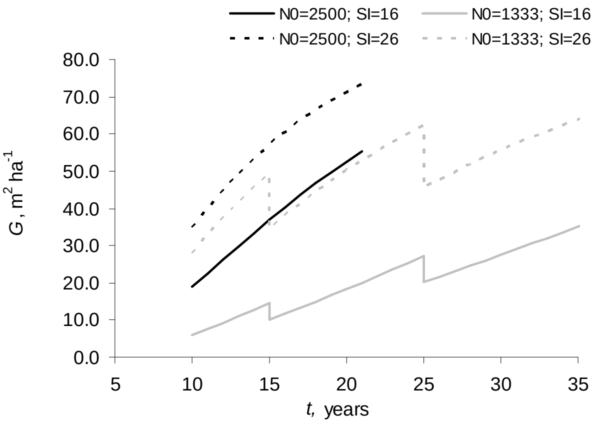

Figure 2.1 Changes in basal area over the rotation for the two silvicultural schedules simulated.

The predicted diameter distributions at clearfelling for the two silvicultural alternatives of the example are shown in **Figure 2.2**.

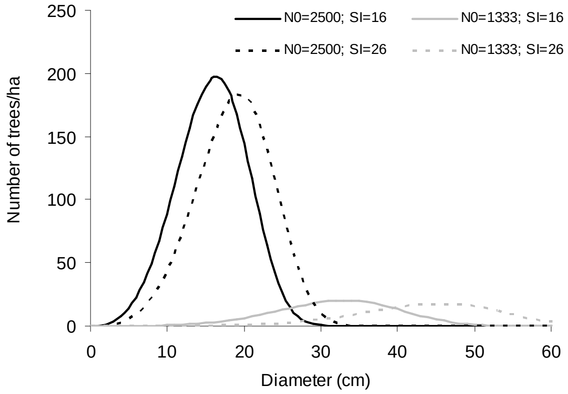

Figure 2.2 Predicted diameter distribution at clearfelling in the two alternatives simulated

The model also allows the development of curves of volume current annual increment (CAI) and mean annual increment (MAI). These curves are useful tools for the correct management of forest stands and contribute to estimation of the timing of intermediate and final cuts. As an example, both curves for the silvicultural schedule first considered, are shown in **Figure 2.3**.

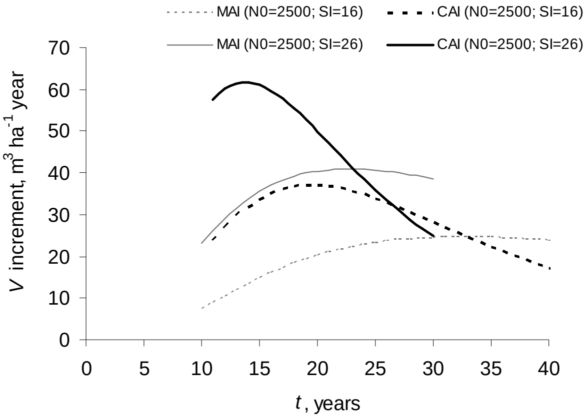

Figure 2.3 Volume mean annual increment (MAI) and current annual increment (CAI) for the silvicultural schedule corresponding to an initial stand density of 2500 stems per ha under two site conditions

Likewise, **Figure 2.4a** and **Figure 2.4b** show the changes in basal area over the whole rotation for several silvicultural alternatives under the same two different site quality scenarios defined by *SI* of 16 m and 26 m. The first alternative corresponds to the treatments usually applied in Galicia (**Rodríguez et al. 2002, Dans-del Valle et al. 1999**): planting densities (N_0) of 833, 1142, 1612 and 2126 stems per hectare with and without commercial thinnings, and rotation age of around 40 years (see **Table 2.1** for more details of each of the regimes).

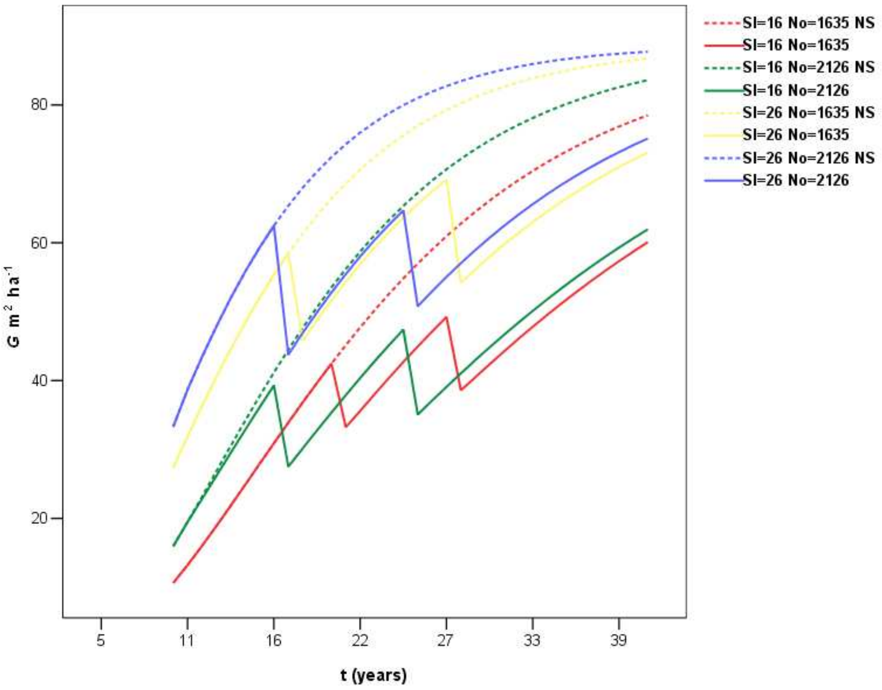

Figure 2.4a Basal area (m^2 ha^{-1}) along the rotation (based on Rodríguez et al. 2002)

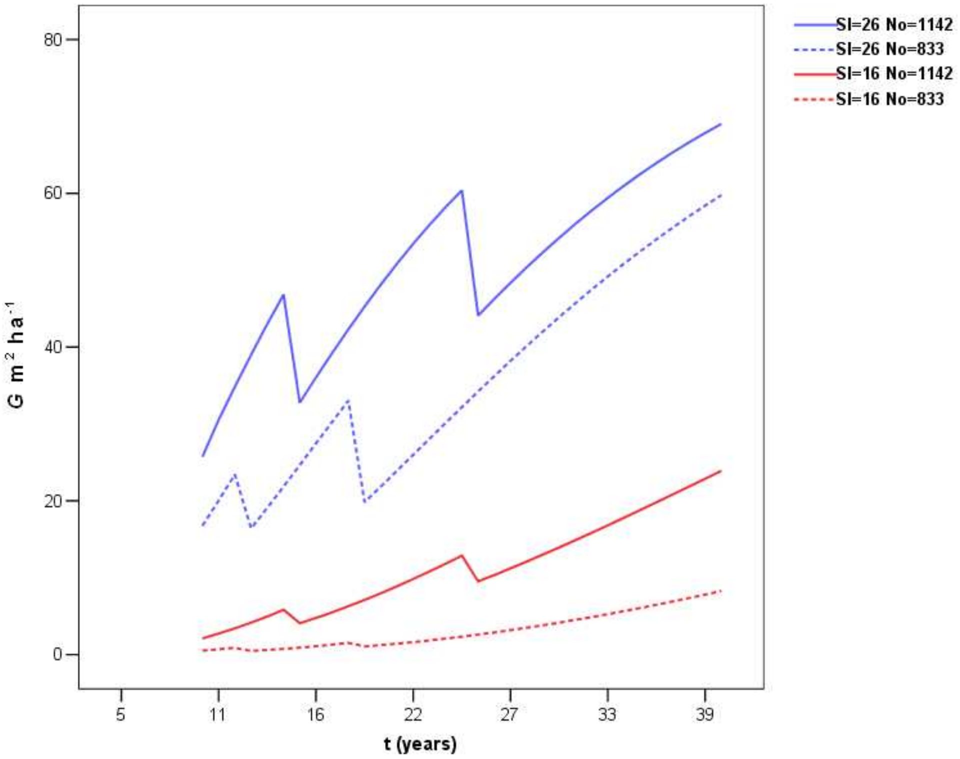

Figure 2.4b Basal area (m^2 ha^{-1}) over rotation (based on Dans-del Valle et al. 1999)

Analogously, **Figure 2.5a** and **Figure 2.5b** shows equally the changes in basal area over the whole rotation for another set of regimes, characterized by densities of 1342, 1500 and 3000 stems ha^{-1}), with and without thinnings (see **Table 2.1** for more details of each of the regimes).

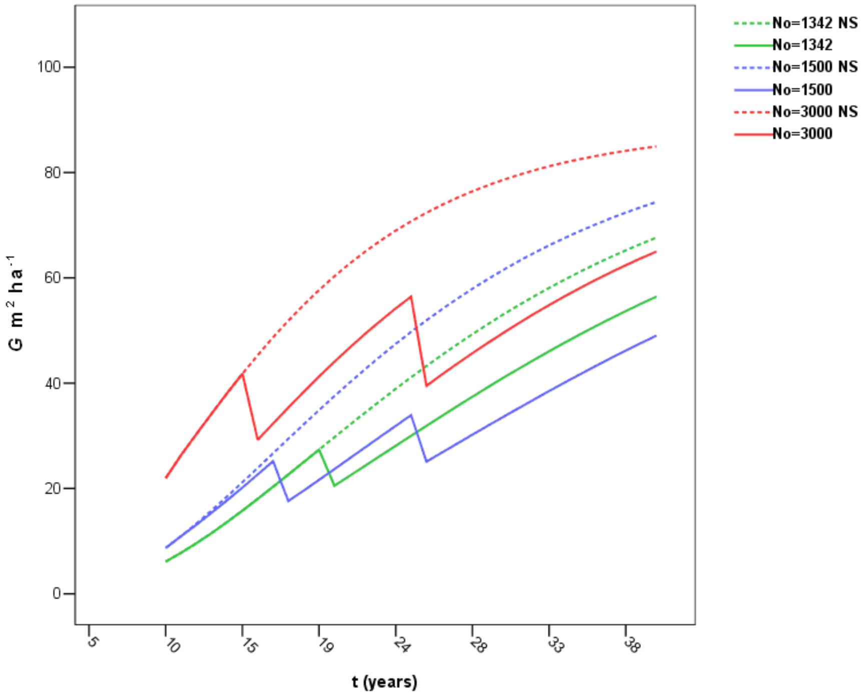

Figure 2.5a Basal area over rotation (m^2 ha^{-1}). *SI* 16 m at 20 years of age

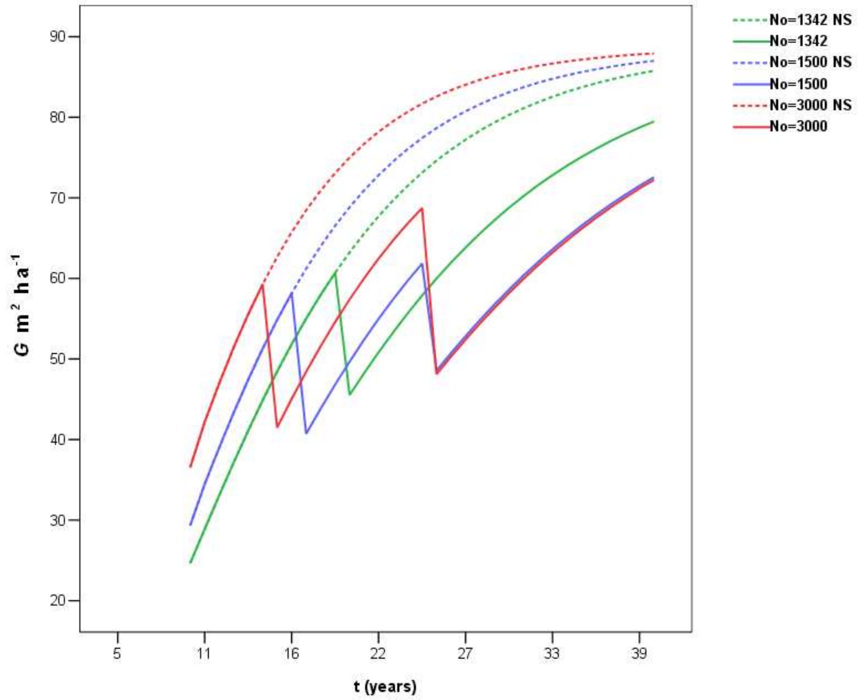

Figure 2.5b Basal area over rotation (m^2 ha^{-1}). *SI* 26 m at 20 years of age

Basal area growth is reaching a maximum for some unthinned regimes. However, it is still increasing with thinned regimes. MAI and CAI curves representing the management alternatives of 2126 stems ha^{-1} for *SI* 16 and 26 m are shown in **Figure 2.6**.

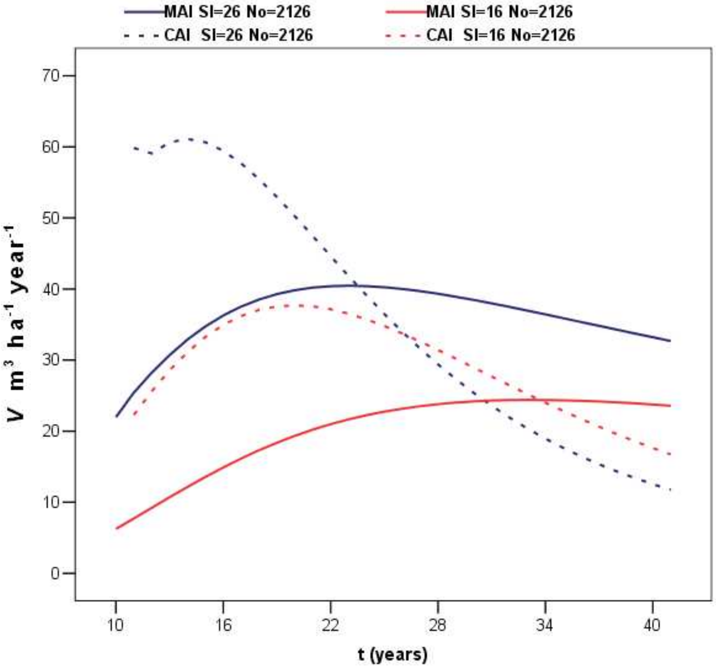

Figure 2.6 Volume mean annual increment (MAI) and current annual increment (CAI) (m^3 ha^{-1} year^{-1}) for 2126 stems ha^{-1}

4 Discussion

Amongst the regimes simulated with the local growth model, as it had been foreseen, some of them couldn't be replicated because the age of thinnings was too young for the data range used in model development. This fact affected specially the simulation of the common regimes applied in New Zealand. Similarly, as it had been expected (**Sevillano-Marco et al. 2009**), too low final crops couldn't be applied. Likewise, N_0 below 1075 stems ha^{-1} provide unacceptable predictions and as stated in Chapter 1, considering final cuttings over 36 years old is uncertain.

Simulation of silviculture alternatives shown in **Table 2.1** confirm that outputs given by the model seem realistic and sensitive both to initial stand density and site quality: dense plantations and better sites produce more stand basal area (e.g. **Figures 2.1, 2.4a, 2.4b**). An interesting finding was that regimes without thinnings (NS on the figures) resulted in higher basal areas. Such circumstance would assure profitability of direct regimes applied in private small exploitations, which matches the property typology dominant in the region. In the long term, basal area of regimes with thinnings might be higher, but it is not the case in the rotations here considered. An advantage of the species is its flexibility as regards response to silviculture (**Sutton 1999**), providing high returns in varied regimes, growth rates depending more on site conditions. In particular, in El Bierzo, MAI values were found to be around 20 m^3 ha^{-1} year^{-1} (*SI* 16 m) and 40 m^3 ha^{-1} year^{-1} (*SI* 26 m). These high values obtained in genetically unimproved stands are easily explained by the high N_0 commonly used in the area (N_0 2126-2500 stems ha^{-1} in the simulations performed) and siting conditions. Finally, depending on production objectives (e.g. size of final products), diameter distribution should be considered.

The model can also express yield in terms of product classes or log quality grade, which is vital management information for harvesting and marketing decision making (**Vanclay 1994**). Information on size class distribution enables much more realistic evaluations of alternative silvicultural regimes in terms of both volume yield and financial returns. As can be observed (**Figure 2.2**), the model takes into account the variation in the diameter distribution due to both stand density and *SI*: higher proportions of thicker trees are expected in alternatives with lower initial stand densities and on better sites. This is an example of how the use of the disaggregation system describes the stand much more thoroughly and readily allows simulation of thinning treatments. It is an important fact that should be taken into account when evaluating diverse densities. In spite of the fact that unthinned regimes produce higher stand basal area (e.g. **Figures 2.1, 2.4a, 2.5a, 2.5b**), the analysis of **Figure 2.2** clearly points out to the necessity of silviculture operations (thinnings). The number of trees in the lower diameter classes is generally higher on inferior sites, but the effect on the diameter distribution of the thinning regime and rotation age is much greater than that of *SI* (**Rodríguez et al. 2002**).

It is well known that the interception between volume MAI and CAI curves indicates the biological rotation age for a given stand. The optimal rotation age when only average annual gain is considered is illustrated in **Figure 2.3**. As expected, biological rotation age is much shorter on better sites than on poor sites. The total volume production was similar for the alternatives simulated, with greater differences between regimes for the poorest site.

All the examples presented in this study can be directly used to optimise timber management planning and to evaluate alternative management regimes at stand level. These situations, in which planning can be carried out independently for each stand, will be the most typical in the region taking into account the typology of small non-industrial private forest owners.

However, it is possible to run scenario simulations not only at the stand level but also at forest and regional level. In this case, where stable patterns of income are important, planning must be coordinated for all stands in the forest being considered (**Clutter et al. 1983**), and the information given by the model must be included in a forest level optimisation model.

In summary, the availability of the model can be considered important, taking into account that growth rates, together with management techniques, timber prices and financial returns are some of the most important factors driving forest management (**Cubbage et al. 2007**). In addition, the relatively simple structure of the growth model makes it suitable for embedding into landscape-level planning models and other decision support systems that enable forest managers to generate optimal management strategies.

However, the nature of the growth model does not apply to wood properties variation and other aspects, which are certainly sensitive to silviculture regimes (e.g. conservation of soil productivity might require reduced densities and extension of the rotation to over 30 years –**Rodríguez et al. 2002**-).

Other aspects should be equally regarded. For instance, although the nutrient export caused by intensive forest management appears to be of a similar magnitude to the capacity of the soils to replenish the nutrient levels (**Worrel and Hampson 1997**), the extension of the rotation length should result in lower nutrient exports (**Bredemeier et al. 2000**). If the expansion of the species to the hills and mountains slopes in El Bierzo was to be considered, regimes and methods consequent to slope stability and tree root reinforcement, new approaches to planning harvesting operations and low impact logging techniques to minimise soil disturbance and protect slope environments may be required. Environmental risks (e.g. wind, fire, snow) could also affect the planning options in certain situations, as slenderness (i.e. height/diameter ratio) is directly influenced by stocking along the rotation. For instance, as regards spreading of the species towards transitional hills and mountain slopes, the prevailing W/NW wind direction in the high lands in El Bierzo should be carefully surveyed. Even though apparently a high risk of fire favours shorter rotations, the concentration of forest fire risk in the first ten years after establishment actually makes the regimes with longer rotations seem more attractive (**Rodríguez et al. 2002**).

5 Conclusions

Simulation of silviculture alternatives confirm that outputs given by the model seem realistic and sensitive both to initial stand density and site quality: dense plantations and better sites produce more stand basal area.

The model can also express yield in terms of product classes or log quality grade, taking into account the variation in the diameter distribution due to both stand density and *SI*. Higher proportions of thicker trees are expected in alternatives with lower initial stand densities and on better sites.

The model allows the development of curves of volume CAI and MAI, which are useful tools for the correct management of forest stands and contribute to estimation of the timing of intermediate and final cuts. High productivity of the existing stands in El Bierzo, between 20-40 m^3 ha^{-1} $year^{-1}$, depending on *SI*, is explained by high N_0 and siting.

By running the model, we have been able to scientifically evaluate different regimes. The simulations are restricted by the data employed in model development. It would be an important recommendation to update the field data survey, in order to cover other situations (i.e. early ages, older stems, initial stockings, sites) more accurately.

There is a wide range of management options available. The species response to silviculture is highly flexible. Other decisive factors as regards silviculture alternatives in the area of study are property and production objectives. In general, a feasible option aimed at saw-timber production (initial stocking around 1300 stems ha^{-1}, intermediate thinnings at ages 15 and 25, extended rotations to 35 years) seems suitable for the local conditions. This regime is similar to the proposed by **Fernández-Manso and Sarmiento-Maíllo (2004)** for the area of study. Moreover, it has proved to be appropriate in other regions, especially in Galicia, which is geographically the closer area with radiata pine plantations to El Bierzo, both regions resembling in most respects in the stands conditions (i.e. property typology, species response to site and silviculture). Particular needs of particular conditions should be appropriately and individually addressed.

CHAPTER 3. Influence of ecological parameters on site index of *Pinus radiata* D. Don plantations in El Bierzo

1 Introduction

High growth rate in temperate climates and seed production, wood versatility, silviculture flexibility, genetic variability among natural populations and such other characteristics have made radiata pine (*Pinus radiata* D. Don) one of the most worldwide important exotic conifer in plantations (**Sutton 1999, Lavery 1986, Scott 1961**). Distance and diversity of locations provide a wide range of ecological conditions certainly influencing productivity of the stands. Local studies seriously contribute to optimize the species efficiency, stating the key limiting factors to its growth and potential distribution (**Louw 1991, Lambert and Turner 1988, Turvey et al. 1986, Truman et al. 1983, Gil-Sotres et al. 1977, Adams and Walter 1975, Ballard 1971**). As regards the ecology of the species, in general, growth limiting factors include severe cold temperatures and frosts, scarce precipitations, markedly irregular rainfall distribution and humidity or warm conditions favouring cryptogamic diseases (**Serrada et al. 2008**). Radiata pine is considered one of the most demanding pines regarding soil nutrients, being particularly vulnerable to plagues when exposed to wind and severe temperatures or growing in shallow or poor soils (**Scott 1961**).

Strictly speaking, stand productivity depends on climate, topography, soil, genetics, vegetation structure, interespecific competition relationships including animal species, human being influence in ecosystems, and time. In order to simplify, most of the latter factors are assumed to be constant or somehow controlled, in particular when dealing with plantations. As topography can be related to soil and climate, productivity is supposed to be chiefly dependent on edaphic and climatic conditions in most research studies regarding environmental factors affecting species growth (**Delmastro et al. 1981**).

SI, defined as “all environmental factors that affect the biotic community” **(Daniel et al. 1979)**, has been evaluated using edaphic and climatic variables, especially for highly productive species. Relationships between *SI* and specific characteristics of the site (mainly soil properties and climate) or nutrient status of the forest provide useful information for decision making and forecasting. Use of these relationships, obtained from predictive or explanatory models (**Hägglund 1981, Carmean 1975**), allows selection of the most suitable species and prediction of the forest growth.

In brief, assessment of *SI* is possible from a direct approach (which implies necessarily the presence of stands of the species being considered) consisting of a series of repeated measures of intrinsic factors (e.g. dominant height, mean height, volume, natural mortality, volume extracted during silvicultural practices) along the rotation. Previous studies of radiata pine in the region of El Bierzo have determined *SI* as a continuous function, a submodule of a local dynamic growth model for the species, on the basis of stand variables (Chapter 1). From this point of is based on the experimental certainty stating that height of dominant or codominant plus dominant trees for a given species and age is more correlated to wood productivity that any other parameter defining productivity capacity of a site (e.g. law of Eichhorn).

However, an indirect approach based on extrinsic factors (e. g. climate, edaphic variables, geology) is also possible, involving statistical relationships where the dependent variable is an intrinsic factor depending on extrinsic factors (**Ortega and Montero 1988, Daniel et al. 1979**). As site dependent parameters are difficult to measure, and results of statistical analyses in this field are not easily read, estimations of one or more extrinsic factors considered individually are normally used. This assumption is generally not totally appropriate but such a consideration can explain in a high percent the productivity of a site (**Ortega and Montero 1988**). Nevertheless, this line is decidedly interesting, enabling estimation of site quality for a certain species prior to the establishment.

SI indirect models can be in turn classified as descriptive or predictive. Descriptive models principal target is depicting factors controlling productivity in a wider area, being useful as a previous step to predictive models, which in turn evaluate quality establishing relationships between factors influencing productivity.

An interesting remark is the fact that interaction of environmental factors results in varied site qualities, which commonly hide the influence of a certain factor (**Mcleod and Running 1988**). This means that even when an individual listing of site parameters is relatively simple, an accurate evaluation of the overall effect of the whole set of site parameters is rather complicated (**Monserud et al. 1990**) as different combinations of individual factors can cause the same outcome on vegetation due to compensatory effects (**Klinka and Carter 1990, Green et al. 1989**).

In addition, as various references mainly dealing with coniferous species conclude (**Hamel et al. 2004, Curt et al. 2001, Beaumont et al. 1999, Wang and Klinka 1996, Monserud et al. 1990, Verbyla and Fisher 1989**), the weight of environmental factors over productivity is related to the scale considered: climate is the main influencing factor in wide areas (**Gerding and Schlatter 1995, Hunter and Gibson 1984, Jackson and Gifford 1974, Gandullo et al. 1974**), physical soil attributes in regional scales, whereas topography or chemical soil properties are highlighted in local studies with homogeneous climatic and geologic conditions. The impact of environmental factors on tree growth varies greatly within tree species (**Reich et al. 1997**) but it may not be relevant within a narrow range or when the environmental factors fall in the optimum conditions for a species (**Wang and Klinka 1996, Klinka and Carter 1990**).

As an example of productivity studies based on environmental factors, in the nearest region, Galicia, **Sánchez-Rodríguez et al. (2002)**, applied principal component analysis and multiple regression between *SI* and soil properties and tree nutritional status in *Pinus radiata* D. Don stands and found a correlation of 0.82 between productivity and edaphic properties. This kind of analysis, where multivariate statistical tests are performed, considers edaphic (**Bará and Toval 1983**), climate regimens, topographic attributes and lesser vegetation (**Pacheco 1991**).

In El Bierzo, the species has been more recently introduced than in coastline northern regions (i.e. Basque Country, Galicia, Asturias) for the most part in former agricultural fields and in *Quercus* sp. degradation shrub lands **(Serrada et al. 2008**). This region can be considered part of the wet Mediterranean area, characterized by rather acid soils and annual rainfall exceeding 700 mm. Although relatively close to the main plantations of the species in the country (northern eurosiberian regions), in the area of study higher altitudinal levels, lower rainfall and several environmental factors dissimilarity should lead to an specific Mediterranean inland microenvironment influencing stand productivity. Thus, some siting diversity and divergences on productivity can be expected when compared to other northern regions of the country located entirely in Eurosiberian environments. The assessment of *SI*, understood as potential productivity, can help in defining proper silvicultural treatments and finding out optimal environments for the spreading of the species and yield improvement.

Despite the importance of the species, to date, the influence of environmental factors on *Pinus radiata* productivity in Spain has only been examined in the climatically and geologically homogeneous areas of the northwest (**Sánchez-Rodríguez et al. 2002, Gil-Sotres et al. 1977**) and in a rather general pine site study for the whole country (**Gandullo and Sánchez-Palomares 1994**). At present, there is very little information available on the status of radiata stands and the corresponding relationships with soil properties and productivity.

Objective

Consequently, the main objective of the present study was to identify the key environmental factors that determine the productivity of radiata pine in El Bierzo, which at the same time implies a much deeper knowledge of the ecological parameters of the region. Specific objectives pursued in the present work are: (1) qualitative habitat description, (2) quantification of relationships by multivariate statistical techniques, (3) cartographic definition of areas of potentiality, and (4) estimate the appropriateness of the specific location of the existing stands based on the defined habitat and potentiality map.

2 Methods

SI, considered a reliable indicator of site quality of forest stands (**Lewis et al. 1976**), is the main reference regarding productivity quantification in our study, as it has been widely proved that dominant height is related to stand volume (**Castedo-Dorado et al. 2005**).

2.1 Ecological parameters and habitat description

Ecological parameters are defined as numeric relationships quantifying the influence of the ecological factors over the species and summarize field data, georeferenced data and laboratory data.

Physiography parameters selected for further analysing are: altitude, slope, superficial stoniness and thermotopographic index. The latter is calculated adjusting the insolation parameter of **Gandullo (1974**), thus measuring incident solar radiation as a function of slope and aspect from a thermic point of view (i.e. taking into account maxim temperatures take place not at midday but two or three solar hours in the afternoon) (**Gandullo 1997**).

Climatic parameters can be classified as related to rainfall (annual rainfall, spring rainfall, summer rainfall, autumn rainfall, winter rainfall, growing season rainfall), temperatures (annual mean temperature, monthly mean of maxims, monthly mean of minims, oscillation/fluctuation, sum of potential evapotranspiration –**Thornthwaite 1948**-), and water availability (surplus sum -**Thornthwaite and Mater 1957**-, shortage sum -**Thornthwaite and Mater 1957**-, hydric index –**Thornthwaite and Mater 1957,1955**-, draught length –**Walter and Lieth 1960**).

Edaphic parameters selected can be classified as physical parameters (fine earth fraction, sand, silt, clay, cementation capacity coefficient, silt impermeability coefficient, equivalent humidity, permeability and water retention capacity) or chemical parameters (organic mater, total and exchange acidity, superficial nitrogen, C/N relationship, phosphorus, calcium, magnesium and electric conductivity). Edaphoclimatic parameters (maximum real evapotranspiration, physiologic draught, calculated soil drainage) were directly obtained from **Sánchez-Palomares et al.** (**1999**).

Following **Gandullo et al. (1974)**, habitat description for the species in the area of study was depicted taking into account absolute maximum and minimum values (these values and the interval including 10 % of the cases considered in respectively higher and lower values defining marginal habitat for the stands) and mean of the ecological parameters together within the interval including 80% of cases defining the optimal or central habitat (45 sample plots data for the physiographic and climatic parameters and the 20 sample plots data for the edaphic parameters). The outcome and calculation procedures are shown in **Pérez-Crespo et al. 2009**.

2.1.1 Environmental factors mapping: potential areas for radiata pine establishment

The process of integrating topographic and climatic parameters in a GIS, together with the parametric information of the radiata pine's habitat allows for the definition of potential areas for the spreading of the species in the area of study considered, in a qualitative bound from punctual information to a territorial model, direct and more intuitive, even though rougher.

A digital model raster is the basic layer where all the information will be integrated. A raster consists of a matrix of points regularly distributed (pixels or cells) with a defined value of the variables considered.

Aptitude of a site can be expressed by a numerical index (global potential index) defining the contribution of each parameter (potential index) as a function of the location in which the value of the parameter is situated within the corresponding optimal or marginal habitat, following the methodology proposed by **Sánchez-Palomares et al. (2004)**.

The core drawback in this step is that digital cartography of edaphic properties, as it often happens, is not available in El Bierzo. Consequently, global spatial analysis including the latter is not possible. Therefore, the territorial model of potential areas of establishment for radiata to be developed will only contemplate physiographic and climatic parameters. The parameters selected for the spatial analysis were: Anr, Spr, Smr, Atr, Wr, Mat, Osc, Alt, Slo.

Georeferenced physiographic parameters

Altitude is directly obtained from a DTM, which basically consists of a digital representation of the spatial distribution of topographic altitude in an area. Slope is also directly calculated by a SIG algorithm from the DTM available (50 m of spatial resolution).

Georeferenced climatic parameters

The digital models obtained from the Digital Climatic Atlas of the Iberian Peninsula (**Ninyerola et al. 2005**), needed to be transformed into an appropriate format to be analysed with ArcGIS software. In the end, climatic parameters are given in a net of 200 m of spatial resolution.

For every parameter considered (i), two digital models corresponding to their respective aptitude indices (pi) applying the methodology proposed by **Sánchez-Palomares et al. (2004)** are generated. Thus, the territory is individually classified for each parameter. The overall result is a digital model with the values of the global potential index, showing a global productivity map for radiata pine in El Bierzo.

In order to ease interpretation of spatial analyses results, a classification of suitability in four categories has been carried out, taking into account the distribution of the values of the global potentiality index obtained. Further details of the procedures can be reviewed in **Pérez-Crespo et al. (2009)**.

Finally, a layer of radiata stands was extracted from the MFN **(DGCN 2000)** and revised using ortophotographies of the area of study and the georeferenced layer of the permanent sample plots network. The layer of radiata stand thus obtained was overlaid to the potentiality map in order to determine the suitability of the existent stands considering the categories defined in this study (i.e. classes of global potentiality index).

Softwares used in this part of the study are ArcGIS/ArcInfo 9.2 and Miramon v.5.2.

2.2 Descriptive exploration of data and Pearson's correlation test

Univariate statistics were calculated for each ecological parameter to check normality of distribution, general statistic adequacy, and guarantee a logical ecological behaviour. This step eases habitat definition and interpretation of results.

The main target of the next stage is to define the highest lineal relationship between parameters, enabling cause-effect and ecological interpretation.

A Pearson's correlation matrix (two-tailed $p<0.001$ and $p<0.05$) was constructed to find out whether a relationship between two parameters existed or not, and in the affirmative case, quantify the dependence connection by the univariate Pearson's correlation coefficient, quotient between covariance and standard deviations product, which must be significantly different from zero (**Lamotte 1971**) not to be caused by random sampling or inexistence of relationship between the parameters considered.

2.3 Multivariate statistical analyses

Multivariate statistics techniques allow for interpretation of ecological parameters and assessment of stand site quality by lineal models obtained with multiple regression tools.

The data analysis was conducted in two steps. The first step was the exploratory analysis (descriptive statistics, plots and Pearson's correlation matrix), thus identifying potential outliers and determining significant dependence relationships within and also between ecological and radiata stand parameters. The second step consisted in selecting and interpreting the major factors that affected *SI* applying reduction techniques, such as principal components analysis (PCA), in order to ease the construction of predictive models using discriminant rules and multiple regression techniques in the final stage.

Not to be forgotten is the fact that understanding of results and extraction of conclusions on an ecological basis will only be valid within the variability ranges of the parameters used in the study. Extrapolation to other stands or environments is therefore too risky.

SPSS© version 14.0 software was used for statistical analysis.

2.3.1 PCA

PCA is a multivariate statistical technique that reduces a wide data set of variables to a narrower set (components) preserving the maximum amount of information from the initial data set. Components are a lineal combination of the original variables. The matching coefficients are the eigenvalues of the matrix correlation or covariances of the variables. Components explain the maximum variance of variables and are classified in descendent order of their corresponding eigenvalues, defined as the sum of variances of the components (**Harman 1976**). The number of components must be chosen considering the balance between simplification of the number of dimensions and the loss of explanatory power implied in the reduction.

The objective is to characterize the main environmental gradients of radiata stands in the area of study, considering the ecological parameters defining the habitat. Should the initial solution be confusing, the factorial subspace axis rotation has proved to be a useful way of showing a high correlation between each parameter and a certain component, easing interpretation of PCA results. Selecting the axis rotation method must be made with caution, not to negatively influence the communalities (proportion of variance of each parameter explained by the whole set of the chosen components).

Observing the projections or saturations of each parameters over the selected components with the rotated solution, a set of parameters showing high saturations over the same component and low saturations over the rest can be defined, easing interpretation of components. The square of the saturation over a factor or component is a measure of the contribution of the parameter over that component. Varimax rotation was selected for this purpose, as the use of orthogonal rotations enhances the sought differences.

2.3.2 Discriminant analysis (DA)

The basic idea underlying discriminant function analysis is to determine whether groups differ with regard to the mean of a variable, and then to use that variable to predict group membership. DA consists of a set of linear functions (classification functions) of independent variables that calculates the geometrical distance between observations and established groups. Observations are classified according to the shortest distance to a group, represented by the highest value of the linear discriminant function (**Gil et al. 2001**).

DA was evaluated using cross-validation. In this kind of validation, sample data are omitted one at a time, the parameters of the model are re-estimated and then the model is validated with the omitted datum.

2.4 Model construction

SI was the stand parameter selected to be the dependent variable in the elaboration of predictive models to assess productivity of radiata stands in El Bierzo.

SI linear models were estimated by weighed least-squares multivariate regression. This method does not alter the model structure and produces a near-constant variance of the residuals. The weighing factor was the inverse of the variance. This analysis was conducted as follows: firstly, individual regressions for each parameter (*SI* dependent variable) are carried out, consequently selecting the parameter most reducing the sum of squares (i.e. the one explaining variance of *SI* on a higher percent); secondly, this parameter is converted to covariable, in order to isolate the remaining set from its influence over *SI*. The process continues until the additional contribution of a new parameter absorbing the variance of *SI* is considered too small.

This stepwise technique may lead to a multivariate regression model containing parameters that did not show significant correlation with the dependent variable in the previous steps, whereas other variables initially included may finally be dropped off the model. Certainly, the inclusion of an explanatory variable in a regression model does not necessarily imply it has a significant influence on the dependent variable. On the other hand, to keep the regression models the simplest as possible, they should contain the minimum number of variables to ease calculations and assure applicability in the terrain. Thus, following the principle of parsimony, other models finally selected were fitted with two independent variables.

The final function was a lineal prediction equation with the smallest probability of failure in its solving using the chosen parameters. Once obtained, accuracy is defined by its multiple adjusted determination coefficient, standard error and variance percent index not explained by the equation.

2.5 Evaluation and assumptions testing

As an independent data set for validation was unavailable, we compared the results as regards ecological range obtained for the species within the area of study with the results obtained for the study of the main species of pine growing in Spain (**Gandullo and Sánchez-Palomares 1994**), measured in calculation of ecological valances, for those ecological parameters that was applicable to.

Ecological valance has been the criterion used to define the species as generalist or specialist regarding its tolerance range for a certain ecological parameter, depending on the range within the central habitat interval (**Gandullo and Sánchez-Palomares 1994**). However, ecological valance must be necessarily related to an ecological factor concept. Not all the parameters selected can be considered as factors, as they may not show direct influence on vegetation (e.g. altitude).

Nevertheless, it is still interesting to quantify the variation of a parameter. Therefore, the variation coefficient, together with the difference and quotient between higher and lower threshold of the optimal habitat, have been calculated only for the plots within the latter interval.

In addition, normality, linear independence and homogeneity of variance of the residuals were studied using the Shapiro-Wilk test, the normal probability plot and the residual values/predicted values plot.

A synthesis of all the steps involved in the ecological analysis is shown in **Figure 3.1**.

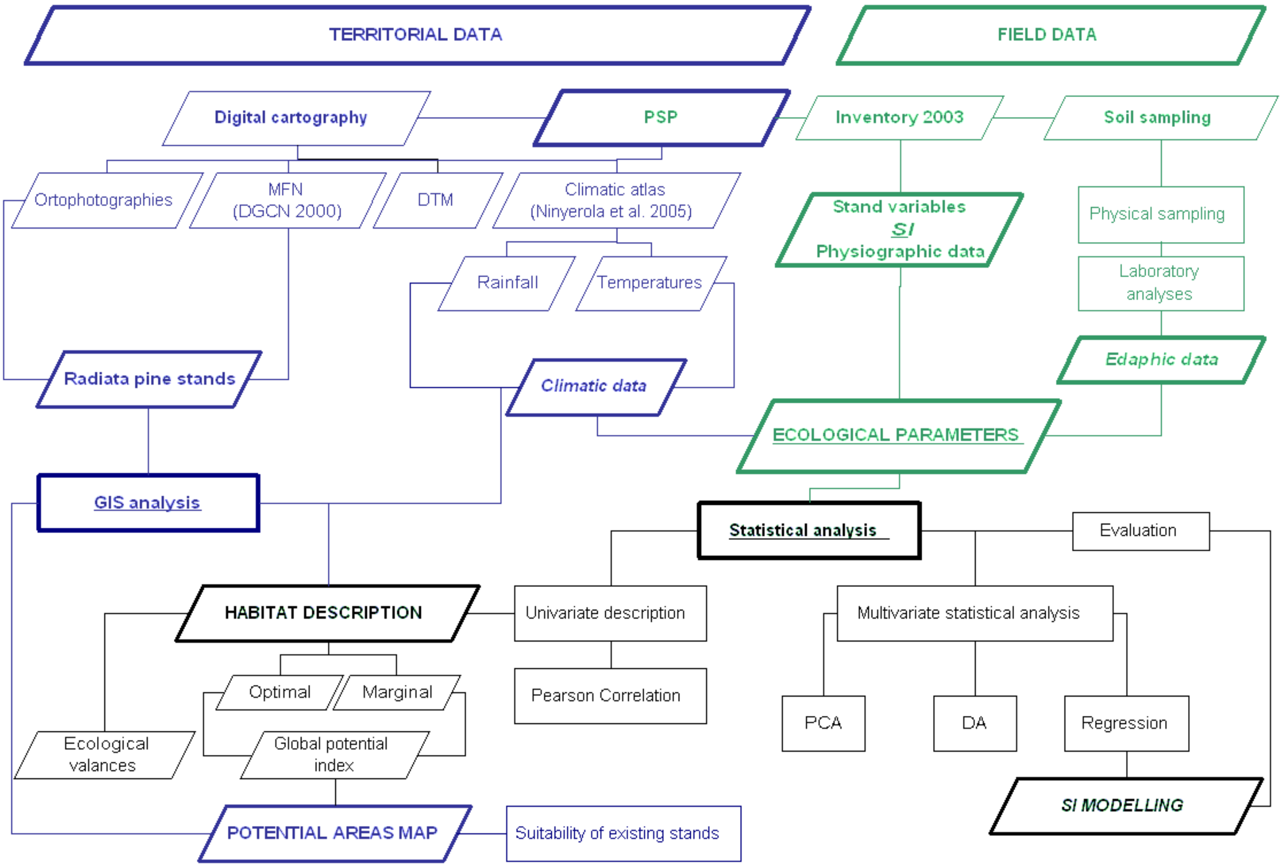

Figure 3.1 Diagram of data sources and methodological processes

3 Results

3.1 Ecological parameters and habitat description

Standardized ecological parameters depicting marginal and central habitat of radiata stands in El Bierzo are shown in **Figure 3.2**.

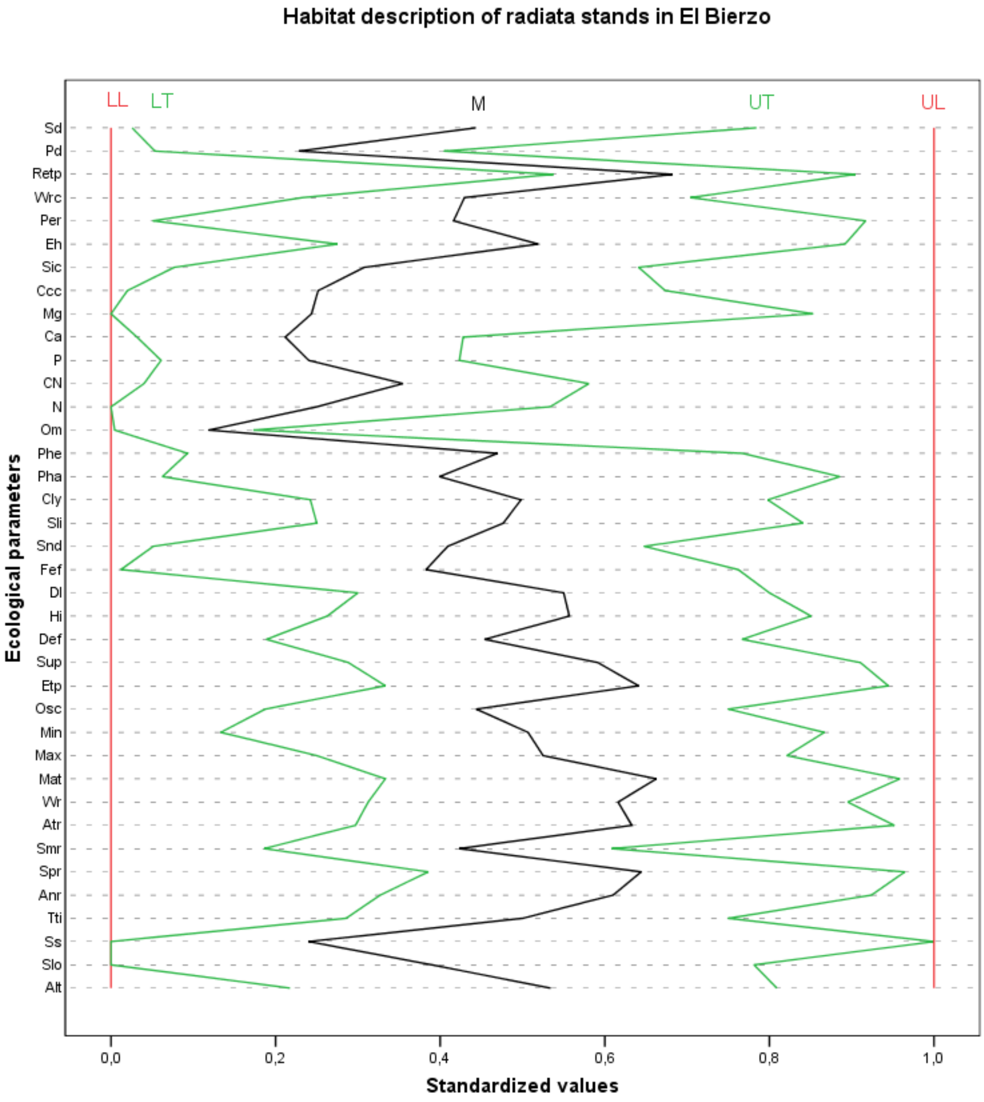

Figure 3.2 Central habitat (LT-UT) and marginal habitat (LL-LT) and (UT-UL) of radiata pine stands in El Bierzo as regards the ecological parameters calculated. LT=lower threshold, LL=lower limit, M=mean, UL=upper limit, UT=upper threshold

3.1.1 Cartography of areas of suitability

Based on GIS layouts of the georeferenced ecological parameters and the results obtained in the habitat definition analysis, two cartographic outputs of the study are shown in **Figure 3.3** (Ecological parameters) and **Figure 3.4** (Central and marginal habitat).

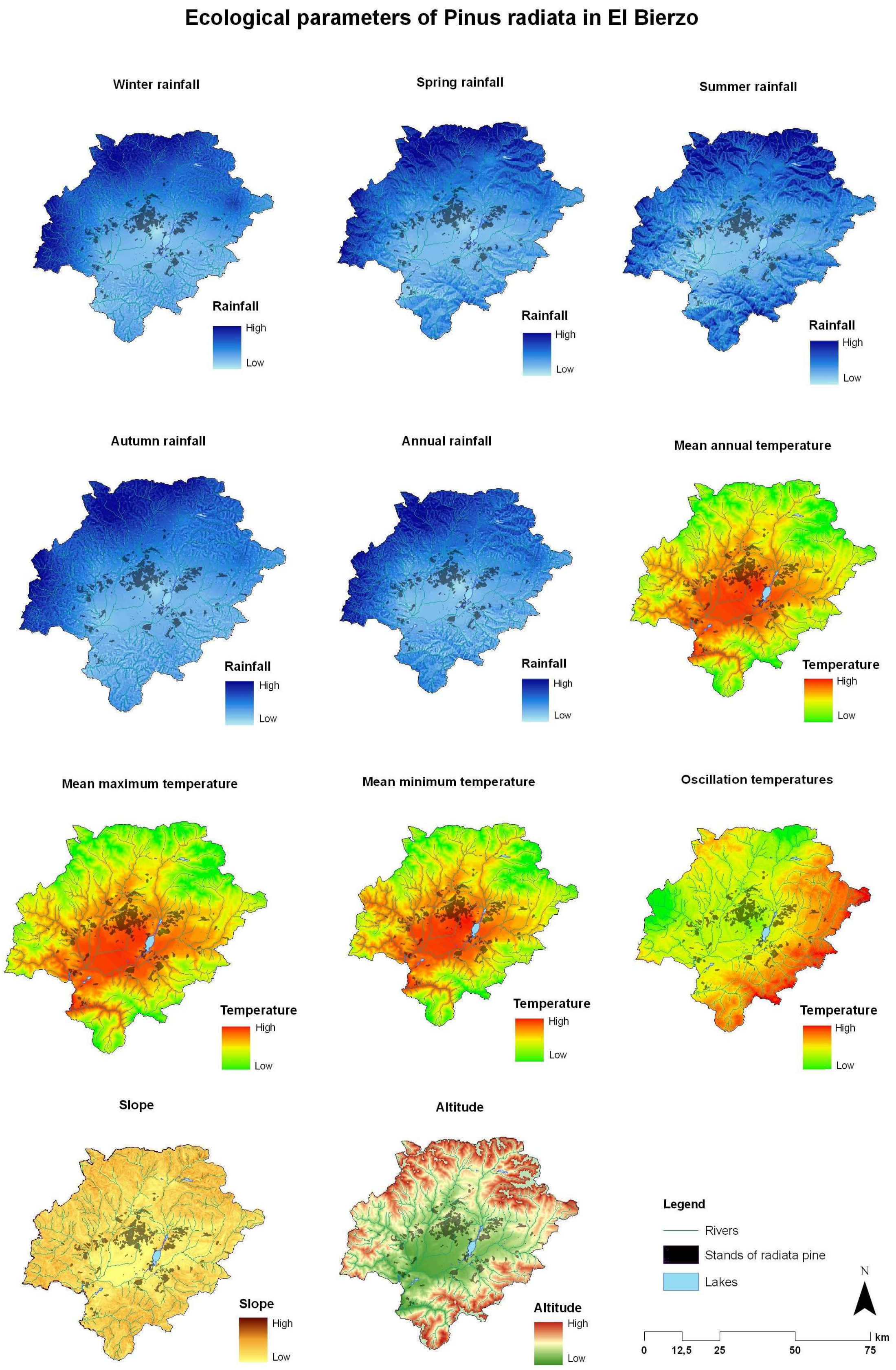

Figure 3.3 Georeferenced ecological parameters in El Bierzo

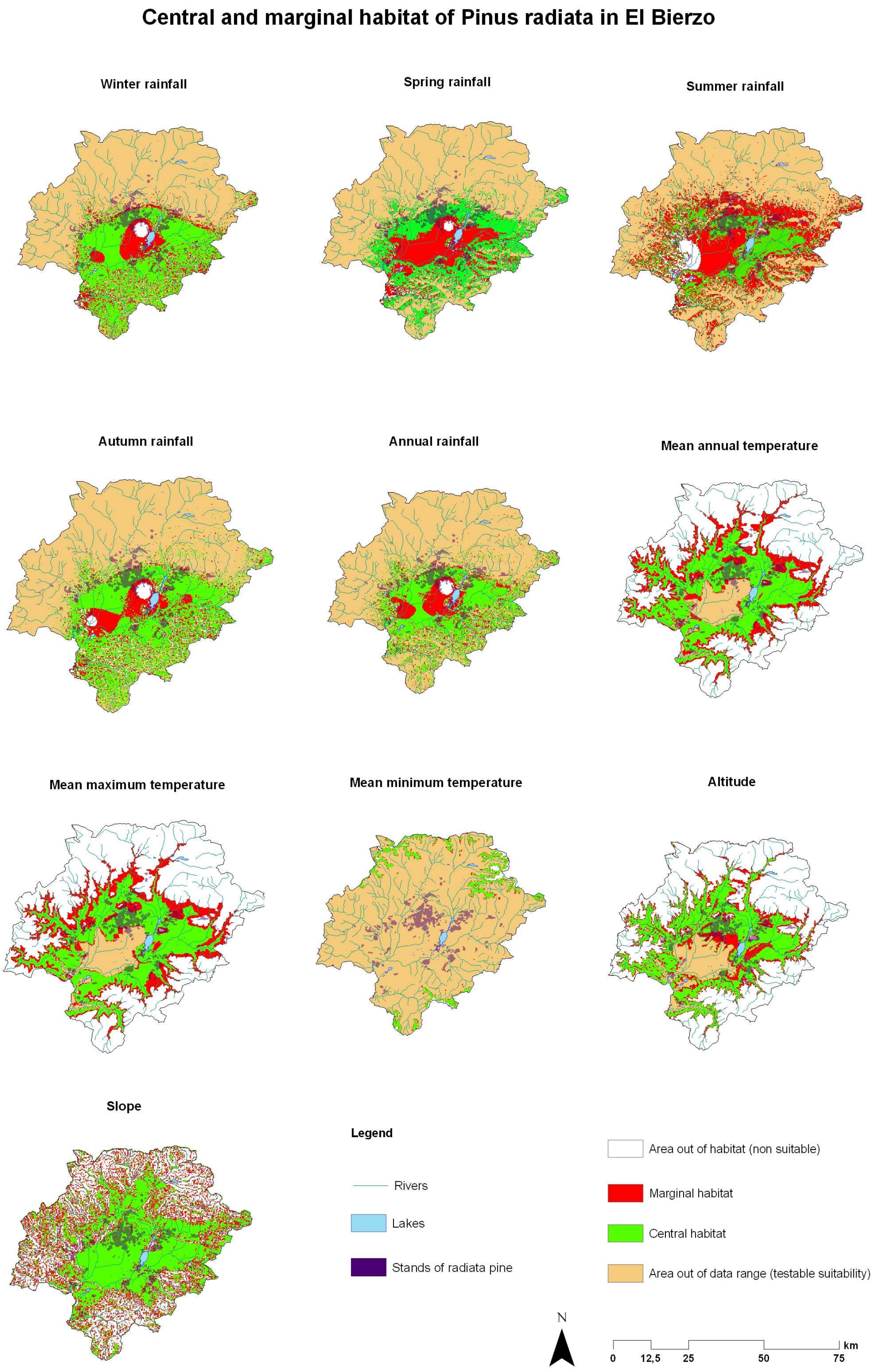

Figure 3.4 Central and marginal habitat of georeferenced ecological parameters in El Bierzo

The final map, incorporating the classification based on the distribution of values of the global potentiality index is shown in **Figure 3.5a**.

Altogether, 144 000 ha fall in the potential surface for the species in El Bierzo. More precisely, 2908 ha are included in the optimal class, whereas 73 292 ha belong to the lowest quality area. In turn, respectively 43 632 ha and 23 880 ha lie respectively within a moderate and high suitability categories. The whole surface of the region is 318.000 ha, which means that about 45.3 % is considered as potential for the species. Only 2908 ha, representing 2% of total suitable surface and less than 1% of the total surface of the area of study, are classified as optimal (**Pérez-Crespo et al. 2009**).

The optimal area refers to the medium altitude lands, between the central depression and the mountain chains bordering northwards, (municipalities of Sancedo, Cubillos and Toreno) and eastwards, entering in the highlands through the river Boeza basin and in a lower extent southwards, following the courses of the rivers Oza and Meruelo.

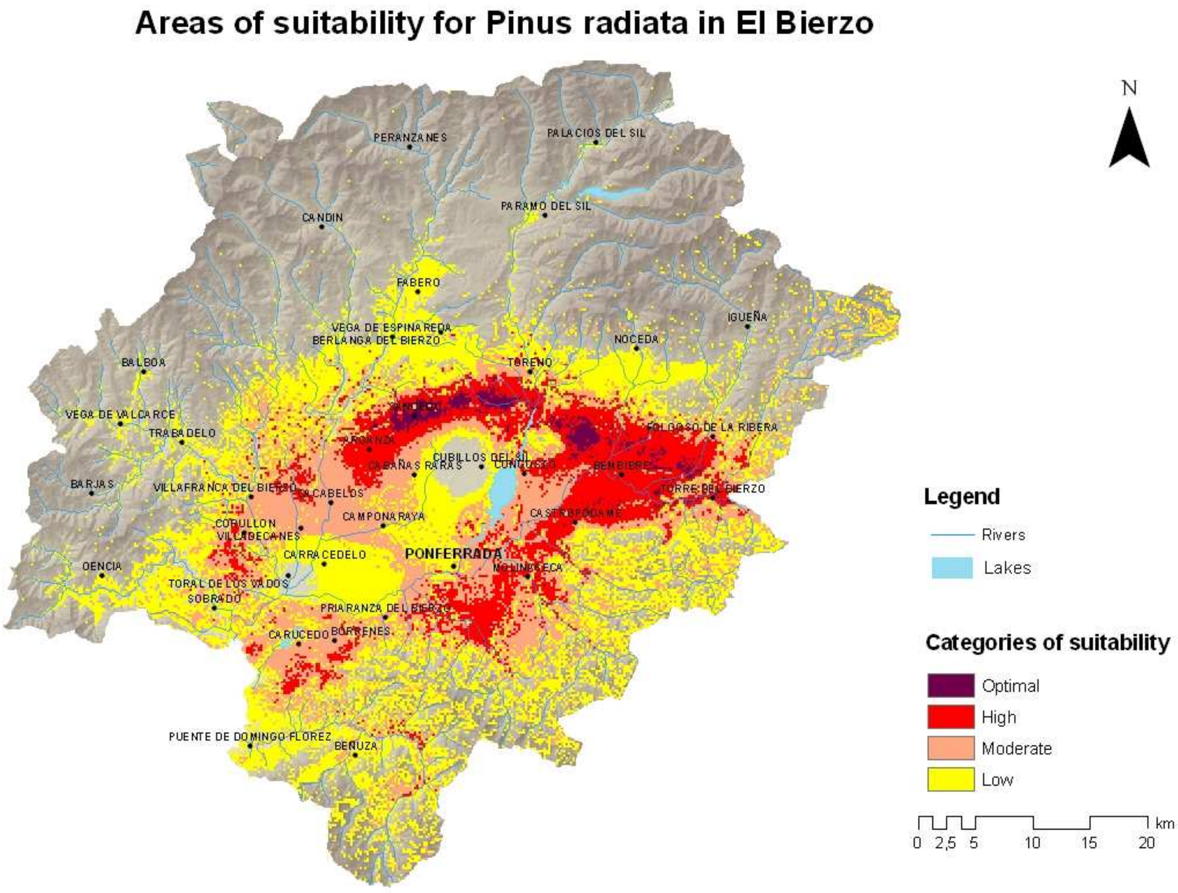

Figure 3.5a Physiographic and climatic potential areas for *Pinus radiata* D. Don in El Bierzo

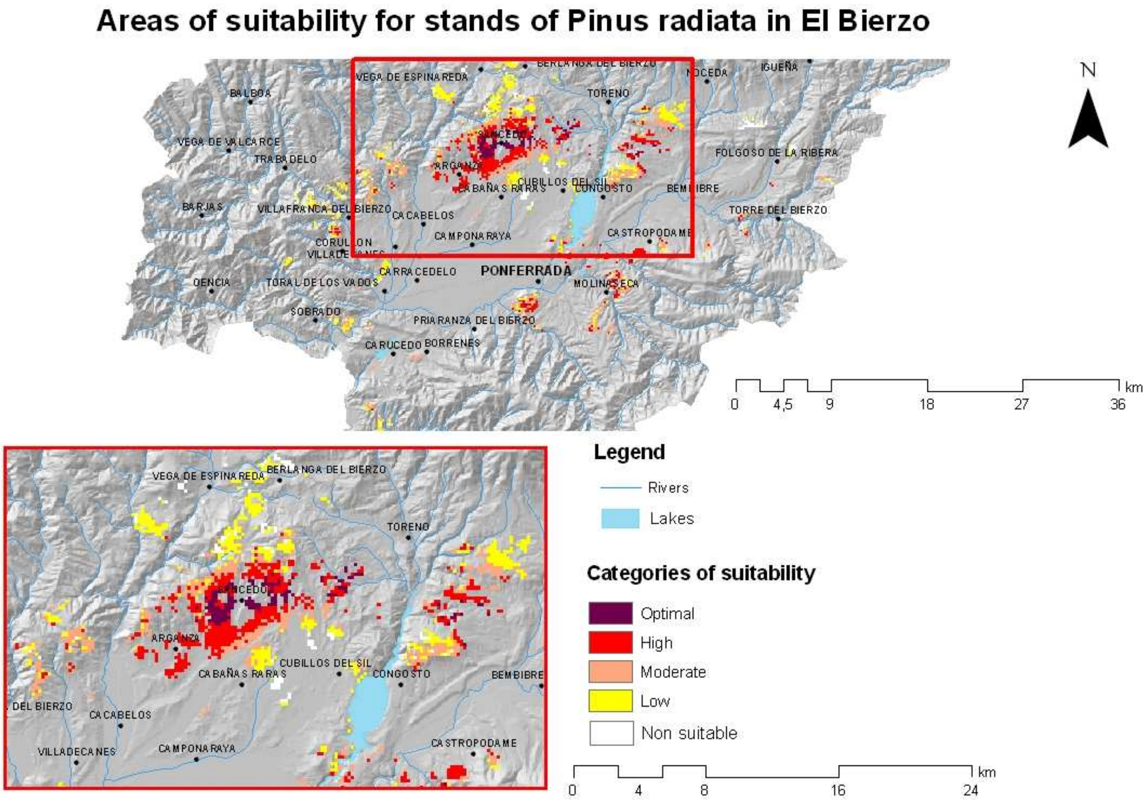

Figure 3.5b Sample of main potential areas for stands of *Pinus radiata* D. Don in El Bierzo

Figure 3.5b shows a zoom of the extracted layer of radiata pine stands in El Bierzo obtained from the MFN **(DGCN 2000)** classified according to the categories of suitability defined. The surface of stands of radiata pine in the area of study is evenly distributed amongst the central classes, with respectively 2520 ha, 2548 ha and 2564 ha (adding up to 84% of the stands) in the high, moderate and low categories of suitability. There are 864 ha (9.5%) of radiata pine stands in the area classified as non suitable for the species, whereas only 584 ha (6.4% of the stands) of the stands are located in the optimal area.

3.2 Description of ecological parameters and correlations

3.2.1 Data exploration

Univariate descriptive statistics provided the following results:

Physiographic parameters

As regards topographic conditions, radiata pine plots in El Bierzo show altitudinal limits between 625-850 m in the central habitat defined, and are mainly located in plains or gentle slopes.

All variation coefficients are high and show normal distribution, except for Ss. Slo and Ss highest values differ greatly from their respective mean values. Ss shows a narrow range of variability, which can be explained by the fact that radiata stands in El Bierzo are mainly planted in former agriculture fields, with even surfaces without rocks, on flat areas or only gentle slopes. In absolute terms, altitudes are high, ranging from 544 to 921 m especially when compared with the area of distribution of the species in other regions like Galicia, Asturias or Basque Country. Tti is clearly influenced by gentle slopes and suntrap aspect, especially regarding the optimal habitat interval.

Climatic parameters

Climatic conditions in the area of study, with cold winters and moderately warm summers, influence the species, clearly specialist in most of the climatic parameters as shows their respective low variation coefficients of the central habitat.

Annual rainfall of the stands is close to 900 mm, with summer rainfall barely over 100 mm in the optimal habitat interval.

Hydric pattern presents relatively wide variations in the sum of surpluses, shortages, hydric index and draught length.

As regards thermic conditions, average temperature of maximum of the warmest month and total potential evapotranspiration show an especially narrow range of variation, only a bit higher in the case of mean annual temperature, around 11.5 ºC, whereas mean temperature of the minimum of the coldest month presents a wide distribution. Osc, around 26.5 ºC, scarcely presents variations.

Edaphic parameters

Analysing the central interval of the edaphic parameters, it can be observed that, leaving out acidity, radiata stands in El Bierzo are generalist. Parameters determining physical soil characteristics are in general almost normal, high values distant from the mean. The species is generalist as regards the latter parameters while it shows a specialist behaviour regarding Eh. Chemical parameters, with a marked peak distribution, do not lie within the normal at all, except for exchange acidity, close to normality. Acidity values show radiata preference for rather acid soils.

Edaphoclimatic parameters

The behaviour of the paramters within this set differs as follows: Retp and Pd do not strictly show a normal distribution, extreme values far from the average. Sd is closer to normality. The species in the area of study is tolerant as regards these paramters, though it shows a slightly less tolerance as regards Retp.

3.2.2 Correlation matrix

Correlations, apart from quantifying dependence relationships between parameters, can help in selecting redundant ecological parameters.

Logically, parameters within a group (physiographic and particularly climatic and edaphic) are highly correlated. However, several remarks should be stated. For instance, in the physiographic group, only altitude and slope are significantly correlated. Edaphic parameters show extreme (high or low) correlation. Mg and Pha are highly and inversely correlated (i.e. less Mg implies higher acidity). Retp and Pd present the only significant relationship (inverse) between edaphoclimatic parameters.

Between groups, physiographic and edaphic parameters are not correlated. Ss and Tti and P are not correlated at all with any other parameter. Generally, physical soil properties parameters do not show relationship with climatic parameters, apart from low correlations with Per.

Anr, Spr, Atr, Wr show high correlation with water pattern parameters (Sup, Def, Dl, Hi). Radiata stands in El Bierzo present a slight summer draught. An interesting remark would be that wetter environments not necessarily match with higher summer rainfall values locations.

All climatic parameters are related to Alt, reflecting the altitudinal gradients influencing temperature and rainfall.

Dl shows a high correlation with Spr, Def, over 0.85 with Max, Etp and Hi with Max.

As regards thermic parameters, Osc show the lowest correlations with the rest. Mat and Etp show the highest correlation (0.995), as Etp calculation depends on Mat. Evidently, elaborated parameters are related to the factors included in their calculation equations (suchlike Ccc, Sic).

The most important results regarding productivity modelling are the significant correlations obtained between *SI* and the ecological parameters (positive March, October and November monthly rainfall, Atr and inverse with Pha and Mg).

A summary of the most significant relationships is given in **Table 3.1**.

Table 3.1 Highest Pearson's correlation coefficients obtained between *SI* and ecological parameters

Pearson's Correlation between *SI* and ecological parameters

Climatic parameters	October rainfall	Atr	March rainfall	November rainfall	September rainfall	February rainfall	January rainfall	Wr	Sup	Spr
	0.621	**0.593**	**0.586**	**0.565**	0.553	0.534	0.500	0.475	0.465	0.451
Edaphic parameters	Mg	Pha								
	-0.530	-0.470								

Correlation is significant at the 0.05 level (2-tailed)

Bold: Correlation is significant at the 0.01 level (2-tailed)

Atr=autumn rainfall; Mg=magnesium; Wr=winter rainfall; Pha=Total acidity ; Sup=superavit; Spr=spring rainfall

3.3 Multivariate techniques

3.3.1 PCA

The number of factors retained in the PCA was determined using the factors/eigenvalues plot. Three principal components, explaining a 79.34**%** of the total variance, were included in the models. Principal Component 1 (PC 1) had a marked water balance dimension (Etp, Sup, Def, Hi, Dl), and to a slightly lesser extent seasonal precipitations, minimum temperatures, maximum temperatures of November, December and January (coldest months), and altitude and monthly precipitations of the out of growing season months*.* Principal Component 2 (PC 2) was also strongly correlated with climate, but specifically with maximum temperatures in autumn and with spring and autumn rainfall (i.e. climatic factors widening growth season) and finally Principal Component 3 (PC 3) was correlated with edaphic factors: texture, calcium and equivalent humidity. Overall, PCA evidenced the influence of the water pattern and importance of the growing season on the radiata pine habitat. Taking into account the communalities obtained for each parameter, it can be noted that all of them are more or less sufficiently explained by the set of 3 components selected.

3.3.2 DA

Two discriminant functions for productivity (i.e. *SI*) were used to create three groups of productivity based on ecological parameters. Stepwise forward was the selected technique in this analysis. The final Wilk's lambda obtained in four steps was 0.117. The variables selected in the model were Atr, phe, D and Mg. Standarized canonical coefficients were respectively for discriminant function 1: 1.437, 1.092, 2.658, 1.303 and for function 2: 0.884, 0.235, 0.181, -0.751. The canonical correlation of function 1 was 0.923, whereas function 2 obtained 0.464 for this value, remarkably lower as commonly occurs. Consequently, the percentage of variance explained by each functions were 95.4% by function 1 and 4.6 % by function 2. The classification matrix showed that 80% of the original cases were correctly classified within the groups of productivity. Finally, 65% of cross-validated grouped cases were correctly classified. The most frequent misclassification errors occurred between groups 1 and 2, which include the lowest productivity.

3.4 *SI* modelling

Interpreting the sum of absolute values of correlation coefficients within the stand parameters by columns as an indicator of the independence of each parameter related to the rest of them, *SI* shows a clear independence from the rest of stand variables, with a total value of 0.299. Therefore, *SI* is selected as dependent variable reflecting stand productivity. Another reason is that *SI* is the best indicator of quality of the stands, and it is not influenced by silvicultural practices (moreover in the area of study, where up to date, silviculture practices are almost inexistent).

Initially, four predictive models were selected. The principal good-of-fit statistics (multiple determination coefficient R^2, adjusted multiple determination coefficient R^2adj, Durbin-Watson statistic, and standard error of the estimation -standard deviation of the residuals-, fitted parameters (coefficients and constant), and selected independent variables are shown in **Table 3.2**. The statistics obtained in the evaluation tests of model assumptions explained in section 2.5 showed adequate behaviour.

Table 3.2 *SI* (dependent variable) linear regression models selected, independent variables and numeric statistics

Model 1		**Model 2**		**Model 3**		**Model 4**	
Independent	Coefficient	Independent	Coefficient	Independent	Coefficient	Independent	Coefficient
Atr	0.499	***October rain***	0.163	***Atr***	0.073	***October rain***	0.181
Retp	0.057	***Retp***	0.031	***D***	0.036	***D***	0.033
Wr	-0.348						
Sic	-12.045						
Mat	-2.695						
Constant	11.690	Constant	-12.900	Constant	0.337	Constant	1.666
R^2	0.820	R^2	0.559	R^2	0.536	R^2	0.544
R^2adj	0.750	R^2adj	0.507	R^2adj	0.481	R^2adj	0.490
Durbin	2.834	Durbin	2.592	Durbin	2.139	Durbin	2.250
SD residuals	0.961	SD residuals	1.354	SD residuals	1.38	SD residuals	1.373

R^2adj=adjusted coefficient of determination; Durbin=Durbin-Watson statistic; SD residuals= standard deviation of residuals

All models provided mean residuals of zero and adequate behaviour of the F statistic ($p<0.001$) in the ANOVA's test.

Multiple determination coefficient (R^2), is defined as the quotient between the sum of squares caused by the regression and the sum of total squares, whereas the adjusted multiple determination coefficient, is analogously defined using variances instead of sum of squares. The latter is generally preferred as it avoids the fictitious increment of R^2 when including more predictive variables.

To analyse the adequacy of the test, several relevant statistics were obtained. Durbin Watson coefficients show but very slight existence of dependence between residuals. Mean of residuals is zero. F significance in ANOVA's test shows an adequate value (very close to zero) ($p<0.001$). The residual analysis of the final predictive models showed no violations of the assumptions. Because atypical values were representative of the high ecological variability of the sampled area, they were not removed from the models. No multicollinearity problems between explanatory variables were detected.

Standardized residuals plotted against the standardized predicted value of *SI* for all models are shown in **Figure 3.6**.

The predictive equation in Model 1 only shows high standardized residuals in plots 18, 32 and 35, with *SI* values of 21.93, 23.28, and 20.25 respectively.

The first parameter included reflects that the best sites receive higher autumn precipitation. At the same level of Atr, a higher Retp enhances radiata growth. Sic inverse contribution to *SI* indicates that more permeable soils are related to higher productivity. Overall, climatic parameters and an edaphoclimatic parameter (Retp) are the main factors in the equation. The only edaphic parameter included is Sic. Most of the parameters are related to water balance.

The rest of models, were selected to meet the challenge of explaining *SI* variability with a small number of variables following the principle of parsimony.

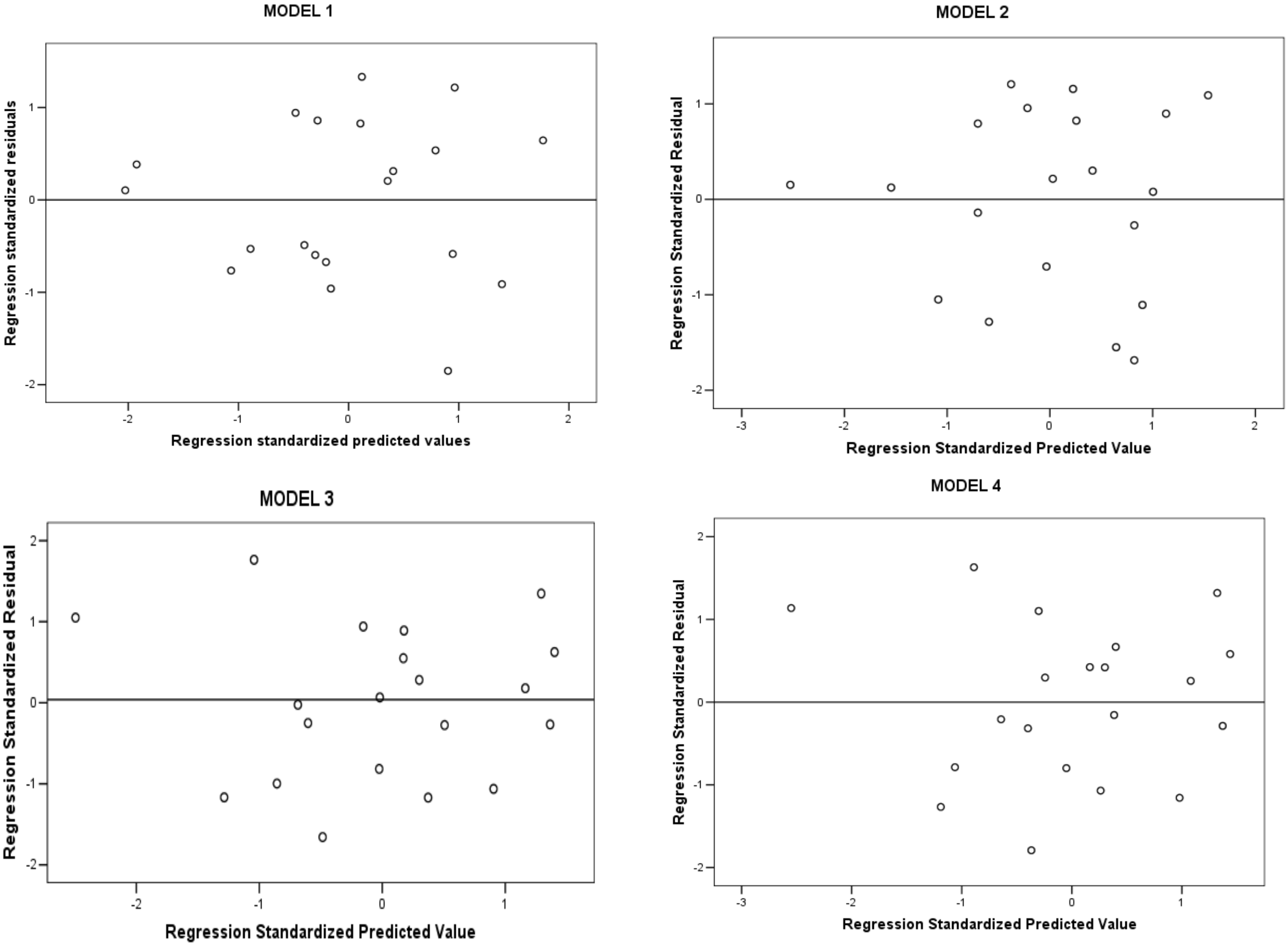

Figure 3.6 Plots of standardized residuals against standardized predicted *SI* values for selected models

3.5 Evaluation

Table 3.3 shows the behaviour of the species in the area of study compared to the rest of the country based on ecological valances calculation following **Gandullo and Sánchez-Palomares (1994)** that enables the classification of the species as tolerant or not for the corresponding ecological parameters.

As regards multivariate techniques, as an independent data set was not available, PCA could not be otherwise evaluated. However, the statistics that state the appropriateness of the technique showed an adequate behaviour. In turn, DA included a cross-validation of the classification process that has been explained in the corresponding section (**3.3.2**).

Equally, several statistics have been examined in the regression test (**Table 3.2**). Nonetheless, in addition, observed valued plotted against predicted values of *SI* for the selected models are shown in **Figure 3.7**.

Table 3.3 Ecological valances calculated for some ecological parameters describing the ecological behaviour of *Pinus radiata* D. Don in El Bierzo and comparison with the behaviour of the species in the rest of the country

	LT	**UT**	**EV**	**Ecological behaviour**		**LT**	**UT**	**EV**	**Ecological behaviour**
Alt (m)					**Fef** (%)				
Spain	125	550	2.4	I	Spain	35.9	97.3	6.7	T
El Bierzo	626	849	1.3	I	El Bierzo	29.2	72.7	7.1	T
Slo (%)					**Snd** (%)				
Spain	0	65	8.5	T	Spain	10.1	65.9	6.7	T
El Bierzo	0	25	3.9	MI	El Bierzo	17.6	51.3	6.1	MT
Wr (mm)					**Sli** (%)				
Spain	330.7	579	4.8	MI	Spain	22	60.5	6.4	MT
El Bierzo	303	359	2.3	I	El Bierzo	25	46.5	5.6	MT
Spr (mm)					**Cly** (%)				
Spain	238.7	489.1	5.7	MT	Spain	10	35.8	5.7	MT
El Bierzo	193	229	1.5	I	El Bierzo	20.7	38.6	6.9	T
Smr (mm)					**Per**				
Spain	117.6	289.6	5.9	MT	Spain	1.3	5	9.7	T
El Bierzo	87	102	0.9	I	El Bierzo	1.5	3.4	5.1	MT
Atr (mm)					**Wrc** (mm m^{-1})				
Spain	303.4	576.4	5.8	MT	Spain	67.4	371.3	8.5	T
El Bierzo	226	268	1.5	I	El Bierzo	140.2	347.4	6.8	T
Anr (mm)					**Om** (%)				
Spain	1065	1927.1	5.4	MT	Spain	2	9.4	8.0	T
El Bierzo	817	959	1.7	I	El Bierzo	0.53	3.6	4.1	MI
Mat (ºC)					**Pha**				
Spain	10.4	13.7	4.2	MI	Spain	4.4	5.8	3.4	MI
El Bierzo	10.7	12.2	1.3	I	El Bierzo	4.5	5.3	5.7	MT
Max (ºC)					**Retp** (mm)				
Spain	16.2	20.1	3.3	I	Spain	591.5	695.7	2.4	I
El Bierzo	16.3	17.7	2.9	I	El Bierzo	572.4	619.3	4.5	MI
Min (ºC)					**Pd** (mm)				
Spain	4.2	8.1	2.7	I	Spain	2	87.9	1.8	I
El Bierzo	4.9	6.8	0.8	I	El Bierzo	42.2	87.7	5.3	MT
Osc (ºC)					**Sd** (mm)				
Spain	10.1	14.1	2.9	I	Spain	423.2	1274.2	6.7	T
El Bierzo	11.3	10.9	0.7	I	El Bierzo	499.8	659.4	2.0	I
Etp (mm)					**DI** (months)				
Spain	643.7	735.2	2.5	I	Spain	0	0.01	1.7	I
El Bierzo	653	697	4.8	MI	El Bierzo	1.7	2.2	0.8	I
Sup (mm)					**Def** (mm)				
Spain	562.5	1329	5.9	MT	Spain	26.3	204	3.2	I
El Bierzo	412	537	1.7	I	El Bierzo	240	292	2.9	I
					Hi (mm)				
					Spain	63.1	186.9	5.7	MT
					El Bierzo	34.6	59	2.0	I

LT= Lower threshold

UT= Upper threshold

EV=ecological valance (based on Gandullo and Sánchez-Palomares 1994)

I=intolerant	MI=moderately intolerant
T=tolerant	MT=moderately tolerant

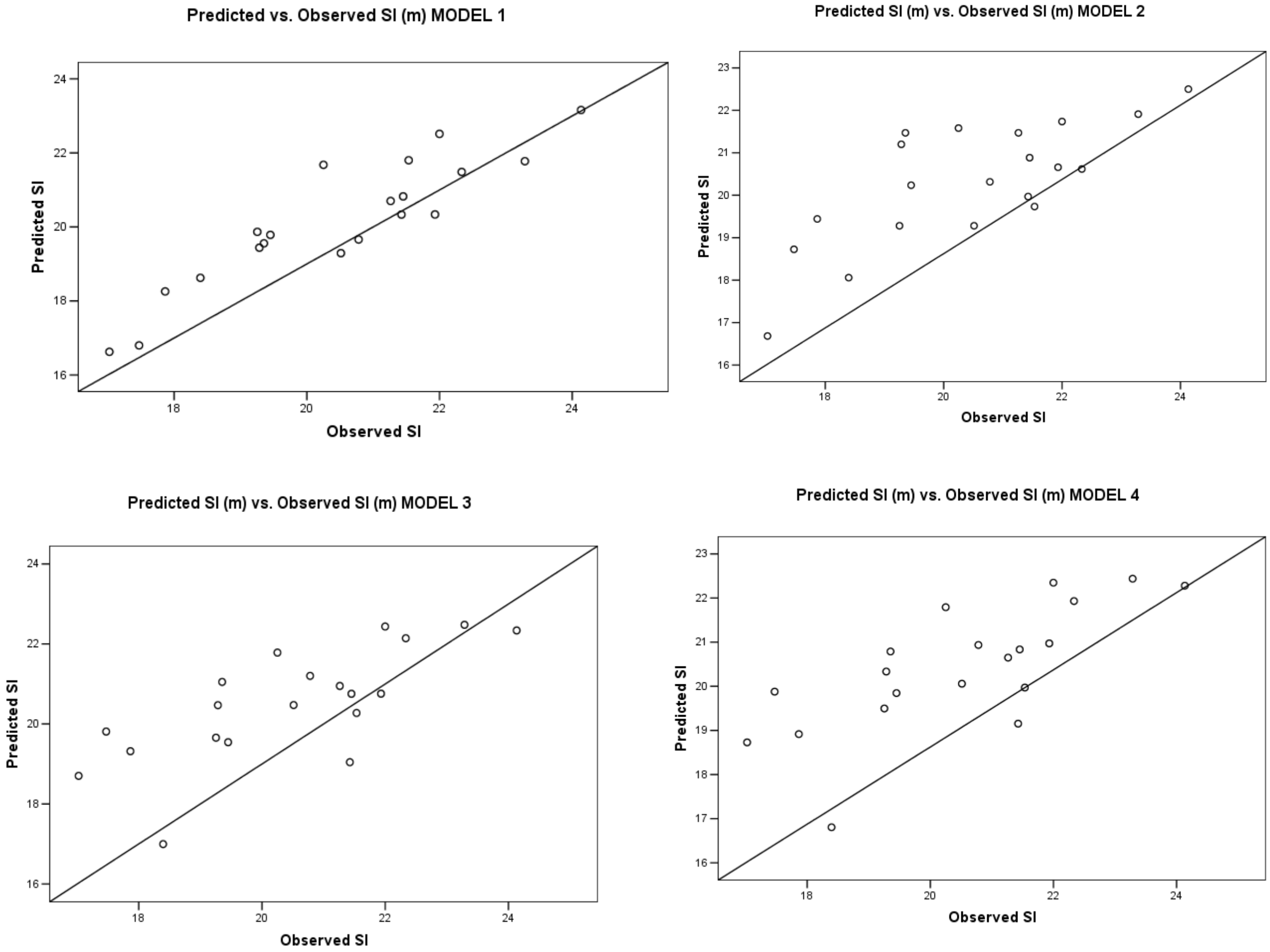

Figure 3.7 Plots of predicted values of *SI* provided by Models 1, 2, 3 and 4 versus observed *SI* values. *SI* (m, reference age 20 years). All models tend to overestimate *SI*

Finally, the Shapiro-Wilk's test values obtained for the models were respectively 0.95, 0.92, 0.97 and 0.97, all of them significant.

4 Discussion

Selection of *SI* as the quantifying parameter of stand productivity is adequate, and the general choice in related studies (**Bravo-Oviedo and Montero 2005, Romanyà and Vallejo 2004**). Strictly speaking, some considerations to this parameter should be taken into account. For instance, in plantations, intraspecific competition is certain to influence dominant height. Therefore, *SI* would not be strictly only dependent on site, at least when the stands are young. Likewise, silvicultural practices can affect the dominant stratum in a particular time. These remarks are not considered relevant regarding the results obtained, especially considering the main objective of the study and the accuracy intended.

Ecological variables used in many site index studies are edaphic and climatic. Statistical methods find and attempt to quantify the relationship between these attributes and *SI* using correlation coefficients, multiple regression, principal components analysis, or discriminant rules. The results indicate that variables related to climate, above all, autumn rainfall (key months October and November, followed by March) and to a lesser extent, soil properties (inverse relationships found with Mg^{2+} and pH) are associated to site classes. **Bravo-Oviedo and Montero (2005)** state that elevation along with texture and other ecological parameters should explain site quality. However, in our case, physiographic factors suchlike elevation and slope have not affected *SI* directly. Our results are in accordance with the ecological study of radiata pine in nearby Galicia (**Sánchez-Rodríguez 2001**). In addition, as stated by **Sánchez-Rodríguez (2001)**, to string together, pH has an indirect relationship with altitude through the correlation between the latter and precipitation, and it can be indirectly linked with the *SI* and pH relationship found. Moreover, this fact is in agreement with the ecological requirements of the species, confirming that radiata pine grows well on acid soils (actually it grows well in most types of soils). The water demand of *Pinus radiata* is high -as high as that of broadleaved forests (**Gholz et al. 1990**), and, accordingly, also as stated by **Gerding and Schlatter (1995),** productivity in the region is optimized in locations with higher autumn rainfall and lower winter rainfall. Particularly, autumn rainfall relevance is explained because it is in this season when the second annual growth of the species occurs. Other local vegetation and planted trees do not show this autumnal growth pattern and it seems thus logical that better conditions during this period, in which there is less competition with other vegetation species, favours radiata productivity.

Thus, in sum, even though due to the territorial scale considered a higher influence of soil parameters should have been expected, on the whole, *SI* of radiata stands in El Bierzo is distinctly influenced by climatic factors. Rainfall was also crucial in other studies, e.g. **Snowdon et al. (1999)** showed that *Pinus radiata*'s growth is highly sensitive to annual rainfall when planted in areas with moderate rainfall. Also, **Sands and Mulligan (1990)** stated that the species growth slows down during the summer drought.

The spatial analysis could be superior if better resolution digital cartography becomes available. The data used affect the output, especially potential areas quantification, smallest than the estimated in other studies in the region (**Fernández-Manso et al. 2001**), most probably explained by the different techniques applied. A strict consideration of a narrow range of ecological parameters in a small sample clearly generates inexactness when generalizing to a wider area. Nevertheless, even if roughly, the final map is a good generalization of the knowledge of the aptitude of the terrain for the establishment of radiata stands, extending the conclusions from punctual locations to wider surfaces. Its usefulness regarding forest management is out of doubt. About 45.3 % is considered as potential for the species, though only 2% of the suitable area is classified as optimal.The overlapping of the existing radiata pine stands with the potentiality map shows that the stands are distributed mostly evenly in the high, moderate and low classes of suitability. The fact of 62% of the stands being classified from the moderate to the optimal classes of suitability is not surprising, as radiata pine in the area of study has been mainly planted on abandoned agricultural fields of the central plain.

PCA results (e.g. importance of rainfall during immediately prior months that would favour the growing period if water supply is adequately stored) are also consistent with the rest of findings (habitat description, correlation matrix, DA, regression models) and in agreement with **Gandullo et al. (1974)**.

This pine also needs good soil aeration (higher productivity where Sic is low) and is able to grow with lower mean annual temperatures when compared to other species of the same genus. The sensitivity of *Pinus radiata* to temperature has been pointed out by several authors (**Hunter and Gibson 1984, Rook and Corson 1978**), who reported optimum mean annual temperatures for growth of 10– 12 ºC, similar to the mean annual temperature in El Bierzo (11.5 ºC). According to **Romanyà and Vallejo (2004)**, radiata pine is closer to its optimum temperature conditions in the Mediterranean area than in the Eurosiberian regions. This could be attributed to the environmental conditions in its natural area of distribution, Mediterranean California coastline or of other areas where it has been successfully introduced, in similar latitudes of the southern hemisphere (e.g. New Zealand). The larger water storage capacity associated with the deeper soils of Mediterranean sites may reduce the water deficit during the summer drought. As a result, the highest growth of *Pinus radiata* plantations in the Mediterranean area is confined to high quality soils (**Romanyà and Vallejo 2004**), with appropriate depth as main growth limiting factor. *SI* models developed for other conifers also show a strong influence of soil volume on site quality (**Corona et al. 1998, Wang 1995**).

Unlike in other regions (**Romanyà and Vallejo 2004**), fertility and other soil properties have not proved to be a key factor. This is explained because afforestations with radiata pine in El Bierzo have been located in former agriculture fields, in flatter areas, with adequately fertilized and laboured soils.

Besides, topography in El Bierzo favours haze and mists formations that surely contribute to the water supply of the stands, especially in the dry seasons. Even though this effect has not been quantified and therefore it was not possible to include this variable in the study, it has been proved to be an important fact as regards the growth of the species in other regions (**Serrada et al. 2008, Scott 1961**). All these findings point out that El Bierzo is a suitable location for the species. Nevertheless, it should be kept in mind that radiata pine is also a high nutrient demanding species. Therefore, soil fertility and water supply management may improve site productivity throughout the Mediterranean plantations when needed.

These considerations, together with the unexpected fact that the lowest productivity of the plantations studied in Spain coincided with the highest rainfall area (**Romanyà and Vallejo 2004**) for the Spanish radiata stands, confirms that radiata stands in a Mediterranean environment can reach high productivity levels, even if rainfall is lower when compared to Eurosiberian conditions. This is a particularly relevant finding, as in the latter is where the species has been previously and more widely introduced in our country and where traditionally forest productivity is clearly superior. On the other hand, considering the Mediterranean origin of the species, the preceding statements could somehow have been foreseen. Other studies have noted a higher sensitivity of *Pinus radiata* to soil resources such as water storage and nutrients rather than to climate (**Nambiar 1991**), but these studies tend to consider a wider area and a certainly different environment. Anyhow, water storage was also highlighted in the regression models, as Retp and Sic appeared as predictive variables in model 1.

As regards multiple regression models, frequently, edaphic and climatic parameters explain between 50-60% of *SI* total variability (**Rayner 1991, Covell and McClurkin 1967 cited in Daniel et al. 1979**). Rarely, when a specific variable is expressly a growth limiting factor, 100% of *SI* variability is explained by this single variable. Furthermore, as stated before, interaction between environmental variables results in multiple site qualities and compensatory effects, masking the influence of a certain factor when analysing several (**Mcleod and Running 1988**). Thus, whereas habitat description of individual factors is a relatively simple task, an accurate overall evaluation is rather complicated. Some authors like **Gale and Grigal (1988)** state that the simplest models (one limiting factor) are the best way to approach this subject. However, such models can only be applicable in homogenous areas and certainly is not practically useful when attempting to establish a new species in so diverse a region. Hence, the approach undertaken was intended to be applicable to the case of study, even though the productivity functions derived dependent on environmental variables should be carefully considered and coarsely interpreted. In many cases models are not really practical (**McQuilkin 1976**) other than from a qualitative approach, enhancing relative importance of certain parameters. In sum, generally, as in many ecological studies, unique and unanimous statements are risky (**Snedecor and Cochran 1984**), as ecological parameters are not independent, synergies and mixed effects being difficult to unravel.

In the present study, some results were discarded because factors difficult to be measured were involved. Indeed, one of our priorities must be the use of factors easily to obtain, allowing landowners to effortlessly predict *SI* in their lands. Climate and soil physical properties (especially textures), together with topography, slope and location will help because they are related to other soil properties (nutrients in mountains slopes are washed and transported to flatter areas, thus contributing to more fertile soils on the flatter areas than the original materials would initially venture). Following the principle of parsimony, the inclusion of a small number of variables in models diminishes multicollinearity problems. Thus, the simplest *SI* model, with autumn rainfall and soil depth (model 3) as predictive variables is highly applicable to the terrain. Soil depth is definitely one key factor as regards radiata productivity (**Romanyà and Vallejo 2004, Sánchez-Rodríguez 2001, Hunter and Gibson 1984**).

The examination of the ecological valances calculated showed that radiata pine in El Bierzo behaved similarly to the description of the species stated by **Gandullo and Sánchez-Palomares (1994)** on almost all parameters considered. Most of the differences could be explained by the range of variation of the environmental set of parameters that characterised the area of study. For instance, noticeably radiata pine in El Bierzo grows at a higher altitudinal level than in the rest of the country. This is easily understandable, because radiata pine has been mostly planted in coastline regions, with lower altitudinal levels. On the whole, the comparison resulted in accordance to the conclusions as regards habitat description stated by **Gandullo and Sánchez-Palomares (1994)** and **Pérez-Crespo et al. (2009)** and the general ecological description for the species elsewhere. Radiata pine needs higher precipitations than other species of pine, and its growth is highly dependent on water supply during the summer months of draught. In this sense, summer haze and fogs derived from abrupt topography favours the species. It is sensible to frosts, especially during the growing season.

When compared to other countries (e.g. Australia, New Zealand, Chile), Spanish plantations present lower productivity. The reduced water stress of New Zealand plantations can explain this fact, as was the case when comparing New Zealand standards with the levels found in Mediterranean South Australia (**Hunter and Gibson 1984, Lewis et al. 1976**). Generalization in these countries of successful breeding programs would also affect these differences.

In other models predicting *Pinus radiata* site quality, climatic variables such as the mean annual rainfall and an array of variables linked in some manner to air temperature (e.g. altitude and longitude) and soil texture have been essential in Chile, Australia, and New Zealand. In contrast, the relevance of soil nutrient availability is rather country specific. For instance, P is important in Australia but not in Chilean plantations, in which N and K were limiting factors (**Hunter and Gibson 1984**). The New Zealand model (**Hunter and Gibson 1984**) revealed the strong influence of the A horizon depth, while it was hardly sensitive to changes in the supply of some nutrients. These authors attribute the low sensitivity of their model to nutrients to the fertilization practices applied to the low nutrient soils. In Spain, in spite of the lack of fertilization practices in *Pinus radiata* plantations, climatic variables were more relevant than soil nutrient (NPK) availability for predicting site quality in the moist Eurosiberian sites.

Comparisons with other areas of distribution of the species, however, are risky as the scale and variables considered may differ, and accordingly, the main factors influencing productivity (**Sánchez-Rodríguez 2001, Sánchez-Rodríguez et al. 1998**). Indeed, very diverse findings regarding this species, worldwidely spread, have been pointed out (**Caldentey 1989, Ruiz and Schlatter 1985, Hunter and Gibson 1984, Saunder et al. 1984, Turvey 1983, Truman et al. 1983, Will and Hodgkiss 1977, Reilly et al. 1975, Jackson and Gifford 1974, Ballard 1971**). On the whole, this review confirmed that radiata pine shows a very flexible behaviour in a wide range of environments, reaching a high productivity in varied conditions. Results are highly specific and local. Likewise, the conditions of the sites and management of plantations are also different, thus resulting in varied interferences and relationships between vegetation and environment conditions through diverse ecological processes. Accuracy can be only reached if site factors are constant or within a narrow variability range and the study efficiently designed. Ecological studies conclusions are always difficult to extrapolate and maybe too local to be compared, even with nearby regions. Still, we consider that our study certainly helps to improve the knowledge of the ecological requirements of radiata stands in El Bierzo, where Mediterranean and Eurosiberian conditions meet, isolating these stands from the surrounding radiata plantations of the northern regions of the country, embedded in Eurosiberian environments.

An important limitation of the study is the evident spreading of the species, affecting sampling design, which should be improved by adding more plots and the corresponding edaphic field data in other areas of the region, thus adequately covering the new afforestations recently introduced. It is already evident that the best way to support and improve the results obtained is to carefully survey the evolution of the stands and expand the environmental research over time.

From a management point of view, these statements point out to the fact that favourable climatic conditions in the region may allow these species to be managed in short or medium rotations. However, production varies greatly among plantations and most probably will be related to the nutrient status of the forest, which in turn is related to the type of soil (**Sánchez-Rodríguez et al. 1998**) and/or the site preparation techniques used (**Merino and Edeso 1999**). Finally, productivity standards should be carefully defined when establishing plantations; management practices and sites favouring quick growth may result in high volume yields in detriment of wood properties (e.g. density, stiffness) which in the end affect quality of the final products. The heavily thinned and high-pruned stands show a better adaptation to multiple timber products, pastures and mushrooms (**Rigueiro et al. 1998**). In this respect, the spreading of the species to areas with lower suitability (i.e. global potential index classified as moderate or low) could be still considered adequate for other uses, suchlike environmental protection, soil conservation or biomass and bioenergetic production and carbon storage, as has been pointed out by other authors in other regions (**Palmer 2008**).

5 Conclusions

Accuracy in the ecological approach of *SI*-productivity can only be reached through local studies located in regions with defined soil properties and climatic parameters. In El Bierzo, radiata pine stands are closer to the Mediterranean conditions, differing from the Eurosiberian environment in which the species is already well established in the country. In the present study, relationships between productivity of radiata pine stands (represented by *SI*) and ecological parameters were established. In the correlation analysis, rainfall was undoubtedly the most relevant parameter.

The central and marginal habitat for the species in the area of study was defined and individually mapped for some parameters. Yet, results are only valid within the ecological range considered and this fact must be taken into account when applying the models. Updating of stand variables inventory and ecological parameters is highly recommended because of the quick and recent spreading of the species in other locations in the area of study.

The GIS analysis contributed to synthesize the obtained results. Site class indices and maps may help in defining what silviculture should be applied during the first years up to the moment when the stands reach base age. Our aim was to ease decision making regarding the plausible results of planning plantations. An expression of this target is the map of the species productivity based on the habitat definition and environmental factors that influence radiata plantations growth in the area of study. Overlapping with the current stands, confirmed most of the stands (84% in the central classes, evenly distributed) are planted in suitable areas, though not in the optimal class of suitability locations. The stands located in non suitable areas add up to 864 ha (9.5% of the stands) and should be accordingly managed to the siting conditions, (e.g. short rotations, aimed at low quality wood production).

Simple models, with a small number of variables, can interpret an uncountable number of relationships affecting productivity. We intended to develop models in which easily identifiable environmental factors could be evaluated. This premise enables site quality predictions without the need of previous tree establishment and guarantees practical applicability on the terrain. Accordingly, four *SI* regression models have been fitted, mainly dependent on autumn rainfall and soil depth.

Ecological productivity studies should be framed under other considerations concerning forest policy in the region to assure radiata plantations success (e.g. long term horizons, wood properties, soil analysis, environmental interactions, genetics, perception of forestry industry, market prospects, soil conservation, carbon storage, biomass production). Thus framed, areas other than classified as of optimum or high potentiality for the species should not be completely neglected.

CHAPTER 4. Aboveground biomass modelling and carbon pools estimation of *Pinus radiata* D. Don stands combining inventory and RS data in Northwestern Spain

1 Introduction

The ability of the terrestrial biosphere to sequester and store atmospheric CO_2 has been recognised as an effective and low-cost way of offsetting carbon emissions (**Wise and Cacho 2005, Jalkanen et al. 2005, IPCC 2003**). In particular, forests ecosystems play an important role in the global carbon cycle.

In short, vegetation and soil dynamics results in a continuous interaction with the atmosphere. Forests can shift from sinks to sources of atmospheric C by stocking carbon in living tissues and wood as well as exchanging CO_2 in respiration and photosynthetic processes, depending on the particular practices and processes involved (**Muukkonen and Heiskanen 2007, Dong et al. 2003, Goodale et al. 2002**).

For instance, practices and disturbances, either of natural or human origin, can turn over a particular forest balance (e.g. use of poor harvesting practices, clearings, rotations, burnings, changes in land uses, wildfires, adaptation to climatic changes) (**KimPhat et al. 2004, Gracia et al. 2001, Brown and Gaston 1995**).

There is a growing need for reliable monitoring of forest biomass, in particular to support requirements related to sustainable forest management and carbon accounting (**Labrecque et al. 2006**). Oven-dry wood comprises almost exactly 50% of elemental carbon by weight, and the non-stem biomass can be assumed to have a similar proportion. Certainly, afforestation and reforestation together with consequent management measures can further increase the quantities of C sequestered from the atmosphere (**Backéus et al. 2006, IPCC 2000**). It is comprehensible, therefore, that the establishment of a forest on a non-forested site, as is the case in the area of study, results in a net transfer of carbon from the air to the vegetation.

Forest inventories and RS are the two principal data sources used to estimate C stocks and fluxes for large forest regions (**Krankina et al. 2004**). More commonly, stand biomass is estimated using timber volume information collected through forest inventories. Such inventories employ statistical sampling using field plots, where stand parameters (i.e. height, diameter at breast height, weights) are measured directly. As tree aboveground biomass is strongly correlated with trunk diameter (**Clark et al. 2001**), permanent sampling plots have long been used in assessing the quantity of biomass stored in ecosystems (**Brown 2002, Fearnside 1996**).

Effective forest ecosystem management requires access to current and consistent geospatial information that can be promptly shared with all stake holders.

Satellite imagery can itself be an important asset to the development of landscape scale planning, research, and monitoring because of its large area coverage, repeat viewing and digital nature (**Griffiths and Mather 2000**).

In particular, RS also provides information to assess forest attributes and to manage forest resources in a sustainable manner (**Franklin et al. 2002**). The use of satellite imagery allows researchers to inventory and study the state of vegetation in a large region, while reducing the need to be in the field (**Lea 2005**). The unprecedented variety of remotely sensed data, advanced computing resources and data analysis tools have created new opportunities for major improvements in the global and regional land cover characterization (**Defries and Belward 2000**). RS imagery supplies an alternative, timely and cost-effective approach to monitoring changes in forest cover at multiple scales. Nonetheless, RS scenes are not a substitute for field-based data collection, which is essential for accurate image interpretation and to grant the necessary data on forest characteristics that are undetectable by air- and space-borne sensors.

Hence, even though remotely sensed satellite data could provide some of the required information for updating stand inventories (**Wulder et al. 2004, Danson and Curran 1993**) in managed forests, the relationship between spectral reflectance and important stand characteristics in different geographic settings is still not well documented (**Lu et al. 2004**). Actually, the feasibility of methods needs to be evaluated in a range of scenarios. This is to say it must be tested for different species at different geographic locations and under different management strategies. Thus, the estimation of volume and biomass by satellite RS has been tested considering a wide range of spatial scales and environments (**Stenberg et al. 2004, Laidler and Treitz 2003, Eklundh et al. 2003, Chen et al. 2002, Tomppo et al. 2002, Häme et al. 1997**).

Vegetation shows typically a low reflectance in the visible range of the spectrum, particularly in the blue and red wavelengths, a steep increase in reflectance around 700 nm (red edge) and high reflectance in the NIR. The reflectance of forests is typically highly anisotropic and determined by the optical properties of canopy components, canopy and landscape-level structural characteristics, and topography (**Asner et al. 1998**).

Vegetation monitoring by remotely sensed data has been carried out using mainly SVIs. SVIs are defined as dimensionless mathematical transformations combining the digital values of different bands. The numerous SVIs have been designed to isolate the contribution of vegetation from the contribution of other materials (background, atmosphere) to the reflectance (**Asner et al. 2003**).

These indices are mainly derived from reflectance data of discrete red and NIR bands. Consequently, they operate by contrasting intense chlorophyll pigment absorption in the red band against the high reflectance of leaf mesophyll in the NIR (**Maselli 2004**). Generally, use of SVIs strengthens the association between spectral data and the biophysical characteristics of vegetative canopies.

An alternative approach in RS data processing that has been proved useful when studying vegetation is to use a mixed pixel method or spectral mixture analysis (SMA). This method recognizes that a single pixel is typically made up of a number of varied spectral types, i.e. soil, water, vegetation (**Atkinson et al. 1997**) and it is used to measure the percentage of spectra for each land-cover type in a single pixel. Representing physic aspects of ground covers (**Shimabukuro and Smith 1991**), spectral unmixing shows biophysics properties more easily than original bands.

Most of the techniques have employed a linear mixing approach (**Huguenin et al. 1997, Foody and Cox 1994**). Linear mixing refers to additive combinations of several diverse materials that occur in patterns too fine to be resolved by the sensors. The linear mixture model assumes that as long as the radiation from component patches remains separate until it reaches the sensor, it is possible to estimate proportions of component surfaces from the observed pixel brightness. Thus, the observed pixel value in any spectral band is modelled by a linear combination of the spectral response of a component within the pixel.

Biomass accumulation in a stand depends on the species considered and influencing factors like site quality (**Bravo et al. 2008**). In general, among the different terrestrial ecosystems, fast growth species, especially coniferous, are major C reservoirs (**Laclau 2003**). Furthermore, the species subject of study and the frame of its introduction in the area considered point to be of special interest regarding C sequestering: afforestations have been mainly located in former agriculture fields of rural marginal areas, where forestry is becoming a highly recommended type of land use. Radiata plantations could certainly help to meet the challenges threatening the region (land abandonment, mine restructuring, decline of traditional economy and of population), thus contributing to sustainable development. Bearing in mind a bigger scale, *Pinus radiata* D. Don is the exotic coniferous species most widely introduced nowadays (**Sutton 1999**).

Radiata pine biomass stocks have been specifically investigated in the areas where the species is widely spread (see **Sutton 1999**), such as New Zealand, Chile and South Africa (**Guerra et al. 2005, Snowdon 1985, Madgwick 1985, 1983**). Likewise, previous studies related to the species that have been developed in Spain are the biomass estimation functions by species of **Montero et al. (2005)**, biomass estimation related to soil properties (**Rey 2000**) or nutrients stock (**Barreiro 2003, Merino et al. 2003, Rey et al. 2001**) and variation and distribution of carbon stocking over time in pure stands under different silvicultural alternatives (**Balboa-Murias et al. 2006**). Nevertheless, few studies have investigated C storage and the effect of different stand management regimes on C budgets in forest stands in north-western Spain (**Balboa-Murias 2005**), and definitely none has been carried out for this species in the region.

Objective

On the whole, the main specific objectives of the present chapter were 1) to analyse the significance of possible relationships between field-measured forest variables (basal area, stem volume, stem biomass and aboveground tree biomass -within the carbon storage-) and the visible to shortwave infrared ASTER and CCD-CBERS satellite data in *Pinus radiata* stands located in Castilla y León (NW Spain); 2) to evaluate the potentiality of estimation of stand attributes by fitting adequate model equations derived from the satellite data; and 3) accordingly selecting some of them to outline the spatial distribution of the main stand variables in the stands from one of the scenes.

2 Methods

Field data from the permanent sample plots network recorded during the inventory carried out in 2003 were used in the calculation of stand variables which will be the dependent variables in this study (see Chapter 1 for a more detailed description of inventory measurements). In addition, as will be further explained, the calculation of biomass variables implied the use of biomass equations developed for the species in Galicia (**Balboa-Murias et al. 2006**).

On the other hand, each of the scenes selected for the study was independently analysed. After the corresponding corrections, data extracted from each of the images generated the RS data which were used as independent variables in the subsequent statistical analysis. In short, RS data consisted of single bands, SVIs, and fraction images, depending on the sensor capabilities and techniques used in image preprocessing.

Note that only the plots matching the area covered by the RS scenes to be used (CBERS and ASTER) are valid data sources for this analysis.

A general flow chart of the data sources and processes involved in this study is shown in **Figure 4.1**.

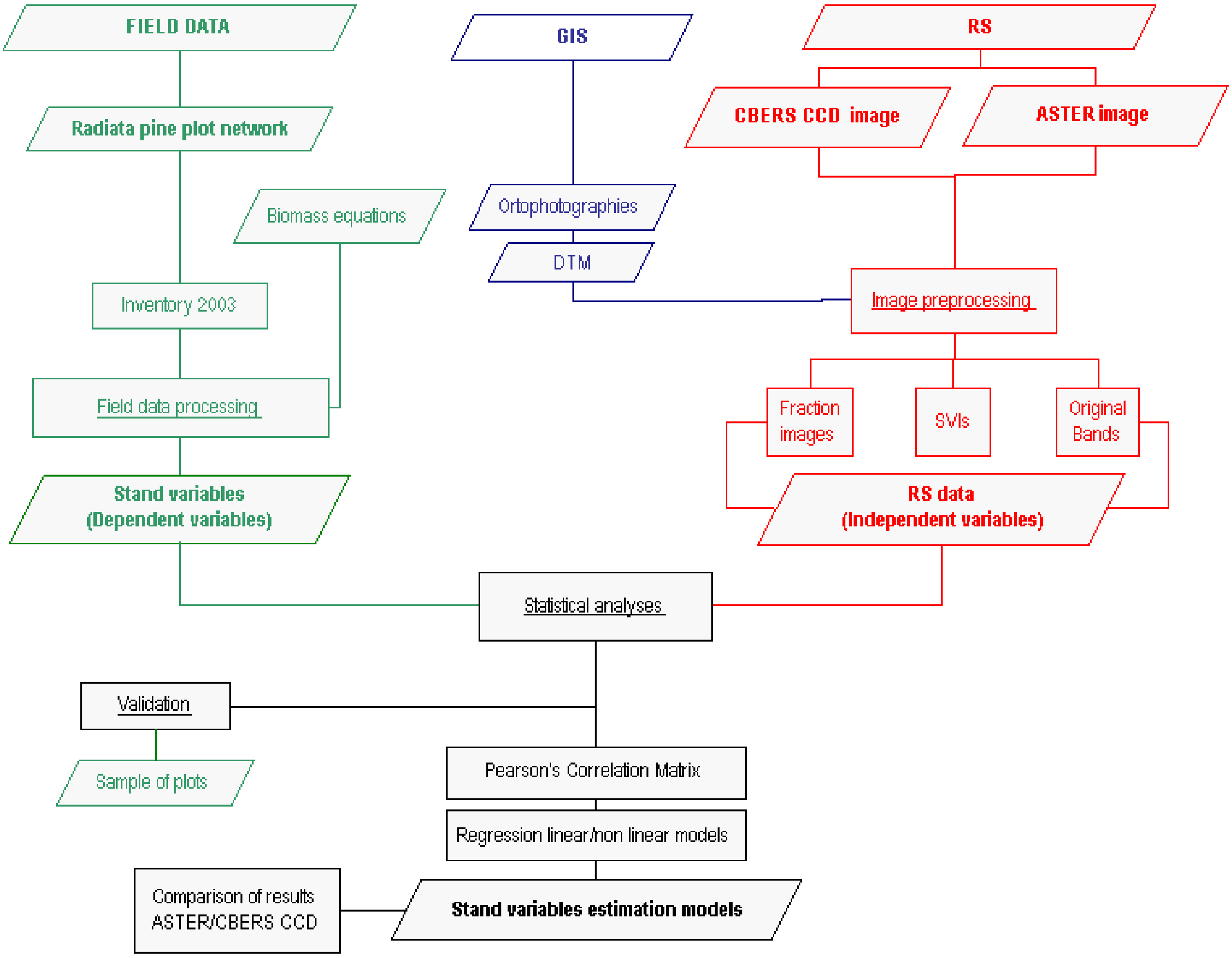

Figure 4.1 Flow chart of data sources and methodological processes involved in stand variables assessment combining RS and field data

As aforementioned, SVIs are often used to reduce the information content from multiple bands to a single band or index that could be related to certain vegetation phenomenon (**Campbell 2002**). The index is computed using several spectral bands that are sensitive to plant biomass and vigour. The selected SVIs to be tested in the study are shown in **Table 4.1**.

Table 4.1 Spectral Vegetation Indices (SVIs) used for model fitting

SVI	Formula		Reference
	ASTER	CBERS	
Normalized difference vegetation index ***NDVI***	$NDVI=\dfrac{V3-V2}{V3+V2}$	$NDVI=\dfrac{B4-B3}{B4+B3}$	Rouse et al. 1973
Green difference vegetation index ***GNDVI***	$GNDVI=\dfrac{V3-V1}{V3+V1}$		Lymburner et al. 2000
Simple ratio ***SR***	$SR=\dfrac{V3}{V2}$		Birth and McVey 1968
Normalized difference moisture index ***NDMI***	$NDMI=\dfrac{V3-S1}{V3+S1}$		Cibula et al. 1992
Global Environmental Monitoring Index ***GEMI***		$GEMI=\dfrac{n(1-0.25n)-(B3-0.125)}{(1-B3)}$ $n=\dfrac{2(B4^2-B3^2)+1.5B4+0.5B3}{B4+B3+0.5}$	Pinty and Verstraete 1992
Soil-Adjusted Vegetation Index ***SAVI***		$SAVI=\dfrac{(1+L)\times(B4-B3)}{(B4+B3+L)}$ *L*=soil constant set to 0.5	Huete 1988

Note: The symbols of the formulas of SVI apply to the convention adopted in bands quotation as shown in **Table 4.** for ASTER and CBERS images bands. Some of the SVIs used are not applicable to both images (see **Table 4.**)

The success of the RS analysis depends on finding the accurate way to represent relationships between the radiance measured by the sensor and the land surface properties. Once the existence of the mentioned relationships is determined and quantified by Pearson correlation matrix coefficients, the statistical relationships between the plot level field measurements (once processed, dependent variables) and satellite images data (once processed, independent variables) are studied using linear and non-linear regression analyses.

2.1 Field data processing

The dry weight (defined as the weight to constant mass at 65^{o}C) of two aboveground tree fractions (stem wood including bark, *Ws*, and total biomass, *W*) was determined by applying allometric relationships based upon diameter at breast height and height developed by **Balboa-Murias et al. (2006)** for the species in Galicia using destructive sampling methods. The system assures additive and all desirable properties stated for biomass equations development. Biomass dry weight (*W* and *Ws,* Mg) was related to surface area (*Wh* and *Wsh,* Mg ha^{-1}). Carbon pools in tree biomass were estimated by fractions as a percentage of the corresponding aboveground dry biomass using the reference found for radiata pine by **Ibáñez et al. (2002)** which states 49.7 g C for every 100 g of dry wood.

Total volume of each tree computation implied estimation of total height of the trees not directly measured using the generalized height-diameter relationship locally developed by **Sevillano-Marco et al. (2009)** based on the **Schnute (1981)** function for the species and subsequently using the compatible volume system developed by **Fang et al. (2000)**.

Stand volume (*V*, m^3 ha^{-1}), stand aboveground biomass (*W*, Mg ha^{-1}), stand stem biomass (*Ws*, Mg ha^{-1}), and carbon pools in stand aboveground biomass and stem biomass (*C* and *Cs* respectively, Mg C ha^{-1}) were aggregated from the corresponding tree values for each plot.

Mean, maximum, minimum and standard deviation for each of the main stand variables used in the study are shown in **Table 4.2**.

Table 4.2 Summarised data corresponding to the sample plots used for model development (n=40 plots)

Variable	**Inventory**			
	Mean	**Maximum**	**Minimum**	**SD**
t (years)	17.2	33.0	8.0	6.0
SI (m) 20 years base age	20.7	24.3	16.9	2.0
N (stems ha^{-1})	1726	2950	400	654
Dg (cm)	16.5	29.2	7.7	4.7
Hm (m)	15.5	24.5	5.6	4.8
G (m^2ha^{-1})	34.2	58.9	8.1	12.6
V (m^3)	9.1	33.8	0.7	6.9
Vh (m^3 ha^{-1})	251.9	529.4	23.7	130.8
W (Mg)	4.6	16.0	0.5	3.3
Wh (Mg ha^{-1})	129.7	274.6	16.6	65.7
*Ws (*Mg*)*	3.5	13.2	0.2	2.9
Wsh (Mg ha^{-1})	93.7	230.6	7.4	58.6
*C (*Mg ha^{-1}*)*	2.3	7.9	0.3	1.6
*Cs (*Mg ha^{-1}*)*	1.7	6.6	0.1	1.4

t=stand age; *SI*= site index; *N*=number of stems per hectare *Dg*=quadratic mean diameter; *Hm*= mean height; *G*=stand basal area; *V*=volume; *Vh*=volume per hectare; *W*=total aboveground biomass; *Wh*=total aboveground biomass per hectare; *Ws*=stem aboveground biomass; *Wsh*=stem aboveground biomass per hectare; *C*=total carbon stock per hectare; *Cs*=stem carbon stock per hectare; SD= Standard deviation

2.2 Image processing and satellite-derived data

Pre-processing of satellite images is a necessary step prior to actual image analysis and has as its unique goals the establishment of a more direct linkage between the data and biophysical phenomena, the removal of data acquisition errors and image noise, and the masking of contaminated scene fragments like clouds (**Coppin et al. 2004**). Besides, the precise co-registration of the field and satellite data can be difficult (**Halme and Tomppo 2001**).

2.2.1 ASTER image preprocessing

Several corrections were performed to the Aster level 1B scene. The first correction is known as crosstalk and reduces the SWIR crosstalk effect which is caused by the dispersion of the incident light of band 4 detector. The correction is only to be applied for bands 5 to 9 of a SWIR image.

Atmospheric corrections were also applied using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) module from ENVI software. FLAASH is an atmospheric radiation transfer model which removes the obscuring effects of the atmosphere and corrects RS images for atmospheric water vapour, oxygen, carbon dioxide, methane, ozone, and molecular and aerosol scattering.

The topographic correction refers to the compensation of the different solar illuminations due to the irregular shape of the terrain. A DTM is needed to calculate the illumination through the studied area. The different terrain illumination is removed by dividing the corrected image between the illumination layers.

As the DTM and the plots were georeferenced in a different coordinate system, a first degree polynomial transformation was performed in order to apply the topographic corrections and to match the plots with the corrected image. A total of 15 ground control points were selected from a 0.25 m spatial resolution orthophoto of the studied area. The rectification process results in an overall RMSE of less than 0.5 pixels.

In order to avoid edge or shadowing effects, one of the plots was rejected as several histograms showed it was clearly an outlier.

As the scene is already geometrically coregistered with a coordinate system defined by a UTM projection and the WGS84 Ellipsoid, pansharpenning was directly applied to the SWIR channel in order to merge the scene into one image of 15 m resolution.

The SVIs used in this study (*NDVI*, *GNDVI, NDMI* and *SR*) are described on **Table 4.1**. The SVIs were calculated from the previously corrected original bands. From this step, thirteen digital numbers (corresponding to the three VNIR and six SWIR bands -see **Table 4.-** and the four SVIs) of the ASTER scene were obtained for each plot, by using a 3x3 window around the central pixel of each of the field sample plots. These digital numbers provided the RS data set for the study. A subsample of 25% of the training plots of the field data set was subsequently used for independent validation.

An overview of the methodological processes depicted in this section is given in **Figure 4.2**.

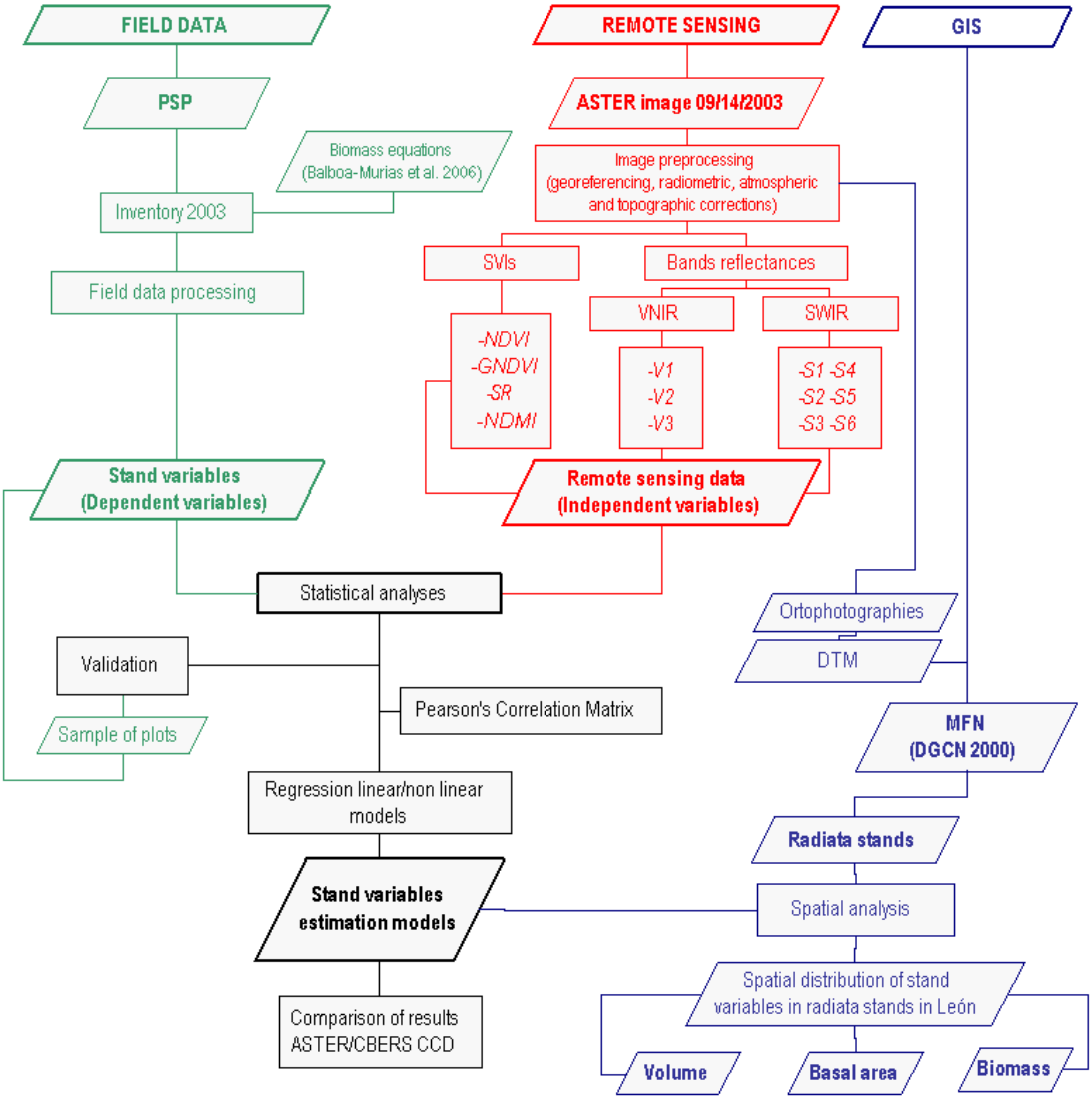

Figure 4.2 Flow diagram of data sources and methodological processes undertaken in the ASTER image analysis

2.2.2 CBERS image preprocessing

The CBERS image was co-registered with the field plots (UTM system, WGS-84 Ellipsoid). The rectification process resulted in an overall RMSE of less than one pixel. Once the co-registration was achieved, SMA was applied to the original image. We defined three endmembers (soil, vegetation and shade) whose spectral signatures were mainly obtained from the scatter-plot of the original image (and with some help of the knowledge of the study area). The algorithm used (based on the proposed by **Shimabukuro and Smith 1991**) allowed us to obtain three fraction images (vegetation fraction –*UV*-, soil fraction –*US*-, shade fraction –*UW*-).

In addition to the fraction images, the following selected indices were used: *GEMI* (**Pinty and Verstraete 1992**), *SAVI* (**Huete 1988**), and *NDVI* (**Rouse et al. 1973**) (**Table 4.1**). These indices have been proved useful in related research (**Vázquez 2008, Lefsky**

et al. 2001) and are suitable to the RS data spectral range.

Finally, an average 3x3 filter was applied to the original bands, SVIs images and fraction images as a previous step to the extraction of digital values for the field plots surveyed.

In sum, the elaboration of the final RS dataset required the extraction of digital values of the original bands from the corrected image, the images corresponding to the *SAVI, GEMI* and *NDVI* indices and spectral unmixing (*US, UW, UV*) in the plots under research. These values, stored with the information supplied by the field inventory containing the radiata pine stands attributes described above, constitute the complete work data set corresponding to the CBERS CCD scene to be statistically analysed.

A detailed diagram of processes is given in **Figure 4.3**.

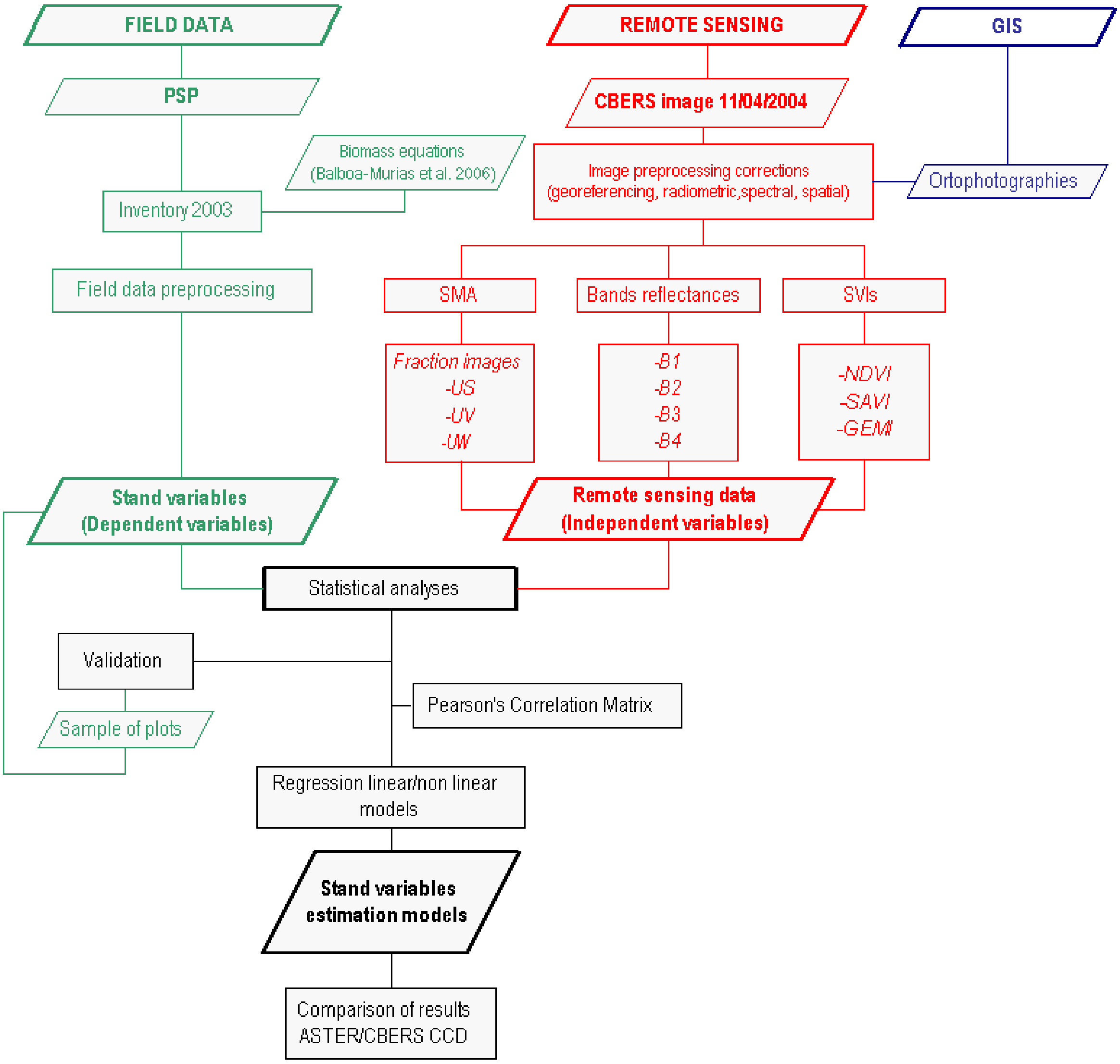

Figure 4.3 Flow diagram of data sources and methodological processes undertaken in the CBERS image analysis

2.3 Statistical analysis

A Pearson's correlation matrix was used to verify the existence of relationships between the RS data and the field data. One linear and seven non linear regression models were selected (see **Table 4.3**) and examined with the data set of the area of study in order to quantify the relationships between the stand variables and reflectance data.

The examined spectral features include the single spectral bands, six spectral vegetation indices (*NDVI*, *GNDVI*, *SR* and *NDMI* in the case of the ASTER scene and *NDVI, GEMI, SAVI* in case of the CBERS CCD data), and only in case of the CBERS CCD data, fraction images (*US*, *UV* and *UW*).

As Pearson coefficients do not show but linear relationships between two variables and taking into consideration that some models imply more intricate relationships between the dependent variable and more than one independent variable, all RS bands, and not only the ones that best results provided in the correlation test, were used for model testing. This is to say that the model equations were tested taking into account all the possible combinations of independent variables (all bands and vegetation indices) for each dependent variable considered.

Table 4.3 Tested regression models

	Model equation	References
M1	$y = ax^b$	Meng et al. 2007, Heiskanen 2006, Suganuma et al.2006
M2	$y = (a + bx)^2$	Padrón and Navarro-Cerrillos 2007
M3	$y = a\exp^{bx}$	Heiskanen 2006
M4	$y = a + bx + cx^2$	Labrecque et al. 2006
M5	$y = (1 + x_1)^a x_2{}^b \exp^{(c+dx_1+ex_2)}$	Muukkonen and Heiskanen 2007
M6	$y = a + bx_1 + cx_2$	Labrecque et al. 2006, Freitas et al. 2005
M7	$y = a + bx_1 + cx_2 + dx_3$	Labrecque et al. 2006
M8	$y = a + bx$	Heiskanen 2006, Freitas et al. 2005

a, *b, c, d* and *e* are the model parameters, *x* is the independent variable (RS data) and *y* is the dependent variable (stand variables)

Comparison of the different models fitted was based on numerical analyses. Three goodness-of-fit statistical criteria obtained from the residuals were examined: coefficient of determination (R^2), showing the proportion of the total variability in the dependent variable explained by the model, root mean square error (RMSE), which states the accuracy of the estimates and mean percent standard error (S%), that indicates the size of error as a percentage of the mean of the estimated variable distribution.

$$R^2 = \frac{1 - SSres}{SScorr}$$

where *SSres* is the residual sum of squares and *SScorr* the corrected sum of squares

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

where ŷ is an estimated variable, y is the field (measured) variable and n is the number of observations.

$$S(\%) = \frac{100}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}_i\right| / \hat{y}_i$$

where *y* represents observed values and ŷ represents predicted values. The expected value of S(%) is 0.

Other important step to test the selected models was the graphical analysis of the relationship between the observed and the estimated variables of the models selected.

Validation is the process of assessing the accuracy of data products derived from the system outputs by independent means and it determines the usefulness of the product for specific purposes (**Morisette et al. 2002**). The validation of the continuous estimates is usually based on the correlative analysis of the satellite derived products and ground reference data. A subsample of 25% of the training plots of the field data set was subsequently used for independent validation. The same statistics that had served as decision criteria (R^2, RMSE, S%) were calculated for the models that had previously best performed, in the line of the works of **Freitas et al. (2005)** and **Heiskanen (2006)**. Informally, comparison between the results obtained using two different scenes can somehow be considered as an additional particular form of validation statements as regards discussion.

All the statistical analyses were carried out using SPSS© 15.00 software.

2.4 Geospatial analysis

After validation and visual inspection, the regression models which had best performed were used to spatially estimate stand variables from the ASTER data. A layer of radiata stands was generated from the MFN (**DGCN 2000**) for this purpose, imposing radiata pine as main species which assures that above 90% of the stems in the stands are radiata stems. This layer was overlaid to the ASTER image in order to select the surface occupied by the species to be quantified. The values obtained in all the coinciding pixels were accordingly classified and displayed in a spatial distribution of biomass layout. Thus, the best models were extrapolated to a total surface of 6939 ha of radiata stands, enabling sketching of spatial distribution patterns of stand basal area, volume and aboveground stem biomass.

An overview of methodology processes described in this section is included in **Figure 4.2**.

3 Results

3.1 Image preprocessing results

Outputs of image preprocessing that characterize the stands' reflectiveness are shown respectively in **Figure 4.4** and **Figure 4.5**.

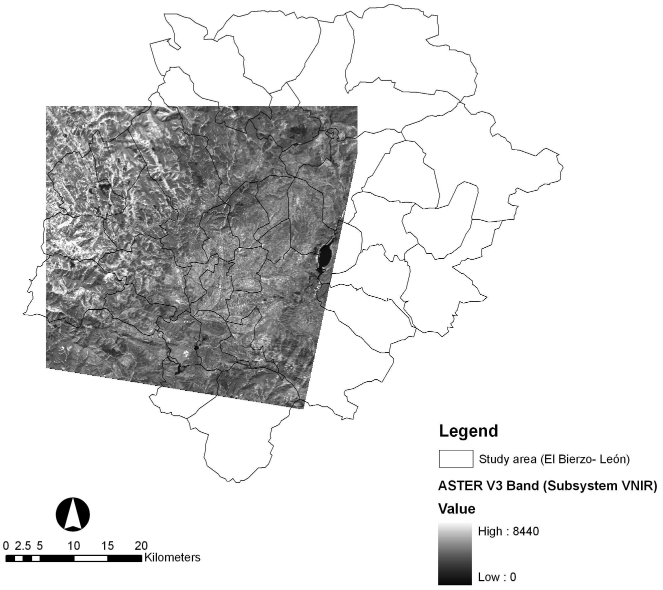

Figure 4.4 NIR band (*V3*) of ASTER image

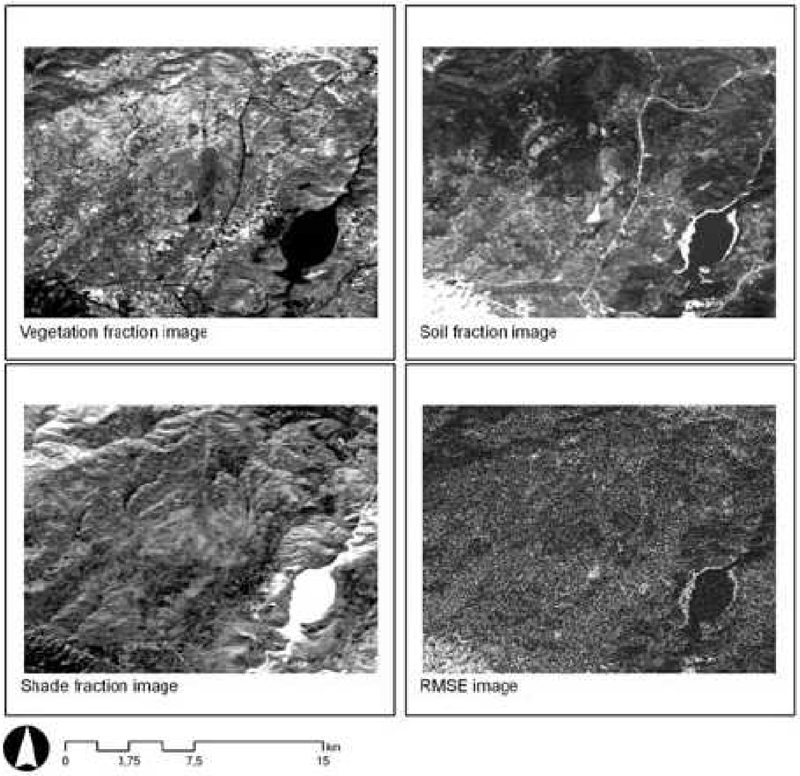

Figure 4.5 Fraction images obtained by unmixing the original CBERS CCD image

3.2 Correlations between RS data and stand variables

A summary of the highest coefficients of Pearson's correlation is given in **Table 4.4**.

Table 4.4 Top Pearson's correlation coefficients (*n=29 plots*) between dependent variables (stand variables) and independent variables (single bands, vegetation indices and fraction images)

Image	RS data	*W*	*Wh*	*Ws*	*Wsh*	*C*	*Ch*	*Cs*	*Csh*	*G*	*V*	*Vh*
ASTER	*V3*	**-0.728**	**-0.696**	**-0.696**	**-0.681**	**-0.728**	**-0.696**	**-0.696**	**-0.681**	**-0.598**	**-0.721**	**-0.702**
CBERS	*UW*	**0.543**	**0.483**	**0.540**	**0.485**	**0.543**	**0.483**	**0.540**	**0.485**	***0.308***	**0.540**	**0.493**
	B4	**-0.524**	**-0.472**	**-0.524**	**-0.479**	**-0.524**	**-0.472**	**-0.524**	**-0.479**	-0.297	**-0.522**	**-0.481**
	GEMI	***0.339***	0.341	0.337	0.341	***0.338***	0.341	0.337	0.341	0.177	***0.335***	0.339

Bold: correlation is significant at the 0.01 level (2-tailed)
Bold and italics: correlation is significant at the 0.05 level (2-tailed)

3.2.1 ASTER image

The spectral reflectance of band *V3* showed the highest correlations with all stand variables (see **Table 4.4**), significant at the 0.01 level (2-tailed test) and is in accordance to the high values of reflectance showed in **Figure 4.4**. All the correlations between bands and stand variables are negative. In order of significance, the following stand variables are related to the *V3* reflectance values of the image: *W, V, Vh, Wh* and *Ws, Wsh* and *G*. By contrast, the vegetation indices calculated (*NDVI*, *SR, GNDVI* and *NDMI*) showed low results.

3.2.2 CBERS image

The corresponding correlation matrix is shown in **Table 4.4**, where the peak Pearson's coefficients are highlighted. Positive correlations between stand variables and RS data were only found for all stand variables for *GEMI* and *UW*. Thus, the key finding of this step was that negative coefficients were the general trend between most of RS variables and all forest attributes.

Clearly, the highest values (see **Table 4.4**) were obtained with *UW* and *B4*, followed by *GEMI*.

Closer relationships between stand variables and RS data were found for *W*/*C* and *Ws*/*Cs*, followed by *V*.

3.3 Statistical models and stand variables estimation

The linear and nonlinear regression models for stand variables and the statistics of comparison for both scenes are given in **Table 4.5**. Likewise, statistics obtained for the validation subsample are given in **Table 4.6**.

Table 4.5 Selection of models, dependent and predictive variables (see **Table 4.**), parameters, numerical statistics (R^2, RMSE, and S%) calculated for data extracted from ASTER and CBERS images

y	Image	Model	Parameters					$X_1/X_2/X_3$	R^2	RMSE±	S%
			a	b	c	d	e				
G	ASTER	M7	208.38	-0.05	-210.07	1.82	208.38	*S6/GNDVI/SR*	0.518	8.8	22.8
Vh	CBERS	M5	15.26	7.92	-12.83	-10.61	-0.30	*UW/B1*	0.441	79.5	21.1
	CBERS	M5	8.29	2.66	-21.03	-0.31	-0.05	*B1/B4*	0.430	80.3	21.8
W	ASTER	M5	-0.19	2.89	0.56	-0.02	-4.00	*V3/NDMI*	0.688	1.67	28.0
Wh	ASTER	M7	783762.30	-45.71	-159.55	-493815.00		*V3/S6/GNDVI*	0.584	42.4	25.5
	CBERS	M5	16.02	8.90	-15.79	-11.25	-0.34	*UW/B1*	0.453	39.9	19.9
	CBERS	M5	9.33	2.94	-25.12	-0.34	-0.06	*B1/B4*	0.447	40.2	20.3
Ws	ASTER	M5	3.96	2.31	0.98	-0.02	-6.74	*V3/NDMI*	0.749	1.4	34.8
	CBERS	M5	22.19	-20.45	55.17	-6.59	0.37	*US/B1*	0.731	1.4	39.9
	CBERS	M5	-71.84	-7.59	28.94	56.74	0.08	*US/B4*	0.698	19.1	29.5
Wsh	ASTER	M5	-12.87	5.77	-0.06	-0.03	-0.09	*V3/NDMI*	0.585	42.3	37.0

G=stand basal area; *Vh*=volume per hectare; *W*=total aboveground biomass; *Wh*=total aboveground biomass per hectare; *Ws*=stem aboveground biomass; *Wsh*=stem aboveground biomass per hectare

Table 4.6 Numerical statistics (R^2val, RMSEval, and S%val) corresponding to the validation data set of the selected models shown in **Table 4.5**

y	Image	Model	$X_1/X_2/X_3$	R^2val	RMSEval	S%val
G	ASTER	M7	*S6/GNDVI/SR*	0.813	19.9	31.5
Vh	CBERS	M5	*UW/B1*	0.609	215.5	62.1
	CBERS	M5	*B1/B4*	0.701	214.2	65.4
W	ASTER	M5	*V3/NDMI*	0.799	6.8	66.8
Wh	ASTER	M7	*V3/S6/GNDVI*	0.799	108.6	45
	CBERS	M5	*UW/B1*	0.509	104.2	62.1
	CBERS	M5	*B1/B4*	0.609	105.7	66.9
Ws	ASTER	M5	*V3/NDMI*	0.589	6.8	74.2
	CBERS	M5	*US/B1*	0.932	58.2	71.7
	CBERS	M5	*US/B4*	0.925	45.9	61.4
Wsh	ASTER	M5	*V3/NDMI*	0.589	88.7	47.7

G=stand basal area; *Vh*=volume per hectare; *W*=total aboveground biomass; *Wh*=total aboveground biomass per hectare; *Ws*=stem aboveground biomass; *Wsh*=stem aboveground biomass per hectare

3.3.1 ASTER image

As regards the function for *G* estimation, among all the equations tested, model M7 (**Labrecque et al. 2006**) provided the best results (R^2= 0.518, RMSE= 8.9 m^2 ha^{-1}, S%= 22.8). M5 (**Muukkonen and Heiskanen 2007**) was selected for *Vh* estimation, providing the best results (R^2= 0.541, RMSE= 318.7 m^2 ha^{-1}, S%= 52.6). For the estimation of *W, Ws* and *Wsh*, Model 5 (**Muukkonen and Heiskanen 2007**), with *V3* and *NDMI* as predictive variables provided the best results (R^2= 0.688, 0.749, 0.585 RMSE= 1.678, 1.430, 42.390 m^2 ha^{-1}, S%= 28.07, 34.82, 37.09 respectively), while model M7 was selected for *Wh* (R^2= 0.584, RMSE= 42.408 $m^2\ ha^{-1}$, S%=25.55), being *V3*, *S6* and *GNDVI* the independent variables (**Table 4.5**).

In general, when considering one single predictive variable, the results were poorer than the ones obtained when combining two or three independent variables. The combinations between bands and vegetation indices showed especially good behaviours. In our study, band *V3* is a predictive variable in all the selected models, which is in agreement with the results obtained in Pearson's correlation matrix. Moreover, all the vegetation indices are calculated using the band *V3*.

The R^2 of the ASTER data were higher for *W* and *Ws*, (0.749 and 0.688 respectively), and both variables were achieved by combining *V3* and *NDMI* in model M5. On the contrary, the poorest R^2 resulted when modelling *G* (0.518). RMSE and S% values were higher for the validation plots. The lowest $S\%_{Val}$ resulted from the combination of *S6*, *GNDVI* and *SR* in model M7 for *G*.

A comparison between estimated and observed stand variables is given in **Figure 4.6**. In accordance to the RMSE and S% values inferred (**Table 4.5**) an overview of the estimated/observed values confirms that *G* shows the best behavior, although an outlier stand presented an observed *G* of approximately 10 $m^2\ ha^{-1}$ whereas the estimated value is over 60 $m^2\ ha^{-1}$ (**Figure 4.6a**). Another remark is that, in almost all the cases, the model selected for volume estimation tends to overestimate (**Figure 4.6b**). Finally, there is not a clear pattern to be discerned from the plots of *Wsh* and *Wh* (**Figure 4.6c and 4.6d**).

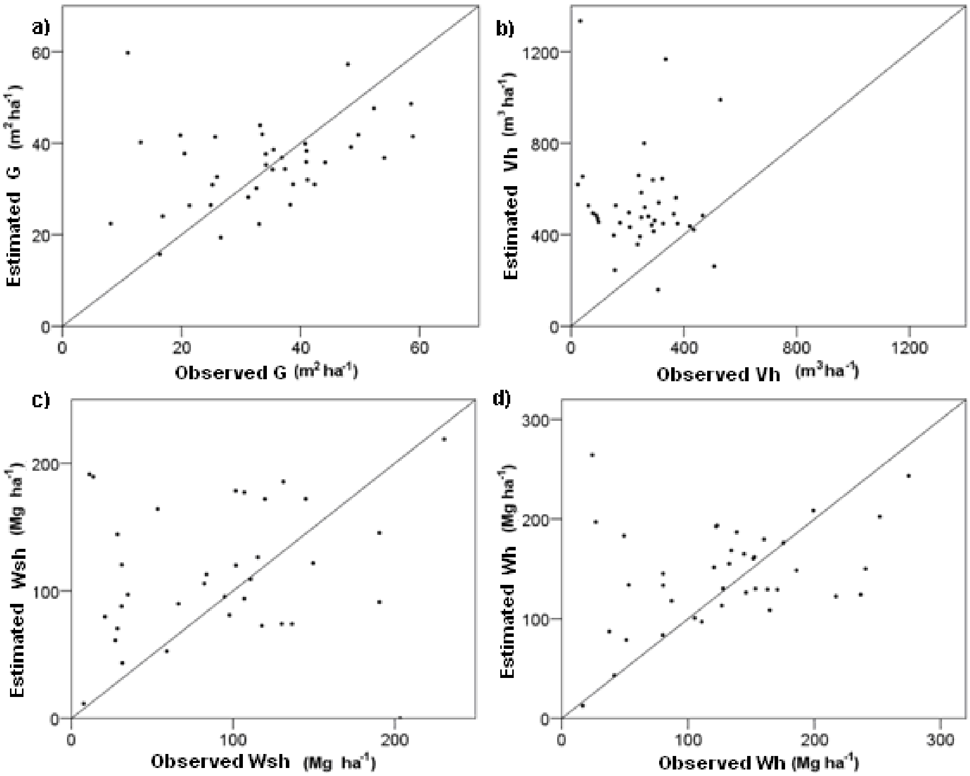

Figure 4.6 Predicted stand variables values plotted against observed values

3.3.2 CBERS image

Regardless of model type, the fits of non-linear regression models were the best for stem and total biomass, closely followed by stand volume, with only minor differences among them (R^2 between 0.73 and 0.72). The disparity with the rest of stand variables (the ones related to surface; *Wh, Wsh, G, Vh*) was sounded (the highest of them, *Wh*, showing a coefficient of determination below 0.5). Noticeably, *G* was the stand variable that supplied the poorest values in all models.

The relationship between biomass and carbon stock was also plainly confirmed: all the biomass stand variables (*W, Ws, Wsh*) found their correspondence in model fitting with their related carbon variables (respectively *C, Cs, Csh*): model performance, R^2 and model parameters where equal, with just slight variations (0.001 order in both parameters and coefficient of determination). This trend had been also appreciated in the correlation analysis (equal or almost equal coefficients in all bivariate combinations). Therefore, hereafter, unless specified, all statements related to biomass variables would be also applicable to their corresponding carbon stock and the latter will not be further mentioned although model testing and calculations have been equally carried out and results stored for the carbon stocking attributes.

The model that best fitted for all dependent variables was M5 (**Mukkonen and Heiskanen 2007**), providing the higher coefficients of determination (R^2) with but very few exceptions. Calculation of the numerical statistical criteria (RMSE and S%) confirmed the clear superiority of M5 for all stand variables. The rest of the models, except for M7 which was the model that best performed when considering *Wsh* as dependent variable (predictive variables *UW, B1, B3*) and presented some combinations of almost R^2=0.5, provided distinctly poor results. Specifically, all combinations tested using models M1 to M4 provided R^2 below 0.4 and in the case of M8, all tests were even more unsuccessful (R^2<0.3). Only M5 provided values of R^2 over 0.5. Thus, it was confirmed that models with more than one predictive variable performed better than models with a single independent variable.

The numerical statistics, RMSE and S% showed clear trends. RMSE was low for the stand variables with better fittings (i.e. higher R^2), suchlike *W*, *Ws* and *V (±1.8 on average, ±1.5 on average, and ±3.7 on average respectively)*. For *Wh* and *Wsh* was around ±40. Finally, for *Vh* was around ± 80. *G* was in the end rejected because, besides the low value of the coefficient of determination, these statistics generated errors in their calculation. In turn, S% varied between 33%, 41% and 36% respectively for *W, Ws* and *V*, whereas *Wh, Wsh* and *Vh* resulted in a better performance of this statistic, i.e. lower values of respectively 20%, 29% and 21% approximately, inverting the trend detected in RMSE analysis. M7 in the prediction of *Wsh* (*UW*, *B1* and *B3* independent variables) was also discarded due to the unacceptable results of the statistics. The poor results (R^2 below 0.5) obtained for *Vh* and *Wh* (M5, *UW/B1* and *B1/B4* as predictive variables) were confirmed by the validation data set statistics (high RMSEval –over 100 for *Vh* and 200 for *Wh*-), and very likely caused by the small sample size of the field data set.

The graphical analysis is shown in **Figure 4.7** where predicted values applying the selected models are plotted against observed values of the corresponding stand variables.

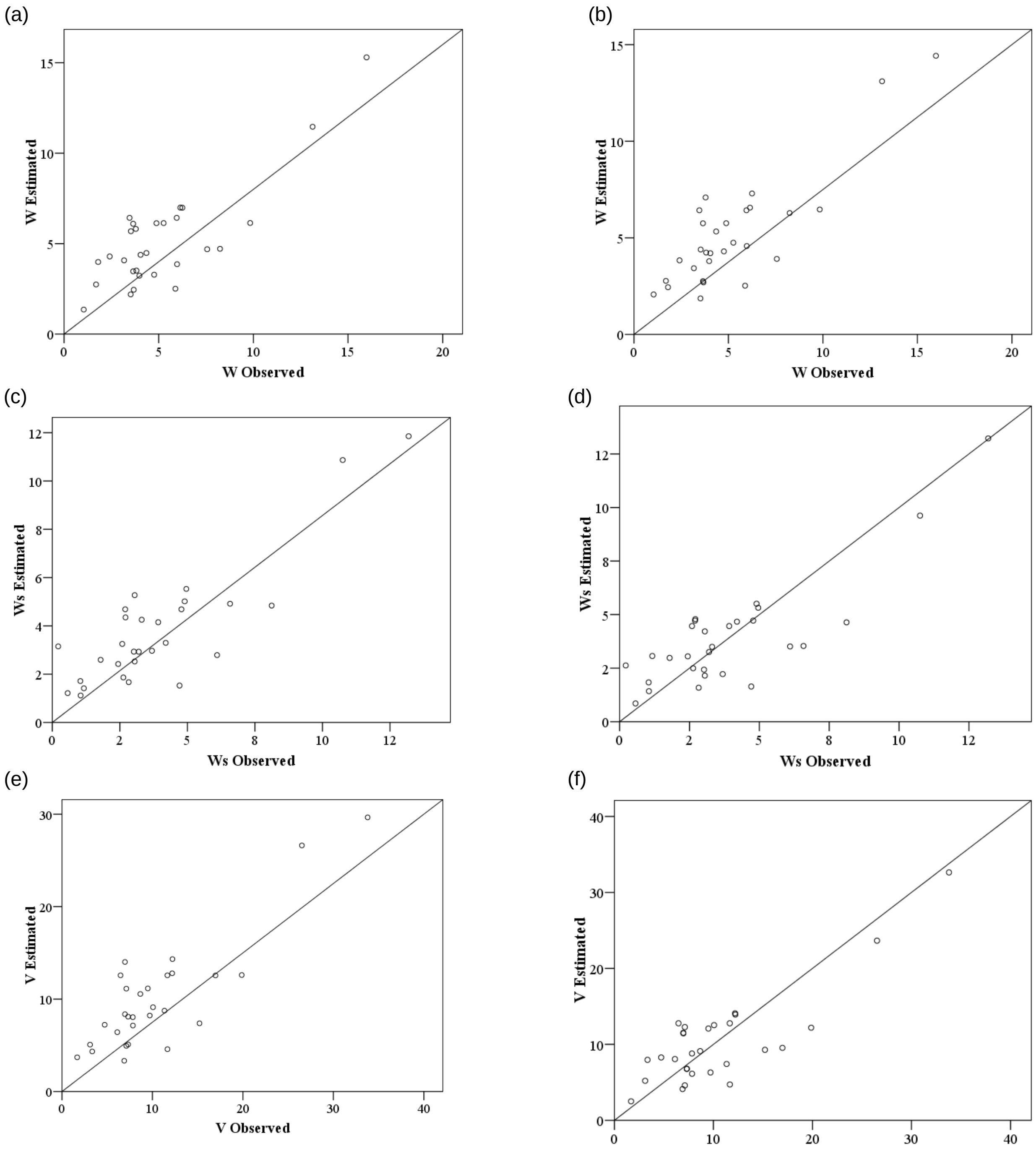

Figure 4.7 Selected sample of scatterplots (amongst the selected models that best performed and presenting a mean value of residuals around zero): predicted plotted against observed values of stand variables (*W, Ws, V*). *W* (Mg) M5, predictive variables *US/B1* (a), *W* (Mg) M5, predictive variables *SAVI/B1* (b). *Ws* (Mg) M5, predictive variables *US/B1* (c), *Ws* (Mg) M5, predictive variables *NDVI/B1* (d). *V* (m^3) M5, predictive variables *US/B1* (e), *V* (m^3) M5, predictive variables *NDVI/B1* (f)

As a general rule, stand variables result overestimated by the selected models, which was found particularly obvious in the models selected for the prediction of *Wh*. Overall, the residuals showed an appropriate behaviour, distributed around a mean value of zero.

3.4 Spatial analysis using ASTER data

The spatial distribution of the obtained results of stand basal area, volume and aboveground biomass for the whole surface of radiata stands covered by the ASTER scene are respectively shown in **Figure 4.8**, **Figure 4.9** and **Figure 4.10**.

A relationship between values of *G*, *Vh* and *Wsh* can be observed in **Figures 4.8, 4.9** and **4.10**: among the sectors with high biomass, the application of the models provides high estimated values for volume and basal area.

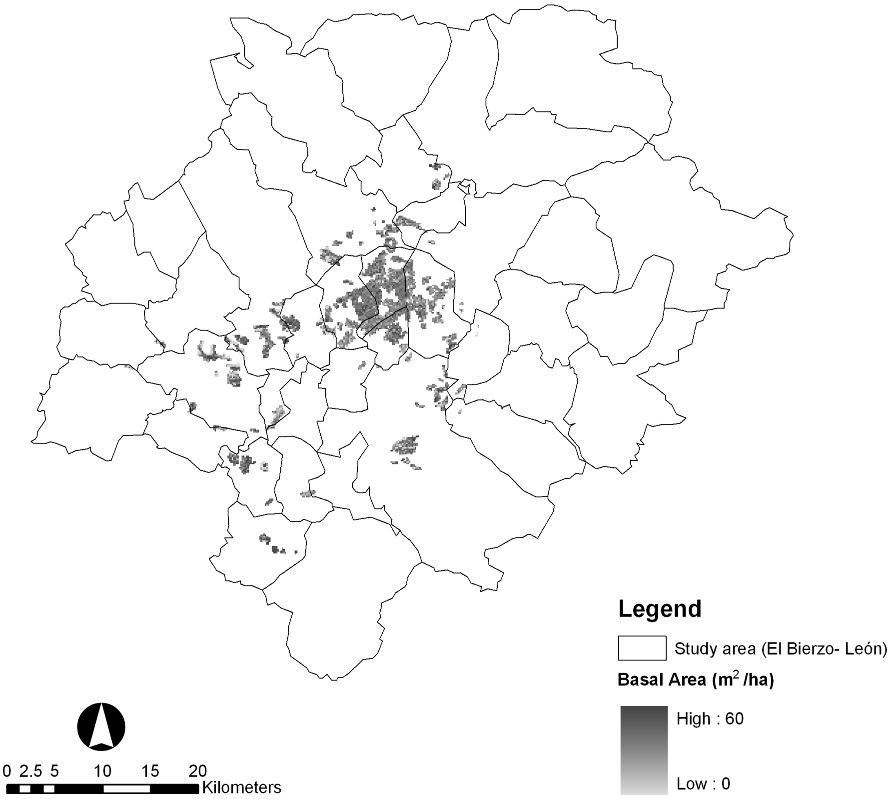

Figure 4.8 Estimated stand basal area (m^2 ha^{-1}) in radiata stands in the area of study

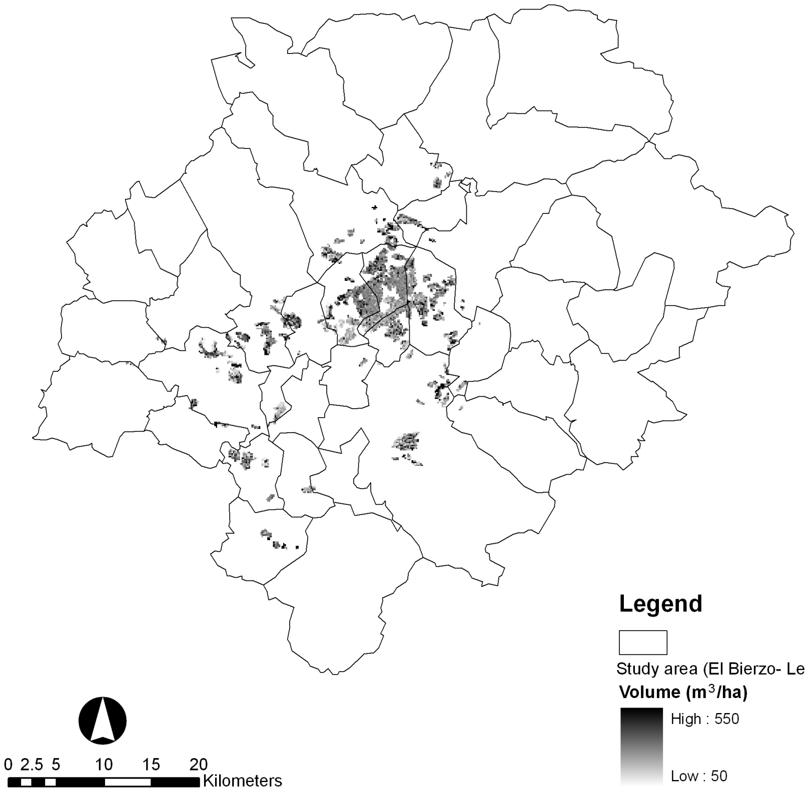

Figure 4.9 Estimated volume (m^3 ha^{-1}) in radiata stands in the area of study

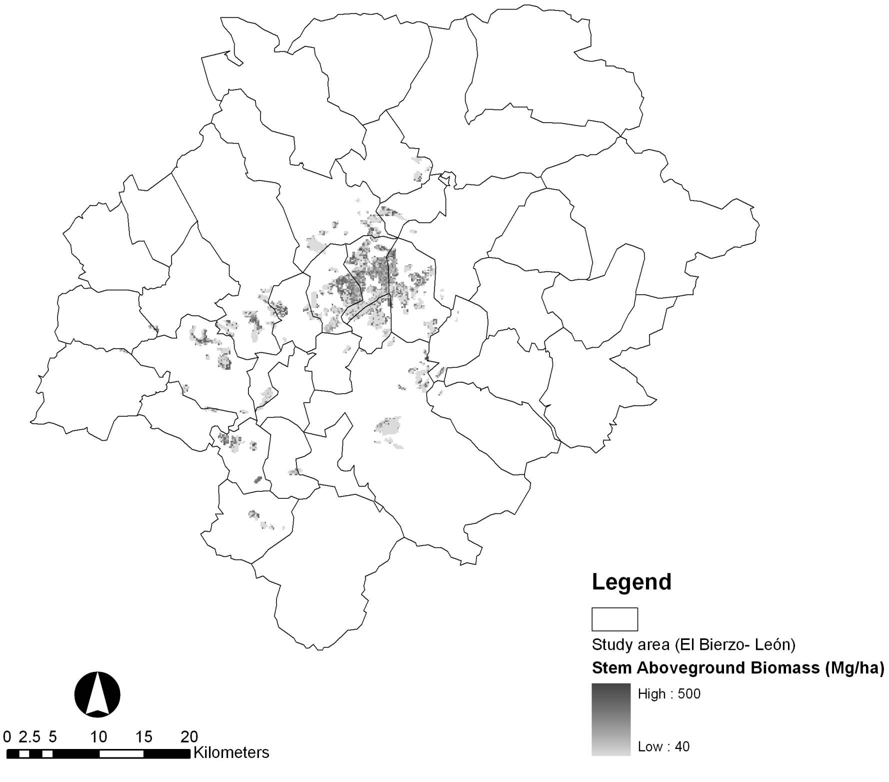

Figure 4.10 Estimated stem aboveground biomass (Mg ha^{-1}) in radiata stands in the area of study

3.5 Validation and comparison of results

The correlation matrix carried out for the validation plots showed some distinct patterns, particularly when considering the results obtained for the main data set. In general, correlation coefficients and R^2val were higher for the validation data set.

In the study with ASTER, *V3* was clearly the most recurrent RS variable. In case of the CBERS scene, outstandingly, *US, B1* and *B2*, exchanging positions depending on the stand attribute measured, were the RS data presenting a closer relationship with the stand variables under consideration. Although this could at first sight seem in disagreement with the principal data set correlation matrix, a closer look to the models selection processes points out that these variables are very frequent in the predictive variables that best performed.

When the regression models were applied to the validation data, RMSE always increased, although in rather usual margins. S%val was always between around 31-75% and 61-72% respectively for respectively the ASTER and CBERS data sets, also higher than the S% found for the principal data set.

Highlights of the comparison of the obtained results (using and ASTER and a CBERS image independently) follow: (i) *G* was rejected in the work with CBERS CCD. In the ASTER image, it was also the stand variable that worst performed but in the latter case, the R^2 was over 0.5 for M7. (ii) *V* selected model performed best in the CBERS CCD analysis, all statistics showing better behaviour. (iii) *Vh* also performed better in the CBERS CCD tests in the whole (RMSE and S%), but the coefficient of determination was significantly lower in the present work. (iii) On the contrary, *W* supplied a higher R^2 in the CBERS test, and similar and lower behaviour of RMSE and S% respectively. However, the difference in S% is not really significant. (iv) On the other hand, both for *Wh* and *Ws,* statistics were superior in the ASTER analysis, specially as regards model fitting (R^2), even though the differences in RMSE were small. (v) The same applies for *Wsh*, except for the fact that RMSEs, being very close, is smaller in the CBERS CCD case, and, remarkably, S% presents a better behaviour in the latter analysis.

4 Discussion

The sustainability requirements of present-day ecosystem management necessitate resource data that are accurate and continuously updated (**Coppin and Bauer 1996**). Accordingly, satellite images are currently an important data source in forest management. RS provides methods to infer land cover information over large geographical areas at a variety of spatial and temporal resolutions (**Heiskanen 2007**).

It is to be noted that biomass and carbon pools cannot be directly measured from space. Estimations must be necessarily related to the field measurements and the range of results depends on many factors (regression equations biases included). In turn, field measurements, even though more precise, have inherent disadvantages, such as costs or extrapolation problems being only valid for small areas and for a certain period of time (somehow solved in the area of study with the development of dynamic growth models).

The estimation of forest attributes such as biomass and other stand biophysical parameters from remotely sensed data is a complex procedure in which many factors interactively affect the estimation accuracy (e.g. **Lu 2006**). In addition to the sensitivity of the optical RS data to forest attributes, other factors include, among others, spatial resolution, correspondence of the reference and satellite data, data quality, and selection of estimation and evaluation methods. Understanding and identifying the sources of uncertainty in the models is indispensable for improving estimates of the forest attributes and land cover characterizations.

Potential errors beyond the undertaken approach, could be associated with the accuracy of land-cover map, sampling errors, confounding effects of soil moisture and soil colour on reflectance (especially in open areas), species composition and model utilization. Still, the small sample size can be considered the main drawback and recommends caution in the generalization of the statements hitherto derived (in particular when considering the validation sample). In contrast, the coherence between the RS approaches used in the area of study could hold the validity of the employed data sets. In sum, accuracy and comparison are compromised by errors that cannot be ruled out, causing relatively weak correlations between the image and field plots due to different scales and pixels resolution.

As the risk of abnormal data skewing the overall result is much greater for a small sample size (**Phua and Saito 2003**), it should be considered that in the design of studies and validation a larger sample will always be more reliable. Key findings of the research that had been depicted in this section highly recommend the intensification of field work that could strengthen the fitting and validation processes, significantly enhancing the potential of RS data with a synergic and cost-effective methodology.

Furthermore, the species expansion is certain and on the whole, it can be concluded that in spite of several limitations, multispectral satellite images are useful tools in the estimation of forest attributes at a regional scale (**Fernández-Manso et al. 2007, Hyyppa et al. 2000**).

It has been stated that tree height, stand volume and aboveground biomass are forest attributes which usually show weaker relationships with optical RS data than those related to the canopy cover (**Nilson et al. 2003**). For that reason, the applicability of the RS data is determined by the relationship of canopy cover and the forest attribute. When canopy is closed, the success in the estimation of forest attribute depends on the extent to which a closed canopy can predict them. However, in our case this is not yet influencing our conclusions due to the young age and characteristics of the species introduction in the region. Furthermore, the success in the application of the SMA technique reinforces this assumption.

A positive component of the study is the fact that the stands consisting of multiple tree species weaken the relationships (**Eklundh et al. 2003**). Therefore, the relatively strong relationships observed in radiata pine stands are partly explained by the single tree species. Unlike other RS studies, where classification techniques are needed, the National Forestry Map (**DGCN 2000**) together with ortophotographies of the study area provided an accurate source for setting the limits of the radiata stands when overlaid to the images, enabling spatial analysis of predictive models. Thus, possible mixing of species or erroneousness calculations of such techniques were avoided.

All the relationships with the original bands were inverse, which is typical for coniferous stands (**Eklundh et al. 2003, Häme et al. 1997, Ardö 1992**). In contrast to the broadleaved stands, the reflectance of coniferous stands is reduced in the NIR range (*B4* in CBERS and *V3* in ASTER), because of the pronounced within-shoot scattering (**Rautiainen and Stenberg 2005**). The plant pigments in the green leaves absorb radiation effectively in the red spectral range (*V2/B3*) and the canopy reflectance is inversely related to the quantity of the pigments. In sum, it can be concluded that generally there is an inverse relationship between vegetation amount and reflectance in the visible and mid-infrared region of the electromagnetic spectrum because of the absorption from plant pigments and water content, respectively.

On the other hand, positive relationships between stand variables and *GEMI* and *UW* have been found. The later is easily explained by the fact that the higher the trees and consequently the bigger the shade by them provided, the higher the volume, biomass and carbon stocks. The complexity involved in the calculation of *GEMI* makes it harder to reach a certain conclusion as regards this finding.

UW and *B4* in the CBERS dataset and *V3* in the study of the ASTER image were the RS data showing the highest correlations. In the coniferous forests, green and NIR reflectance have typically had the strongest correlations with stand volume (**Ärdo 1992**). Besides the unmistakable importance of NIR in the bibliography, extensive theory and applications of the SMA approach can be surveyed (**Shabanov et al. 2005, Sa et al. 2003, Drake et al. 1999, Wessman et al. 1997, Settle and Drake 1993**). The appliance of this technique in our work corroborates the influence of age, volume and related stand attributes on the shade spectral band of the stems (represented in the *UW* fraction).

The central assumption of linear spectral unmixing is that each surface component within a pixel is sufficiently large such that no multiple scattering exists between the components (**Drake et al. 1999**). This scattering approximation is valid when the pixel size exceeds the typical patch or component being sensed (**Qin and Gerstl 2000**). This, importantly, is evermore valid for the complex Mediterranean fragmented landscapes where the forest resources present a patchy and fragmented spatial pattern, and in particular, adequate to the size of the stands and plots of the plantations with introduced radiata pine.

In view of the final predictive variables chosen in both studies, the consideration of undertaking regression analysis trials using all possible combinations of independent variables (as explained in section 2.3 of the present chapter) was decisive. For instance, *GEMI* was the index that best performed in the correlation step and nonetheless it never proved to be significant as a predictive variable. Inversely, *US* did not at first sight appear to be relevant and it is a recurrent predictive variable in model selection when working with the CBERS scene.

The disadvantage of empirical models, suchlike the ones here calibrated and applied, is that statistical models are usually highly site and time specific and not transferable to other areas (**Foody et al. 2003**). That is the reason why depending on available datasets and resources, different images might imply different models even assessing the same field variables in the same locations. Nevertheless, the results obtained using two independent images, are coherent and reinforce each other discussions. On the whole, the model fits are comparable or better than in most of the similar studies in broadleaved or coniferous forests (**Eklundh et al. 2003, Chen et al. 2002a, Häme et al. 1997, Ärdo 1992**).

The spectral range overlapping between the two sensors, CBERS CCD and ASTER, restricts comparisons to the visible and NIR (*B1, B2, B3* and *B4,* in the quotation used with the CBERS scene), also affecting some of the SVIs to be applied. Some of the differences between model selection for certain stand variables (e.g. *G* or *V)*, or predictive variables can be evidently attributed to the spectral range variability, (i.e. SWIR bands and various SVIs are not applicable in the CBERS study). In any case, *G* was the stand variable that provided the poorest results in both cases. Furthermore, the statistics calculated suggested that the model initially selected had to be rejected.

Results in the ASTER work are highly dependent on the SWIR region of the spectrum, which has no equivalence in the data recorded by the CBERS CCD. In accordance to the relationship between band *V3* and coniferous canopies, strong correlation has been found between reflectance in SWIR bands and forest variables in coniferous stands (**Eklundh et al. 2003**). SWIR channels are sensitive to vegetation moisture, enhancing the contrast between vegetation and drier areas, and are less affected by atmospheric effects (**Carreiras et al. 2006**). Therefore in the SWIR wavelengths the reflectance will decrease with increasing leaf area as a consequence of increasing absorption due to water in the canopies. **Boyd and Danson (2005)** suggest that medium infrared reflectance (band *S4*, which is implicitly included in the *NDMI* index) may be more sensitive to changes in forest biophysical properties than the reflectance in visible and NIR wavelengths and should be considered when estimating the biomass of forests.

The data of acquisition of both scenes is also a decisive factor, as radiata pine is a fast growing species, and presents two important growths throughout the year (spring and autumn). Consequently there is a difference between the inventory data and the RS data of three growths. A prior concern was that short intervals of time are likely to change the stand variables estimates significantly, and maybe even the calibration of models. The data of a second inventory carried out in 2006 indicates that biomass of this species is growing quite rapidly. Thus, without taking into account disturbances or practices that could seriously reduce the area occupied by the species or affect tree growth, if the method of quantification of biomass in León was to be used in this moment, a higher value would be expected, this fact implying our result is already a subestimate of the existing quantity nowadays.

All the same, the fact that the same model is selected in both studies somehow corroborates the adequacy of M5 in describing forest attributes at least in the short-term. At least the fact that the reflectance of the land surfaces can also vary considerably as a function of time due to the seasonality of vegetation, when working with radiata pine in the area of study (soil ploughing, 15-20 years rotation, monospecific stands), as with coniferous species, is not determinant. In both works, NIR (*B4* or *V3* respectively in the CBERS and ASTER bands) has proved to be relevant, even if implied in SVIs and not as a single independent variable. In fact, the most common SVIs are either ratios or linear combinations of spectral bands, typically calculated from red (*V2* or *B3* respectively for ASTER and *CBERS*) and near infrared (*V3* or *B4* respectively for ASTER and *CBERS*) data. Thus, combining SVIs and single bands results in the summing up of the information of single bands.

Also, the shade and soil fraction images (*UW* and *US*) have proved to be the most important RS variables in the CBERS study. In accordance with several authors (**Peddle and Johnson 2000, Hall et al. 1995,** among others), the shade fraction image was the best band to estimate biophysical stand variables. These results point to the aforementioned fact as regards the shade fraction and to the consideration that *US* contains the proportion of soil, which is inversely related to the space occupied by the stems, i.e. a greater portion of soil implies lower volume, biomass and carbon stocking of the stand. Moreover, this is in accordance with the corresponding signs of the relationships between stand variables and the fraction images.

Anyway, an unmistakable conclusion is the importance, in all statistical analyses involved, of the SMA fraction images in the assessment of the main stand variables (e.g. total and stem aboveground biomass and volume) of radiata pine plantations in El Bierzo.

SVI used have biological consistency: *NDVI* and *SR* highlight the spectral contrast between red band (where chlorophyll barely reflects radiation) and NIR (where green needles reflect a lot of radiation). Therefore it has been widely correlated to biomass and vegetal vigour. Likewise, *NDMI* enhances humidity content of vegetation, reflected in the contrast between NIR and SWIR (radiation is absorbed by water in this wavelength). In the CBERS analysis, the most significant have been *NDVI* and *SAVI*, almost equally important which is shown in the very narrow differences in the statistics values. In essence, these indices involve bands *B3* and *B4,* which is in agreement with the conclusions of the authors of the selected model, who employed *B3* and *B4* as predictive variables from ASTER and MODIS images (**Muukkonen and Heiskanen 2007**). In the ASTER study, the use of the *GNDVI* improve the results for *G* and *Wh*, as the *GNDVI* uses the green spectral region instead of the red region, increasing the sensitivity to the presence of chlorophyll (**Gitelson et al. 1996**). The design of SVIs, as has been described in the introductory section, explains the fact that when using SVIs instead of single bands the behaviour of the model is finer.

The spatial analysis outcome is also coherent, volume and biomass reasonably growing. The values of stand variables estimated applying the selected models to the area of radiata pine covered by the ASTER scene are logical, especially regarding the values provided by the processing of the inventory field data.

Fragmentation of landscape and uses are the predominant features of the area of study, radically different from the large and uniform boreal forests that have been the main object of RS related works. The similarity in the dimensionality of the statistics calculated for the two works carried out in the area of study strengthens the consistency of results, in spite of the poorer results in prediction of stand parameters than the ones obtained in other coniferous plantations in the northernmost regions of Europe (**Trotter et al. 1997, Duncan et al. 1993, Ärdo 1992, Ripple et al. 1991, Spanner et al. 1990**).

Carbon stock has been indirectly calculated from the relationship found by **Ibáñez et al. (2002)**, dependent on wood density. In this respect, it has been proved that wood density increases from the pith to the outer stem, and decreases from the base to the tip of the stem (**Raymond et al. 1998**). Another influencing factor is tree age, wood density increasing over time. This age-related density pattern is so pronounced that it tends to dominate all other effects (**Beets and Brownlie 1987**). Even up to now radiata stands can be considered young, maybe in some future moment, this statement should be taken into account, depending on the stands and distribution of the species evolution, and age-classes treated separately when converting to carbon stocks, if new data become available.

Working with radiata pine, **Merino et al. (2003)** had found a biomass range of 94-240 Mg ha^{-1} in Galicia. In general, the stand basal area and aboveground biomass are in Chile 34.4-71 m^{2} ha^{-1} and 132-470 Mg ha^{-1} respectively (**Schlatter et al. 1998**). Even though our results are lower than these values, as shown in **Table 4.2**, comparisons are somehow risky because our range of age is younger (4 years in average) and biomass is dependent on this last variable, especially remarkably when dealing with a fast growing species. As a reference, in Galicia carbon sequestration in total aboveground tree biomass at stand level in the whole rotation (thinnings and clear-cutting at 30 years) ranged from 3.4 Mg ha^{-1} per year (the lowest initial stocking density, the worst site quality and 35% of thinning intensity) to 5.9 Mg ha^{-1} per year (the highest initial stocking density, the best site quality and 15% of thinning intensity) (**Balboa-Murias et al. 2006**).

The likely trends in plantations, as well as possibilities for monitoring changes, need to be considered when aiming at an integrated strategy for management of stands to mitigate global warming and other environmental effects, as well as socioeconomic targets which should also be involved in rural development and territorial strategies. Revitalising the regions economy implementing forestry uses, implying wood and carbon markets, seems appropriate enough, which is of special relevance due to the present interest in CO_2 emissions and sequestration.

Further research would improve the accuracy of the results, enabling a deeper evaluation of this study and the methodology used, which is especially important when assessing carbon temporal and spatial dynamics. Multitemporal datasets periodically updated could help in monitoring changes taking place within the stands due to management practices and natural factors such as pest infestation and stress. Also, it could be used to select and prioritize stands for detailed field survey.

5 Conclusions

This research utilises RS in combination with terrestrial surveys to quantitatively assess stand variables and carbon stock in radiata pine plantations in El Bierzo. In so doing, this chapter contributes to our knowledge on the application of optical RS for estimation of forest attributes in the region. More specifically, this work is investigating the feasibility of new satellite data at medium spatial resolutions, assessing the potential of multispectral images and providing regional evaluation for global scale land cover data sets. The relationship between stand variables and processed remote sensed data has been proved.

The forest attributes under interest were total aboveground biomass, stem biomass, stand basal area, stand volume and carbon stock. The approach used was inference by testing different models widely used. The model that best performed, both for ASTER and CBERS scenes, was the equation proposed by **Muukkonen and Heiskanen (2007)**. Amongst the independent variables, *V3* and *B4* were respectively the most recurrent single bands, whereas *NDMI*, *SAVI* and *NDVI* were the most important SVIs. Within SMA, *UW* and *US* provided the best results.

The analysis of satellite images was intended to enable radiata biomass mapping in the near future and the spatial analysis carried out with ASTER can be considered the first step in quantification of carbon pools in radiata stands in the whole area.

In short, the obtained results demonstrate that RS data recorded by ASTER and CBERS CCD sensors are helpful in the quantification of biophysical stand variables, in particular aboveground biomass, carbon stocking and stand volume.

Future directions of this project should include more field data to definitively verify the results of the RS studies, as the number of ground plots is considered a major weakness of the data set and the species area of distribution is increasing in the region.

CHAPTER 5. Management guidelines for *Pinus radiata* D. Don stands in El Bierzo: general review of radiata pine experiences and analysis of a Nelder trial in New Zealand

1 Introduction

The forestry sector plays an increasingly important role in New Zealand's economy (**MAF 2007**). It is almost entirely based on a planted forest estate of predominantly *Pinus radiata* D. Don. In the lapse of five years in the nineties, forestry's contribution to the national GDP increased from 3 percent to 5.3 percent. In terms of export contribution, forestry ranks as the third largest contributor. The total area occupied by forests in the country is 7.8 million ha, with over 2 million ha of planted forests, mainly with introduced species and clearly dominated by radiata pine (1.8 million ha in 2006, -**Dzierzon and Mason 2006-**). The predominance of *Pinus radiata* is due to good growth rates, the adaptability of the species to a wide range of sites, its responsiveness to tree breeding and silviculture and the versatility of the wood for a wide range of different end uses (**Cown 1997**).

Radiata pine was already well established in New Zealand by 1865 (**Lavery 1986**) and the first utilization of radiata timber was as early as 1876, whilst in Spain the first documentation of an exemplar in a botanical garden of the Basque Country is given by Cavanilles in 1857 (**Cavanilles 1858**).

In New Zealand, the species has undergone many silvicultural schedules (see also Chapter 2) and breeding trials, during several rotations and has been closely surveyed in different environments and site conditions from the big picture to the detail. Under such a historical background and nowadays importance, it is not surprising that New Zealand’s experiences with the species in all related research areas (establishment, environments, breeding, risks, silviculture, wood properties, marketing, management and planning) is hardly comparable elsewhere (to name a few, **Sorensson 2008, Payn and Clinton 2005, Watt et al. 2005, Dyck and Beets 1987, Forest Research Institute 1982**). Therefore, reviewing the evolution of forestry in New Zealand is a helpful way to understand the complexity of introducing an exotic species and forestry as a new land use, at the same time learning the know-hows from real examples and pointing out essential tips for the future. In this section, a summary of the most relevant aspects as regards the subjects approached in the previous chapters (e.g. productivity, sites, RS) is depicted from the New Zealand’s expertisse perspective.

1.1 Ecological requirements: sites

As aforementioned, the preference for this species is explained by its satisfactory performance over a wider range of sites than almost any other forest tree. In New Zealand, though within regional variance in performance (i.e. worse yields in drier areas), *Pinus radiata* outperforms all other conifers on most sites, growing in all types of soils.

Palmer (2008) provides a thorough review of environmental factors and productivity assessment for radiata pine in New Zealand. The later author states an interesting remark: regions of relatively low productivity may become increasingly desirable because such sites require lower capital outlay and contribute to the sequestration of carbon.

Its main limitations include intolerance to very wet soils and a poor growth on soils with chemical deficiencies, e.g. phosphorus or nitrogen deficient soils. Planting beyond climatic limits (altitude, rainfall) can be damaging, as can be planting on sites subject to severe frosts, dumping of heavy wet snow or strong winds. Productivity values generally decrease at higher elevations. Expert knowledge suggests productivity values should reduce to about 12 to 15 m^3 ha^{-1} $year^{-1}$ at around 900 m elevations. Evidence suggests that temperature is important for radiata pine stands height (i.e. SI), but not as important for plantation volume.

In any case, influence of environmental factors in productivity might be highly local, depending on the territorial scale considered (**Sánchez-Rodríguez 2001**), and has been under research in El Bierzo (**Pérez-Crespo et al. 2009**).

Taking into account that radiata pine in El Bierzo is established principally in abandoned agricultural fields, expertise in farm-site areas is to be considered. In particular, quality is markedly inferior if the site has a low site index, a high wind risk or the stand has been grown at low stockings. Physiological ageing, tree breeding and higher stockings can overcome some of the drawbacks, while retaining the benefits of volume growth. It has been proved that generally, the best way to take advantage of the extra volume that is produced on farm sites is to maintain higher stockings throughout the rotation (**Maclaren and West 2005**). This captures the extra growth potential without incurring major quality problems.

A comparison between different regions of *SI* curves from the two countries should be made with caution, as the relevance of the breeding programme in New Zealand cannot be obviated. Indeed, growth is the result of the interaction between genetic traits, the environment, and siting conditions.

1.2 Genetics

A distinctive feature of afforestation with radiata in New Zealand is the diversity of breeds being produced. While tree form of radiata pine often left much to be desired, the nature of tree-to-tree differences in form and branch habit, and in health and vigour, strongly suggested much genetic variation (**Burdon et al. 2008**). The breeding programme is made possible by the availability of control-pollinated seed orchards and supplementation of seed production by vegetative multiplication of nursery stock, and in the last few years, marker technology, obviating the need for controlled-pollination for producing advanced generations of the breeding population

(**Kumar et al. 2007**). This assortment of breeds reflects two major breeding constraints, namely the problems of obtaining large simultaneous gains in both growth rate and wood density and both internode length on the one hand, and growth rate and tree form, on the other (**Burdon 2005**). Siting is a determinant factor (e.g. genetic gains for stem volume production are evidently greater in absolute terms but less in relative terms on high quality sites –**Carson et al. 1999**-). A detailed and updated review of the breeding programme can be found in **Burdon et al. 2008**.

Seedlots collected from local stands of introduced conifers typically give somewhat faster growth than collections from the native stands. This can be attributed to the effects of a breaking down, under plantation culture, of the neighbourhood inbreeding of natural stands, plus the effects of natural and silvicultural selection in the adoptive environments. There is now a rapid shift towards use of vegetatively multiplied stock, in the form of nursery cuttings (**Menzies et al. 1992**), instead of seedlings as such, extending availability and diluting costs of seed. Clonal forestry offers the prospect of capturing gains in crop performance that are independent of competitive ability, which would take domestication to a new level (**Burdon et al. 2008**). It must be kept in mind, though, the implied risks in clonal forestry management (**Aimers-Halliday and Burdon 2003**).

Climbing select seeds, as the first breeding approach, simply consisting in manually selecting seeds from the dominant trees of unimproved stands (12-20 years old –**Burdon et al. 2008**-), can be considered the closest to natural selection and has therefore been used as control in related research experiments. The breeding series used in the present study are the 268 and 870, seedlings and cuttings, as well as climbing select. The 268 breeding series was predominantly selected for good stem form, multinodal branch habit and fast diameter growth, while the 870 breed was a special purpose breed selected for long internodes. Various advances in technology are now facilitating genetic improvement in wood properties which had hitherto been far more difficult to address (**Burdon et al. 2008**).

Many of the benefits of tree breeding interact with management practices. Indeed, with genetically improved stock available, it proved possible to drastically reduce the number of trees planted (**Wilcox and Carson 1989**), owing to both there being fewer malformed stems and other improvements in tree form. However, initial stocks of under 1000 stems ha^{-1}, particularly if final crop stockings are correspondingly low, can lead to reduced control of branch sizes, reductions in wood stiffness, and (at very low stockings) losses in mean annual increment (**Burdon et al. 2008**).

1.3 Management

An overall review of the management of plantations of *Pinus radiata* in New Zealand has been depicted in Chapter 2. The focus in the latter were initial stocking, thinnings and rotation ages due to the relevance of these silvicultural practices as regards the dynamic growth model application. Nonetheless, some recommendations on densities and pruning will be added in this section to ease the understanding of the complexity of the whole subject.

Initial stocking has traditionally been computed by working backwards from a determined final crop stocking and an appropriate selection ratio (e.g. 2:1 or 4:1 **Maclaren 1993**). As improved genetics and other techniques have reduced the need for high initial stockings, it now appears that initial stockings should be determined by other factors, including the need for mutual protection of young trees against exposure (e.g. frosts, draughts, snow, wind, and livestock) and to ensure that final crop trees are distributed evenly. Other risk factors must be equally comprehended, suchlike poor stem form or oversized branching. The best trade-off of cost versus risk will depend on site factors and suitability of wood properties, stem form and branching patterns, within specific log grades criteria.

Even though appropriate databases were not available and therefore the topic of pruning has not been tackled in the present work, it is undoubtedly an essential forestry operation. The main objective of pruning is to enhance the value of the butt log, by increasing the proportion of clearwood. The intensity of pruning is determined by a trade-off between removing too much green crown (thereby unduly slowing tree growth) and removing too little (resulting in additional pruning lifts). Note that trees should be treated as individuals, and pruned according to their height. Stability pruning aims to reduce toppling at a young age and has shown to be effective at minimal cost to tree growth. Market demand and hence pruned log prices, including biomass profitability, for fixed lengths of clears are likely to be a more important determinant than biological behaviour.

1.4 RS

In New Zealand, RS has been largely used as a research tool in radiata pine studies (e.g. studies with images from the satellites HYPERION and ALI-EO 1, and with airborne Light Detection and Ranging – LiDAR- measurements). Applied research to radiata pine include fields like forest health (**Sims et al. 2007**), productivity (**Coops et al. 1998**) or biomass and carbon sequestration assessment (e.g. **McNeill and Belliss 2002, Ellis et al. 1978**). For instance, Hyperion has been employed in the assessment of severity of infection caused by the fungi *Dothiostroma* sp., at early ages (less than 15 years of age, between 8-15 years of age of the stands). Depending on the objectives sought, many SVIs combined using partial least squares regression techniques, have been tried in suchlike trials, which have resulted in highly accurate models (i.e. R^2 around 0.7). Lidar combined with DTM or with satellite images have been used to quantify stand volume and biomass.

Some important restrictions have been pointed out: optical satellites frequently imply errors in correlations with field data due to silvicultural noise (e.g. silviculture introducing sudden artificial mortality unable to be accurately measured in multitemporal RS works or saturation, see Chapter 4). This fact especially affects productivity assessment.

To avoid this limitation and improve accuracy of correspondence between field data and reflectances, a new type of inventory is being developed, in which sample plots design is adapted to RS techniques requirements. Another major restrain is that the time of flight of the satellites over New Zealand (i.e. illumination conditions) particularly affects the reflectance of the dark tone of radiata pine needles, influencing the perception of terrain reality. The latest trials involve the use of the Discrete Anisotropic Radiative Transfer (DART), a 3D model for simulating satellite images and studying surface radiation budget (**Gastellu-Etchegorry et al. 2004**).

In view of these considerations and the analyses carried out in Chapter 4, RS in El Bierzo is an appropriate tool, as up to now, silvicultural noise and saturation can be practically rejected. Nonetheless, the solving of these limitations should be taken into account in the middle-term future.

Objective

Through utilising data from a Nelder trial, which included two commonly planted breeding series within New Zealand and ten initial stand densities, the first objective of this study was to practically examine the main and interactive effects of initial stand density and breed on growth and standing tree velocity (as an indirect measurement of stiffness) of 25-year-old *Pinus radiata*. Secondly, the experience in Rotorua (New Zealand) was intended to contribute to the theoretical addressing of each of the topics analysed and the search of answers for some of the questions that the establishment of the species in the area of study necessarily poses.

2 Methods

2.1 Field inventory of a Nelder trial

In November 2000, information on branching and stem shape was collected to determine the effects of seed source and initial stocking on branch diameter and stem shape. The main conclusions of this previous stand characterisation are to be compared with the data obtained in the inventory carried out in February 2009, the principal data source from the Nelder trial specifically collected for this study.

In 2009, following the methodology carried out in 2000, it was decided to measure a third of the trees, those on the middle two spokes of each block of 6 rows. If a tree was missing, then the next tree of the same tree stock in that circle was measured. Thus, a sample of 177 trees was measured.

The ATLAS Cruiser System used (**Forest Research 2003**) can analyse forest assessments where stem quality is recorded either in discrete codes or fully described with new methods of stem description. By simply describing the position and length of long internodes with the new description, the yield of any type of internodal log can be estimated.

It is not usually efficient to spend time attempting detailed quality descriptions of the upper half of the stem. In an average radiata pine stem prior to harvesting, 50% of the total stem volume is below 12 m, and 80% below 20 m. typically over 95% of the value is found in the lower 60% of the stem (**NZ Forest Owners Association 2003**) so the description effort should be concentrated on the lower stem to make best use of the investment in pre-harvest assessment.

Variables recorded during inventory include: identification of each tree and its pieces by its spoke number (tree number in PSP system) and circle number (1 inner, 10 outer) (plot number in PSP system), diameter at breast height (*d*) at 1.4 m, measured in centimetres using a tree diameter tape, total tree height (*h*), in meters using a vertex height instrument, when the stem was considered height representative (i.e. straight stem without a broken tip close to general stand height) and standing tree velocity (*st*) in km s^{-1} using the DIRECTOR ST300 (produced by Fibre-Gen Limited) and visual estimates of stem form and branching patterns (described below).

A summarised description of the data collected is shown in **Table 5.1**.

The use of speed of sound for assessing the quality (mechanical and physical properties) of wood and wood-based materials is known and well documented (e.g. **Pellerin and Ross 2001**). Acoustic tools use sound or stress waves to calculate the modulus of elasticity (MOE), a measure of stiffness (**Wielinga et al. 2009**). Thus, standing tree velocity is one of the components of stiffness.

Stiffness is a combination of density and microfiber angle (**Kininmonth and Whitehouse 1991**) and therefore it was chosen as an interesting parameter to represent wood properties in the trial. Standing tree velocity has the advantage of being easily recorded. In fact, it can be considered the easiest and quickest to be obtained from field inventories.

Table 5.1 Mean values of main stem variables recorded in field inventory of the Nelder trial

Observations	**Stocking**	**Growth**		**Wood properties**	**Stem form**	**Branching**		
n (stems)	(stems ha^{-1})	*d*	*h*	*st*	% td	*clm*	*blcl*	*dcl*
20	400	65.5	33.6	4.2	40	0.42	6.4	16
20	489	48.6	38.1	4.5	60	0.38	7.8	8.7
20	601	44.2	37.5	4.8	60	0.29	6	6.6
20	738	41.9	34.7	4.7	70	0.42	6.5	6.3
19	902	35.4	34.5	4.8	74	0.42	6.7	5.5
19	1104	36.7	36.2	4.7	74	0.38	7	6.1
16	1362	36.7	33.5	4.7	63	0.39	6.4	4.5
14	1666	33.7	33.0	4.7	64	0.40	6.5	5.1
17	2047	29.8	32.2	4.8	76	0.37	6.0	4
12	2500	30.0	29.9	4.7	75	0.40	5.5	4.36

h=height (m); *d*=diameter at breast height (1.4 m) (cm); *st*=standing tree mean average velocity in km s^{-1}); % td= % of trees with at least one defect; *clm*=number of branch clusters per m; *blcl*=number of branches in the lowest branch cluster; *dcl*=estimated diameter of the largest branch of the lowest branch cluster (cm)

Due to the presence of forks or other defects, for some variables there were less than 177 observations.

Branching assessment was based on the following variables recorded for each tree (and piece when applicable):

-number of pieces (if not a single leading stem above 1.4 m) in a stem

-the height of the lowest and highest cluster included in a count of the lowest ten clusters (or height of the lowest and highest cluster when the cluster count is less than ten, noting number of clusters in the latter case)

-number of branches in the lowest cluster

-diameter of largest branch in the lowest cluster and whether it was alive or dead

In turn, stem shape assessment was based on a stem description system (**Gordon 2005**), noting the occurrence of categories of sweep (**Figure 5.1**). Sweep is a difficult quality to assess. Rather than use sweep classes, which relate the maximum deviation form a straight line (over a specified length) to a proportion of the small-end diameter (**Whiteside and Manley 1987**), a two-dimensional trace of the stem centre-line can be constructed by recording the pattern of sweep:

-number of occurrences of simple bends, if extreme, the stem was classified as collapsed

-number of occurrences of normal sweep

-number of occurrences of hockey sticks

-number of occurrences of leader replacement

-number of occurrences of wobble

-number of occurrences of top outs (height non representative)

-number of occurrences of forks

-number of occurrences of spike knots

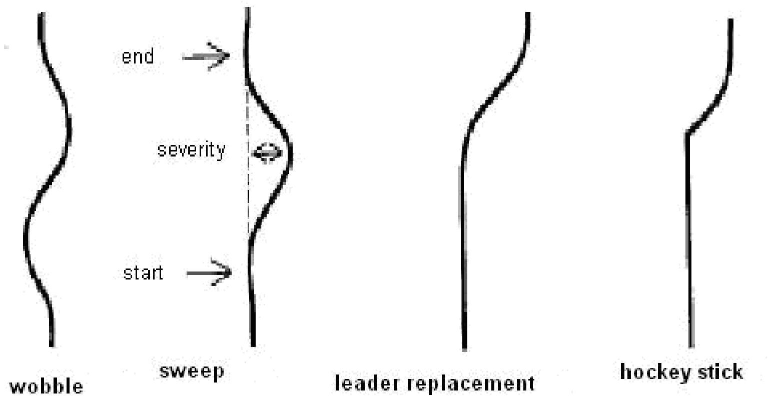

Figure 5.1 Diagram illustrating some categories of stem defects. These categories are part of a stem description system of common use in New Zealand (based on Gordon 2005)

The stems defined as collapsed are more strictly suffering Euler buckling occurrence (**Watt et al. 2006**), which is a typically recurrent stem defect when growing trees at high stockings to an old age.

2.2 Statistical analysis

SAS 9.1 software (**SAS Institute 2000**) was used to ascertain the influence of stocking and tree breeding on growth (*h* and *d*) and wood properties (*st*). The SAS procedure PROC GLM was used to determine which tree and branching characteristics were significantly influenced by initial stocking and tree type. Additional statistical analyses included ANOVA, plotting (GPLOT procedure) and non linear regression models to examine the distribution of tree stocks, and to predict the growth of individual trees. SPSS 15.0 software was also used for statistical analysis (i.e. graphs).

3 Results

3.1 Field inventory of a Nelder Trial

As regards appearance, the trial has suffered wind damage on the exposed site to the west, with some trees exhibiting poor form and others blown over. Though the trial is not completely in the open (i.e. it is surrounded by other stands and trials), the outer ring around the whole trial looks bad due to the edge effect: the trees are very large and the branching is also extremely large on the outer side. It has been noticed that the general form of trees is not as good as expected (i.e. there are a lot of malformed trees with such defects as forks and stem wobble). There is a large variation in tree appearance within each seedlot, both in size and form. There are three factors that are likely to have an effect on these results: (i) there is no buffer around the perimeter of the trial, (ii) the prevailing wind direction, and (iii) lack of silvicultural practices (i.e. no thinnings). It must be kept in mind that there was no release felling. Only dangerous trees have been removed recently. Overall, the appearance of the trial is probably very typical for plant and leave radiata pine.

Among the variables considered representative of growth (*d, h*), wood properties (*st*), branching patterns (*clm, blcl, dcl*) and stem form (sweep, wobble, leader replacement, spike knots, hockey sticks, collapsed), the ones influenced by initial stocking (significant at a probability level ≤0.01) were *h, st* and *dcl*. In turn, the only variable influenced by seedlot was *clm*. Other relationships found were between *h* and *d*, *d* and stocking, *st* and *d*, *dcl* and *d*, and *dcl* and stocking. However being significant, when testing models, some of the relationships can be doubted to be of any biological meaning as the value of the good of fitness statistic, R^2, appeared to be very low (e.g. st/stocking R^2=0.16; and clm/seedlot R^2=0.13).

Model testing, specifically homogeneity of slopes model, pointed out the convenience to attach to simpler models, provided that whereas the single variables showed significant results, the corresponding model did not. In addition, seedlot had a small effect in homogeneity of slopes model, which would be an interesting remark for a breeding program planning.

3.2 Growth patterns and wood properties

Influences on growth (patterns of *d* and *h* by stocking and seedlots) are given in **Figure 5.2**.

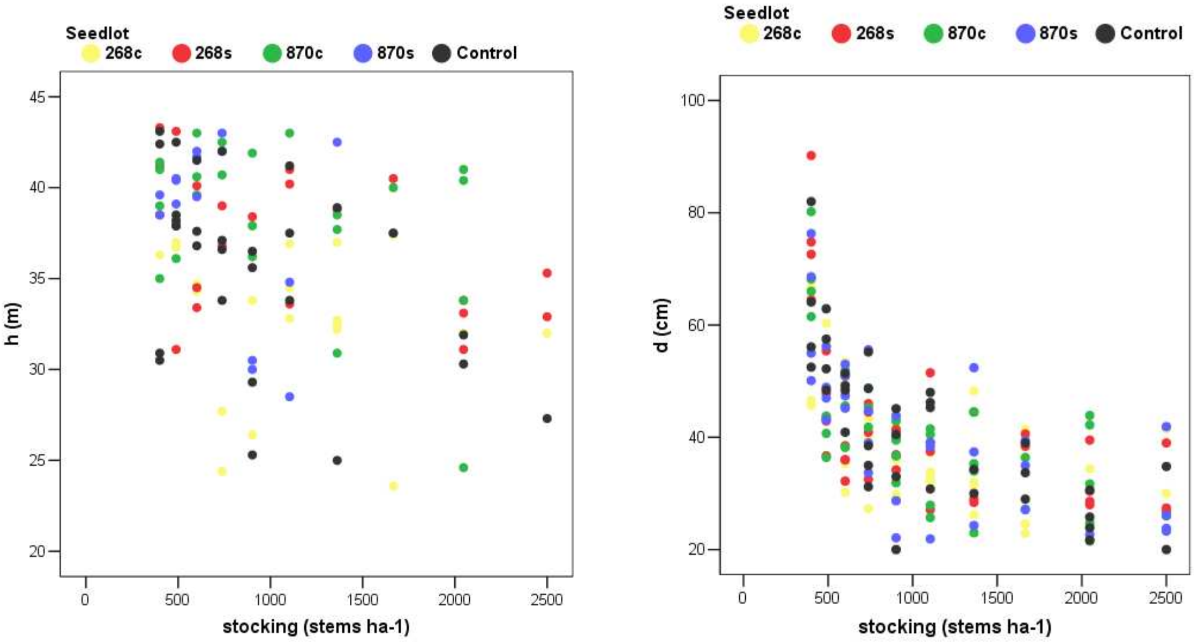

Figure 5.2 Influence of stocking (stems ha^{-1}) and seedlot in growth (*h* and *d*)

The graphs show a logical pattern: h is less affected by stocking than *d*, the latter variable showing a clearer trend (i.e. lower *d* in higher stockings).

Analogously, relationships between standing tree velocity and stocking by seedlots (i.e. influence on wood properties) are shown in **Figure 5.3**.

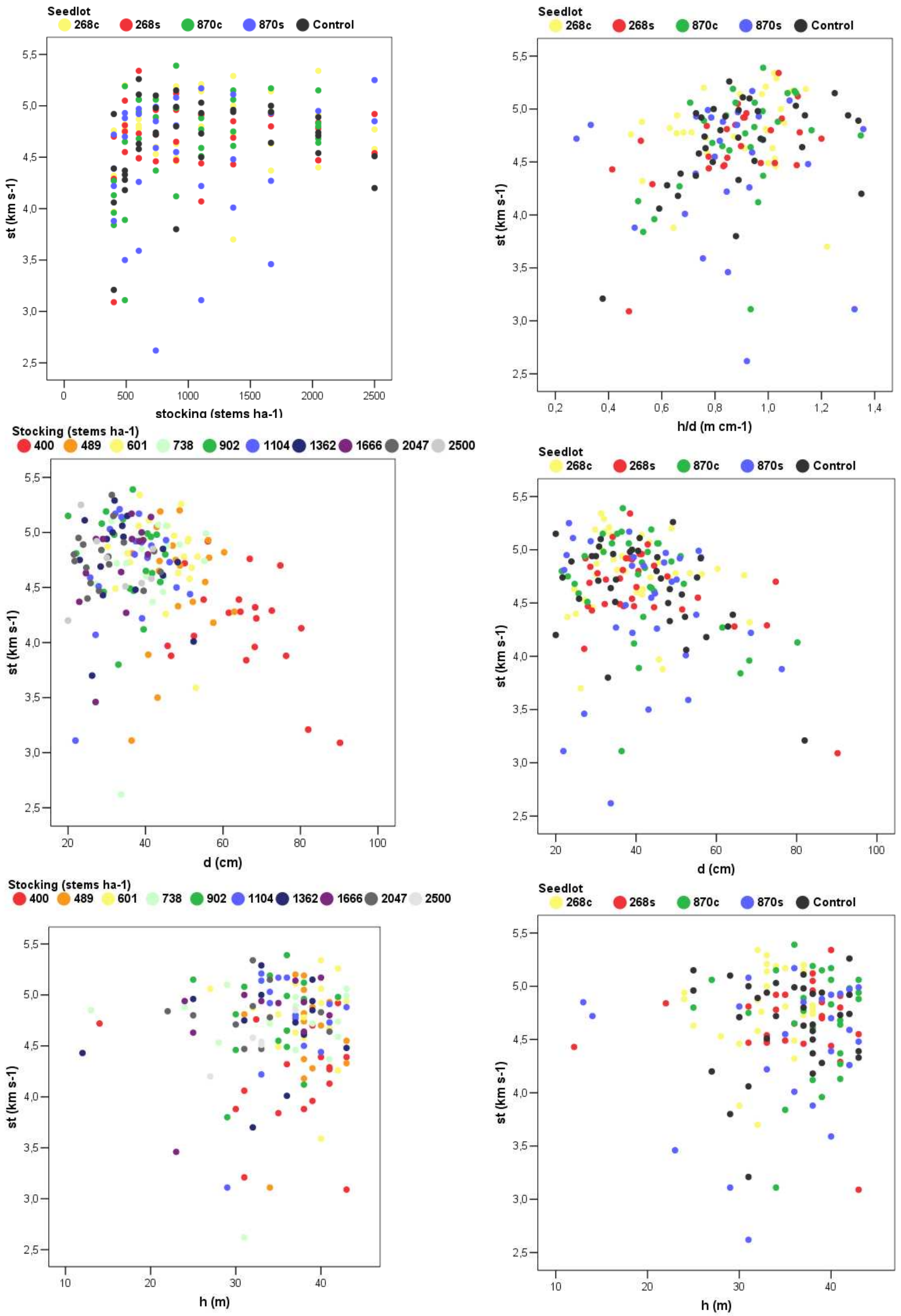

Figure 5.3 Influence of slenderness (*h/d*), *d, h*, stocking and seedlot on standing tree velocity

The plots showed some logical relationships: for instance, between *d* and stocking, lower d corresponded with higher densities, as a result of competition and space restriction between stems. The 870 series in general shows lower values of *st*, and at the same time higher values of *h* but lower of *d* than the 268 breeding series. In general, the plot shows a relationship between *st* and *h* (i.e. higher trees present high *st*), whereas the relationship between *st* and *d* is inverse. As regards slenderness (*h/d*), a slight increasing trend with increasing stockings can be discerned. The lowest *st* value (<3 m s^{-1}) corresponded to a malformed tree with many dead pieces.

3.3 Branching patterns

A visual inspection of branching variables (*clm, blcl, dcl*) is shown in **Figure 5.4**.

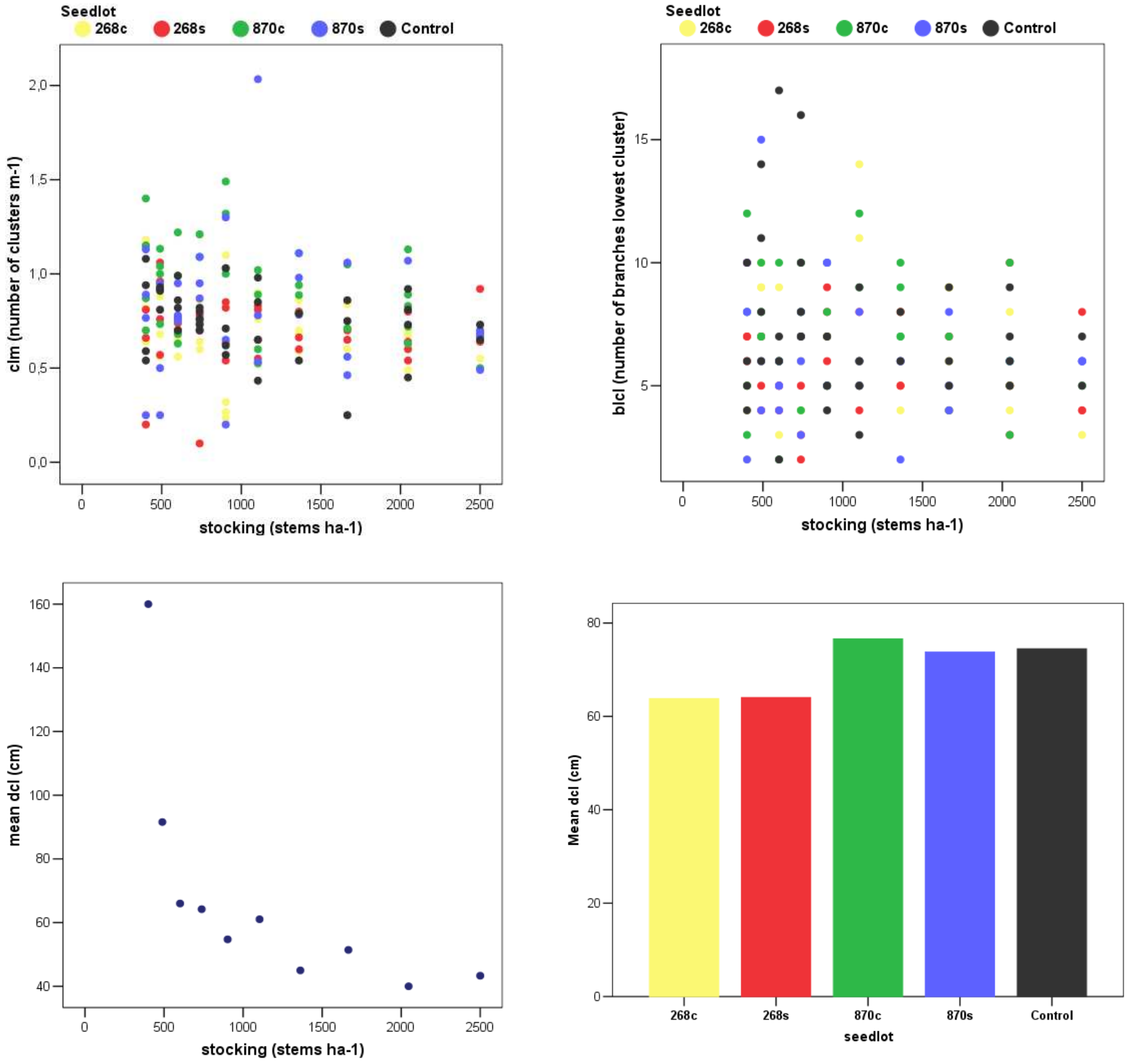

Figure 5.4 Influence of stocking and seedlot on branching

3.4 Stem form

Finally, as regards stem form, the most interesting findings were that over 65% of the trees exhibited some defect. More precisely, sweep was the most recurrent defect (23.3% of the trees), followed by wobbles (17.04%) and spike knots (16.5%); 19.3% of the trees were collapsed. Hockey sticks and leader replacements were by far the less recurrent defects, well below 5% of the stems exhibiting any of them (1.1% and 3.5% respectively). Details of distribution of stem form defects by seed classes and stocking are shown in **Figure 5.5**.

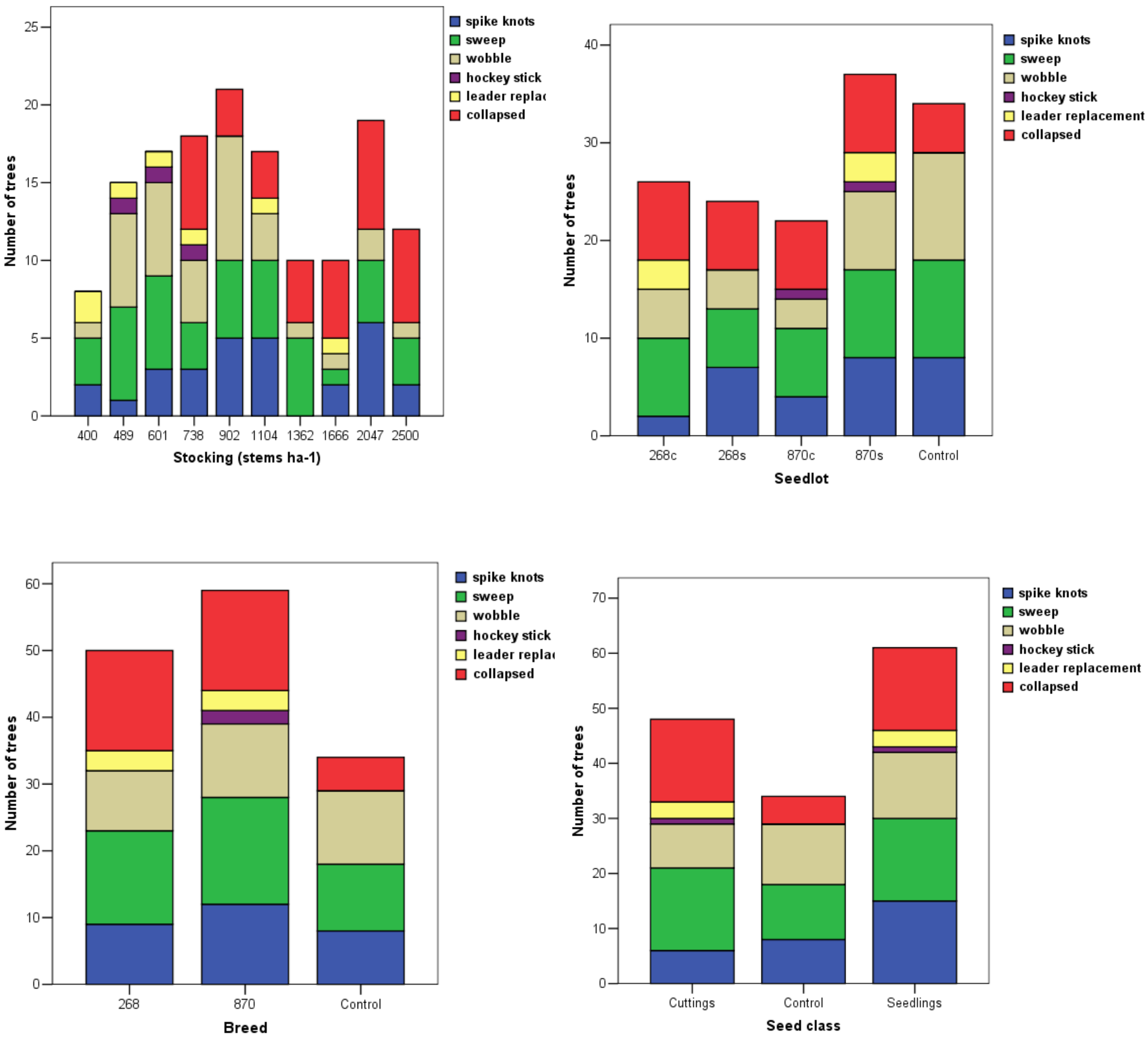

Figure 5.5 Stem form defects by seedlot and stocking

At the light of the plots, collapsing seems to increase with increasing stocking. As regards breeds, the 268 seedlot presents less stem defects. Analogously, cuttings show fewer wobble and spike knots, though similar patterns of the rest of defects than seedlings. An interesting remark is that the control seedlot (unimproved) on the whole presents fewer stem form defects.

4 Discussion

Two important management decisions made during establishment of a radiata pine forest plantation which have been shown to significantly affect wood properties are selection of an appropriate genotype and initial stand density (**Lasserre et al. 2005, Sorensson et al. 2002**). The evaluation of the effects of spacing, thinning and pruning regimes on the amount and value of timber produced, and the production risk, is an important task of silviculture, since these effects can be directly controlled by forest management (**Savill et al. 1997**). A first attempt to point out the basics is made in this chapter. The objective of the Nelder trial analysis was to illustrate the effect of different initial stockings and breeds in an unthinned situation. On the whole, the variables selected are relatively easy and quick to be measured in a field inventory (e.g. number of branches and diameter of the largest branch in the lowest cluster).

Fast-grown plantation softwoods all variously suffer from wood quality problems, such as unacceptable appearance, dimensional instability, and low stiffness. In the plantations in El Bierzo, as in many other areas in Spain, up to now, the focus of research has been on volume productivity. From the field survey, some problems as regards production of high quality wood can be pointed out: most of the stands show branching and stem defects (e.i. knots, straightness problems, infection by *Rhyacionia buoliana*) and the predominance of stems with small diameter. Apart from genotypic trade-off between internode length and general growth and form, the trade-off between growth and wood density, and some other wood properties (**Wu et al. 2008**) will continue to pose challenges.

As regards genotype, preliminary studies have shown moderate to high heritabilities of wood stiffness in radiata pine (**Baltunis et al. 2007, Kumar 2004**, **Shelbourne 1997**), whereas others, to whose conclusions we add in view of the obtained results, (**Whiteside and Manley 1987**) state the contrary. It is to be noted that tree type was not significant in this study (except for influencing the number of branch clusters per meter, which is in turn logical to the specific characteristics of the breeds considered). As expected (**Watt et al. 2000, Jayawickrama et al. 1997, Carson and Inglis 1988**), the 870 long internode breed had significantly longer internode lengths than the 268 breed, demonstrating its defining physical characteristic, and as in previous research (**Grace and Carson 1993, Siemon et al. 1976**), it was found no correlation between stocking and internode length. However, it should be borne in mind that the fact of tree types not influencing any other variable may be due to the small sample size.

In the Spanish case, in which unimproved stands are analysed, we can attach to the fact that tree morphology is markedly affected by intra-specific competition (**Smith et al. 1996**). Intra-specific competition is a function of initial stand stocking and the growth rate of trees and subsequently influences diameter (**Sjolte-Jorgensen 1967, Cromer and Pawsey 1957**), height (**Carson et al. 1999, Maclaren et al. 1995, Mason 1992**), stem slenderness, and branch size (**Grace 1999, 1998**). Our results, though general, are in accordance with the latter authors and the previous analysis of the trial: in most cases for conifers, the mean top height of the stand positively increases with stocking and that this factor had far more influence on tree *d* and tree *h* than did tree type. This is consistent with other results (**Carson et al. 1999**).

Even if a breeding program is not likely to be started immediately in the region of study in Spain, the results of our study show that in any case, such an issue should be approached differently to assure its success in the local conditions. Though overall there are good prospects of simultaneous genetic improvement of a suite of wood properties, it would likely be at some cost in potential genetic gain for stem volume production. Most experts agree that the species remains largely un-mined genetically, particularly for traits such as high wood stiffness (**Sorensson and Shelbourne 2005**). Currently, it seems more interesting to breed for stiffness or density instead of attaching to branching patterns. Disease resistant breeds adapted to local conditions would be an asset.

Both the number of branches in a cluster and branch diameter were found to have a large effect on the value of premium timber products (**Pont et al. 1999**), and in our study are also influenced by initial stocking. As it was expected, the diameter of the largest branch in the lowest cluster was influenced by diameter (larger branches normally grow on larger trees), though not by height. An interesting finding is that branch diameter is not influenced by seedlots, which could have not been anticipated as the 870 breeding series tends to have larger branches.

Branch diameter, adjacent to the stem, increases rapidly for a number of years and then remains approximately constant. Branch diameter in radiata pine is influenced by many factors, among which, the available space in the direction the branch is growing (**Tombleson and Inglis 1988**). The general trends in branch diameter with stocking are: high densities imply less available space for branches and resources for branch growth. The tree is forced to grow upwards, without being able to develop large side branches. For instance, the severe edge effect resulting in extreme growth of the branches on the side of stems facing outwards the largest circle, as the Nelder trial presents no buffer, provides a clear demonstration of this fact. It is likely that stands planted in open areas of agricultural fields will suffer this effect.

In New Zealand, branches between 6-14 cm of diameter are part of the wood production, adding economic value to radiata stands. Even though in the plantations in El Bierzo the presence of branches over 6-7 cm of diameter is rare, this input value should not be thrown away (e.g. small branches could be profitable for bioenergetic uses and stands adequately managed could include branching profitability).

When studying stem form, it appeared to be more sweep at the lower stockings in this trial, as previously stated for the trial. Sweep causes variability in wood properties within a given stem growth ring. The other point with sweep is that compression wood, presenting a higher density but a lower stiffness than normal wood (**Low 1964**), is formed to correct for lean and sweep (**Cremer 1998**). Tree breeding and plant propagation techniques have slightly reduced the number of trees exhibiting lean and sweep. Nevertheless, there are still large numbers of trees exhibiting collapse and defects at all initial stockings. The number of collapsing stems increased slightly with increasing stocking. This is in accordance to the previous analysis of the trial.

Tree type has been proved to have influence on stem form (e.g. long internode might have more wobble). Cuttings generally show improved form and therefore increased recoverable volume, whereas seedlings show better diameter and volume growth. An interesting remark is that planting rooted cuttings can lead to the achievement of considerable improvement in form without any loss of growth. Site conditions have also proved to be determinant on the growth and stem form defects, farm fertile sites enhancing the differences between tree types.

In New Zealand, lower initial stockings have been recommended for improved seedlots based on the improved number of acceptable stems (e.g. **James 1990**), though final crop stockings are increasing in recent years. There have been also direct regimes, in which approximately 500 stems ha^{-1} were planted and left to the end of the rotation without any thinning or pruning (e.g. **Dyck and Thompson 1999**). A ratio of 1:4 or less between the number of trees at clearcutting and those removed during thinnings has been recommended if genetically selected plants are not available (**Maclaren 1993**).

Many trees will be inferior in growth rate or form owing to either poor genetics or an unsatisfactory early history. Thus, planting more trees than required allows an opportunity for later selection of the best trees. This is not to say that high initial stockings are a satisfactory substitute for improved genetic stock (**Maclaren 1993**). Trees raised in tight stands will tend to be taller, straighter, and have smaller branches than those grown at low stockings, but they will also have smaller diameters (**Rodríguez et al. 2002**). On the contrary, generally low stockings incur a higher incidence of wind-damage. Evidence to date suggests that 600 stems ha^{-1} is the minimum initial stocking required for mutual protection (**Maclaren and Knowles 2005**). If a site is not fully occupied by acceptable crop trees, the costly investment in land purchase and land preparation will be ineffective. On the other hand, the cost of planting (and thinning out) superfluous trees can be justified by the reduction of the risk of patchy establishment. On very unstable slopes, low-stocking regimes are probably not as efficient in protecting slopes against mass wasting. Management of steep terrain forests should aim both at soil protection and wood production (maybe for biomass uses). This could be a relevant remark as for the expansion of the species in El Bierzo, as there is plenty of available land for forestry uses in the transitional hills and valleys between the central plain and the mountain range.

There is indeed a varied range of options available (**Whyte 1988**), and one of the explanations of the success of radiata pine in plantations is certainly that even if sub-optimal regimes are selected, the chances are that no great loss will result, provided that extremes are avoided. Regimes can be tailored to suit individual requirements by judicious use of both modelling systems and local expertise. Advantages and weak points of each option must be conveniently weighed under practical experience. In the end, real scenarios and experiences should be regarded when defining regimes and treatments.

In sum, whereas simulations made in Chapter 2 show that a higher volume is obtained with plant and leave regimes, the Nelder trial analysis points out the risks with respect to branch size, stiffness (velocity) and stem form for different stockings and seedlots. Were there a shift in production objectives towards higher quality final products, which could certainly imply higher benefits, the current problems of the stands in El Bierzo would show up more evidently. Nonetheless, the most important challenge for the area is the lack of market prospects, forestry culture and final products usage.

5 Conclusions

A thorough review of the experiences with the species in New Zealand (depicted in the introduction section of the present chapter and implied comments in other chapters) highlights the main points and weaknesses of forestry and related research issues, leading to the solving of some of the initial objectives and at the same time defining future lines of investigation.

The two supreme virtues of radiata pine –to grow very large very fast, and to respond vigorously to silvicultural treatment – have been preached for a long time. Given a defined objective, the tree may be grown to meet a range of requirements, including branching, stem form and growth rates versus wood quality standards.

Genetic quality, type of stock (seedlings or cuttings), and planning are important considerations in forest establishment. It must be regarded as it has a significant impact on the profitability of plantations and the quality of the final crop at harvest. Furthermore, the choice influences initial stocking decisions, seedlings requiring higher densities than cuttings.

Nearly half of a merchantable radiata pine stem at harvest comprises core wood that tends to be deficient in stiffness and dimensional stability. Therefore, a breeding program focusing on such traits would be highly profitable. Investment and research on this topic in New Zealand has led to considerable advancements in improving the growth and quality performance of radiata pine. Nevertheless, stocking has proved to be the most important factor in this study, especially under the light of application in the Spanish plantations which are far from being genetically controlled or improved.

At present, in El Bierzo, risk management decisions, siting options and generalization of silviculture practices that would overcome current problems (e.g. straightness, knots, wood quality, branching profitability) on the one hand, together with development of related industry and market on the other, are the most decisive factors for the species success and establishment. Without an appropriate scope, most of the potential of the species could be lost.

CONCLUSIONES

Los modelos de crecimiento son herramientas de gestión especialmente útiles en la evaluación de la productividad de las masas. Aunque simple, el modelo de masa desarrollado predice el volumen, área basimétrica, índice de sitio y densidad de las masas de pino radiata en El Bierzo. Constituye un paso crucial para el establecimiento de la especie en la zona de estudio, al precisar un ajuste local.

El análisis de régimenes silvícolas viables debería incluir la evaluación de objetivos regionales específicos, fines de producción, costumbres locales y restricciones de las plantaciones en consideración. La optimización de los usos forestales no depende en último término de un régimen específico. En cambio, factores críticos son la calidad de estación, las tasas de descuento y por supuesto, la selección de la especie apropiada.

El desconocimiento sobre la potencialidad de una superficie para el establecimiento de una especie determinada impide a los gestores la selección de las mejores áreas de cara a la reforestación, así como la adopción de las correspondientes medidas de planificación que aseguran la optimización de beneficios y sostenibilidad de los recursos. La definición del hábitat central y marginal de la especie y los modelos de calidad de estación en función de variables ambientales, aunque imprecisos, aportan guías útiles en este sentido.

Los modelos empíricos no explican los procesos físicos, sino que ajustan mediante técnicas estadísticas las propiedades de las superficies terrestres y atributos forestales a los datos de TD. La ventaja de los modelos empíricos es que permiten un uso muy eficaz de los datos, aunque su aplicabilidad depende básicamente de la proximidad de la relación entre los datos de TD y la variable de campo de interés. El análisis de imágenes de dos sensores diferentes (ASTER y CBERS CCD), junto a fuentes de datos digitales complementarias, confirma la utilidad del uso de técnicas de TD para la evaluación de propiedades dasométricas a escala regional.

Las experiencias con la especie de otras regiones apuntan a la necesidad de establecer un equilibrio entre las tasas de crecimiento y la calidad de las propiedades de la madera para un uso industrial de los productos. La productividad en volumen frente a los riesgos implicados, entendidos como defectos del tronco, ramas demasiado grandes para usos determinados, daños por viento, riesgos de incendios y variabilidad en las propiedades de la madera, es un tema relevante para la gestión de la especie. Esta afirmación es particularmente importante para pino radiata, ya que se trata de una especie de crecimiento rápido que muestra una respuesta muy flexible a los tratamientos silvícolas. Además, los programas de mejora genética en otros países han tenido un éxito rotundo.

La revisión de los conocimientos forestales adquiridos en otras zonas puede resultar un procedimiento efectivo en tiempo y costes para orientar el éxito del establecimiento y expansión de la especie. Aportando un ejemplo práctico, la parcela Nelder muestra los riesgos en cuanto al tamaño de las ramas, defectos del tronco, rigidez y procedencias genéticas, mostrando la necesidad de llegar a un compromiso entre el crecimiento en volumen y otros factores que influyen en el valor de las plantaciones forestales.

Los suelos de la depresión central en El Bierzo, con un clima más suave, son superficies muy fértiles, en que se abandonan cultivos agrícolas como resultado del declive de las actividades económicas tradicionales y la disminución de la población en la zona. El Bierzo es de hecho una zona rural marginal, que comparte la problemática que tiene lugar en muchas regiones del interior peninsular. Las plantaciones forestales, especialmente con una especie de crecimiento rápido, pueden sentar las bases de la implementación de usos forestales mostrando un ejemplo alentador. Gestionadas de forma adecuada, pueden además contribuir a invertir las tendencias actuales, añadiendo sostenibilidad al desarrollo en áreas rurales.

FUTURAS LÍNEAS DE INVESTIGACIÓN

Hay todavía una gran superficie de terreno disponible para el establecimiento definitivo de la especie, incluyendo los cerros de transición entre las llanuras de la depresión central y la cadena montañosa circundante (**Pérez-Crespo et al. 2009**), que podría contribuir a la implementación de los usos y mercados forestales.

De hecho, en el momento presente, las plantaciones con pino radiata están sin duda en expansión. Consecuentemente, se genera una indiscutible necesidad de obtener información útil que contribuya de forma significativa a la gestión de las masas.

El valor de las masas puede incrementarse mediante la cuantificación y predictabilidad de las propiedades dasométricas con anterioridad a la cosecha y la consideración de objetivos multipropósito, como por ejemplo la mitigación de los efectos del cambio climático por el contenido en biomasa y las reservas de carbono implicadas en las masas forestales.

El modelo de masa desarrollado podría mejorarse, partiendo de una intensificación del inventario forestal, que incluya datos sobre operaciones selvícolas (claras, podas) y calidad de productos finales (propiedades de la madera, defectos de tronco, ramas), de forma que las salidas del modelo proporcionen información complementaria a las tasas de crecimiento y volumen. La ampliación del rango de datos recogidos en el trabajo de campo, permitiría además superar las limitaciones en la simulación de alternativas selvícolas y del estudio de productividad basada en factores ecológicos e incluso la inclusión de variables como la biomasa. El diseño de los experimentos debe considerar la realidad territorial y los objetivos de la investigación en su conjunto.

Otros campos de interés que han demostrado su importancia en lo referente a la especie, como especie exótica introducida con fines productivos, son la salud e higiene y los riesgos ambientales (fuego, viento, nieve). Asimismo, no hay que olvidar la evaluación del impacto ambiental que las masas pueden generar para garantizar la productividad a largo plazo.

Las técnicas a emplear deberían ser fácilmente actualizables y complementadas apropiadamente con inventarios de campo adaptados a las necesidades de las técnicas de la TD, para adecuarse a las condiciones locales y su contexto socioeconómico, premisas bajo las que se ha planteado el presente trabajo. Se debería profundizar en la aplicación de estas técnicas que permiten abordar los estudios a escala regional, empleando imágenes de sensores de mayor resolución y nuevas metodologías de análisis.

El contacto con la realidad de la especie en otras regiones, evidencia que en la zona de estudio, quedan numerosos campos de investigación relevantes por examinar que aún no han sido abordados. Entre ellos, resultan cruciales la prospección de mercados y análisis de retornos financieros, junto a usos y propiedades de los productos madereros. Además de unas dimensiones adecuadas de las trozas, los usos industriales y la comercialización de productos requieren unos estándares en las propiedades de la madera (**Riesco-Muñoz y Díaz-González 2007**). Efectivamente, es necesario instaurar un vínculo real entre el establecimiento de plantaciones forestales y el destino de los productos finales. A pesar de las grandes diferencias entre la situación de la especie en Nueva Zelanda y El Bierzo (en superficies de las plantaciones y estructura de la propiedad, planificación forestal, industria, investigación y trayectoria), la relevancia del programa de mejora genética en Nueva Zelanda, evidencia la necesidad de investigación en este campo, adaptada a las condiciones locales.

Los usos forestales pueden favorecer actividades alternativas que podrían complementar la economía local y los servicios sociales proporcionados por las masas (usos cinegéticos, aprovechamientos micológicos, refugios de fauna y contribución a la biodiversidad). En este contexto, ligado a la sociología forestal, el desarrollo de enfoques más holísticos en las prácticas silvoculturales y la gestión forestal constituye un reto para las ciencias y prácticas forestales (**Koch y Skovsgaard 1999**).

La transición desde los sistemas de plantación intensivos a una gestión forestal de cosecha selectiva puede ser una opción a largo plazo con beneficios ecológicos (**Kerr 2000**), especialmente aplicable en superficies gestionadas por los servicios públicos.

El logro íntegro de los objetivos de las plantaciones debería ser seguido cuidadosamente desde las organizaciones que puedan contribuir a la difusión de los conocimientos obtenidos en los estudios técnicos de investigación, de forma que sea factible que las instituciones públicas, propietarios y trabajadores forestales apliquen las recomendaciones de los técnicos, y a su vez contribuyan a su actualización aportando sus propias experiencias prácticas.

En resumen, sería necesaria una investigación dinámica, en contacto con la industria y mercados existentes y potenciales, explotaciones agrícolas y sistemas agroforestales mixtos, para abordar de forma definitiva la complejidad de la implementación de usos forestales.

CONCLUSIONS

Growth models are especially useful management tools in the assessment of the productivity of the stands. Though simple, the model developed predicts volume, basal area, site index and stocking of the stands in El Bierzo. It is a crucial step in the establishment of the species in the area of study, as it must be locally adjusted.

The analysis of feasible regimes should include evaluating specific regional objectives, production targets, customs and constraints of the plantation under consideration. The profitability of forestry is not greatly dependent on the specifics of a given regime. Instead, the critical issues are correct siting, low discount rates, and of course the correct species.

The lack of knowledge regarding adequacy of a terrain for the establishment of a certain species prevents managers from the appropriate selection of the best areas for afforestation, as well as the adoption of the corresponding planning measures that would otherwise assure the highest profits and sustainability of resources. Definition of central and marginal habitat for the species and *SI* models depending on environmental variables, though inaccurate, provide useful guidelines in this respect.*)*

The empirical models do not account for physical processes, but are fitted statistically between the land surface attributes and remotely sensed data. The advantage of empirical models is that they can use data very effectively, but the applicability depends primarily on the strength of the relationship between remotely sensed data and the variable of interest. The analysis of two scenes from different sensors (ASTER y CBERS CCD), together with ancillary digital data sources, confirms the usefulness of RS techniques in the assessment of stand variables in a regional scale.

Other regions experiences point out the need of finding a balance between growth rates and quality wood properties for industrial use of the species. Volume growth versus risks, understood as stem malformation, too large branch sizes to make specific log grades, wind damage, fire risk and wood property variation is a relevant issue. This is particularly important when dealing with radiata pine, as this species shows a very flexible response to silviculture.

Besides, breeding programs in other countries have proved to be outstandingly successful. The revision of forestry expertise in other regions can be a time-money saving method of assisting the success of the establishment and spreading of the species. The Nelder trial allows us to see the risks with respect to branch size, stem form, tree stiffness and breeding, showing the compromises that need to be made between volume growth and other factors that impact on forest value.

The central depression soils in El Bierzo, with a milder climate, are highly fertile areas, where agriculture crops are being abandoned as a result of the decline of traditional economy and of population. El

Bierzo is in fact a rural marginal area, as many parts of inland Spain. Afforestation, especially with a fast growing species that could set an encouraging example of forestry uses implementation and, if properly managed, could contribute to invert these trends adding sustainability to development in rural areas.

FUTURE RESEARCH LINES

There is as yet plenty of land available for the definite establishment of the species, including the transition hills towards the surrounding mountainous chain (**Pérez-Crespo et al. 2009**), which would add to the implementation of forest uses and markets. Furthermore, at present, plantations with radiata pine are undoubtedly expanding. Consequently, there is a serious need to obtain valuable information that would significantly assist stands management.

Valorisation of the stands could be enhanced by computing forest attributes prior to harvest and considering multipurpose objectives, suchlike mitigation of climatic change effects by the stands biomass content and carbon sequestration implied.

The whole-stand model developed could be improved by intensification of the forest inventory, including data related to silviculture (thinnings, pruning) and quality of final products (wood properties, stem defects, branching patterns), that would result in outputs providing complementary information to growth rates and volume. In addition, the widening of the data range compiled in the field survey would enable overcoming the limitations as regards simulations of selvicultural regimes and the study of productivity based on environmental factors, or even the inclusion of new variables like biomass equations. The design of the experiments should consider the territorial reality and the research objectives globally.

Other areas of interest that have proved to be important as regards the species, especially as an exotic tree aimed at wood production, include health and environmental risks (e.g. fire, wind, snow). Not to be forgotten, environmental impacts of the stands need to be evaluated in order to guarantee long term productivity.

Techniques to be considered should be easy to update and adequately complemented by field surveys, adapted to the special needs of RS techniques, to meet the local frame conditions, as has been the purpose within this dissertation. A deeper analysis of the application of these techniques that enable approaching assessment of variables of interest from a regional scale, by using scenes recorded by fine resolution sensors and new methods of image analysis, would be recommended.

The analysis of the reality of the species in other regions highlights the fact that there are relevant areas of research that remain untracked in the area of study. Amongst them, financial returns and market prospects, together with wood properties and uses would be crucial. In addition to an adequate log size, industrial uses require wood properties standards (**Riesco-Muñoz and Díaz-González 2007**). Indeed, a real link between plantations establishment and final products destination must be instituted. In spite of the huge divergences between the situation of the species in New Zealand and in El Bierzo (e.g. as regards surface occupied by the stands and property structure, forest planning and policies, related industry and markets, research and trajectory of the species), the relevance of the breeding program in New Zealand evidences the appropriateness of research in genetics, adapted to the local conditions.

Forestry uses can support alternative uses that could complement local economy and social services provided by the stands (e.g. hunting, mycology, wildlife refuge). In such like scenario, bound to social forestry, developing more holistic approaches in silvicultural practices and forest management is a challenge for forest science as well as for practice (**Koch and Skovsgaard 1999**). A transition from plantation forestry to selective harvesting systems may be a longer term option with ecological benefits (**Kerr 2000**), especially applicable to areas managed by public services.

Complete fulfilment of afforestations targets should be carefully surveyed from other organizations that must assist in the spreading of the expertise obtained in specific research studies, making feasible that public institutions, landowners and foresters apply the technicians statements, who in turn could contribute to their updating, adding their own real experiences.

In sum, a dynamic research in contact with real industry and markets, farmlands and mixed agroforestry systems would be needed in order to definitely comprehend the whole complexity of the subject of forestry implementation.

REFERENCES

Adams J A, Walter T W (1975) Nutrient relationships of radiata pine in Tasman Forest, Nelson. New Zealand Journal of Forestry Science 5:18-32

Ainsworth P (1989) Wind damage in radiata pine: The Tasman experience. In Somerville A, Wakelin S and Whitehouse L (Eds) Workshop on wind damage in New Zealand exotic forests. Forest Research Institute Bulletin No. 146. Forest Research Institute, Ministry of Forestry, pp 6-9

Aimers-Halliday J, Burdon R D (2003) Risk management for clonal forestry with *Pinus radiata*: analysis and review. Technical and logistical problems and countermeasures. New Zealand Journal of Forestry Science 33:181-204

Alder D (1979) A distance-independent tree model for exotic conifer plantations in East Africa. Forest Science 25:59−71

Álvarez J G, Castedo-Dorado F, Ruiz A D, López C A, Gadow K v (2004) A two-step mortality model for even aged stands of *Pinus radiata* D. Don in Galicia (Northwestern Spain). Annals of Forest Science 61:439−448

Álvarez M F, Marques R, Fernández-Manso A, Castedo-Dorado F (2004) Influencia de la competencia en el crecimiento en sección de *Pinus radiata* D. Don en El Bierzo (León). Cuadernos de la Sociedad Española de Ciencias Forestales 18:129-134. Congreso de Modelización Forestal, 25-26 March, Palencia, Spain

Álvarez J G, Schröder J, Rodríguez-Soalleiro R, Ruiz A D (2002) Modelling the effect of thinnings on the diameter distribution of even-aged Maritime pine stands. Forest Ecology and Management 165:57−65

Amaro A, Reed D D, Themido I, Tomé M (1997) Stand growth modelling for first rotation *Eucalyptus globulus* Labill. in Portugal. In Amaro A, Tomé M (Eds) Edições Salamandra–Novas Tecnologias, Lisboa pp 99–110

Amateis R L, Radtke P J, Burkhart H E (1995) TAUYIELD: a stand-level growth and yield model for thinned and unthinned loblolly pine plantations. School of Forestry and Wildlife Resources VPI and SU. Report No. 82

Ärdo J (1992) Volume quantification of coniferous forest compartments using spectral radiance recorded by Landsat Thematic Mapper. International Journal of Remote Sensing 13:1779–1786

Asenjo A, Álvarez F, Rodríguez J R, Fernández-Manso A (2005) Estimación de la superficie de *Pinus radiata* D. Don, en la comarca de El Bierzo (León) mediante imágenes de satélite de resolución espacial media. XI Congreso Nacional de Teledetección. Puerto de la Cruz. Tenerife

Asner G P, Hicke J A, Lobell D B (2003) Per-pixel analysis of forest structure: vegetation indices, spectral mixture analysis and canopy reflectance modelling. In Remote Sensing of forest environments: concepts and case studies, Wulder M A and Franklin S E (Eds), pp 209–254 (Boston: Kluwer Academic)

Asner G P, Braswell B H, Schimel D S, Wessmen C A (1998) Ecological research needs from multiangle remote sensing data. Remote Sensing of Environment 63:155–165

Assmann E (1970) The principles of forest yield study. Pergamon Press. Oxford, New York

Atkinson P M, Cutler M E J, Lewis H (1997) Mapping subpixel proportional cover with AVHRR imagery. International Journal of Remote Sensing 18:917–935

Aunós A (1990) Análisis financiero de productos de inversión en repoblaciones forestales. Madrid, ETSI Montes. PhD Thesis. Vitoria-Gasteiz, Departamento de Agricultura y Pesca, Serie Tesis 8, 213 pp

Avila O B, Burkhart H E (1992) Modelling survival of loblolly pine trees in thinned and unthinned plantations. Canadian Journal of Forest Research 22:1878−1882

Backéus S, Wikström P, Lämås T (2006) Modelling carbon sequestration and timber production in a regional case study. Silva Fennica 40:615–629

Bailey R L, Clutter J L (1974) Base-age invariant polymorphic site curves. Forest Science 20:155−159

Balboa-Murias M A (2005) Biomasa arbórea y estabilidad nutricional de los sistemas forestales de *Pinus pinaster* Ait., *Eucalyptus globulus* Labill y *Quercus robur* L. en Galicia. PhD Thesis. Universidad de Santiago de Compostela. España

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

Ballard R (1971) Interrelationships between site factors and productivity of radiata pine at Riverhead Forest, New Zealand. Plant and Soil 35:371-380

Baltunis B S, Wu H X, Powell M B (2007) Inheritance of density, microfibril angle, and modulus of elasticity in juvenile wood of *Pinus radiata*. Canadian Journal of Forest Research 31:2164–2174

Bará S, Toval G (1983) Calidad de estación de *Pinus pinaster* Ait. en Galicia. INIA Comunicaciones INIA, Serie Recursos Forestales 166 pp

Barreiro M A (2003) Estimación de la biomasa y cuantificación del potencial de *Pinus radiata* D. Don para el almacenamiento de carbono a medio y largo plazo en Galicia. Proyecto fin de carrera. Escuela Politécnica Superior de Lugo. Universidad de Santiago de Compostela 139 pp

Barrio M, Castedo-DoradoF, Diéguez-Aranda U, Álvarez J G, Parresol B R, Rodríguez R (2006) Development of a basal area growth system for maritime pine in northwestern

Spain using the generalizad algebraic difference approach. Canadian Journal of Forest Research 36:1461−1474

Barrio M, Sixto H, Cañellas I, Castedo-Dorado F (2008) Dynamic growth model for I-214 poplar plantations in the northern and central plateaux in Spain. Forest Ecology and Management 255:1167−1178

Beaumont J F, Ung C H, Bernier-Cardou M (1999) Relating site index to ecological factors in Black Spruce stands: test of hypotheses. Forest Science 45:484-491

Beets P N, Brownlie R K (1987) Puruki experimental catchment: site, climate, forest management and research. New Zealand Journal of Forestry Science 17:137–160

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

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

Birth G S, Mcvey G R (1968) Measuring the colour of growing turf with a reflectance spectrophotometer. Agronomy Journal 60:640–643

Borders B E, Patterson W D (1990) Projecting stand tables: a comparison of the Weibull diameter distribution method, a percentile-based projection method and a basal area growth projection method. Forest Science 36:413−424

Boyd D S, Danson F M (2005) Satellite remote sensing of forest resources: three decades of research development. Progress in Physical Geography 29:1–26

Bravo-Oviedo A, Montero G (2005) Site index in relation to edaphic variables in stone pine (*Pinus pinea* L.) stands in south west Spain. Annals of Forest Science 62:61-72

Bravo F, Bravo-Oviedo A, Díaz-Balteiro L (2008) Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modelling approach. European Journal of Forest Research 127:225-234

Bravo-Oviedo A, Río M, Montero G (2004) Site index curves and growth model for Mediterranean maritime pine (*Pinus pinaster* Ait.) in Spain. Forest Ecology and Management 201:187−197

Bredemeier M, Lamersdorf N, Schulte-Bisping H, von Lüpke B (2000) Risk appraisal for forest management with respect to site quality and environmental changes. In Risk Analysis in Forest Management, Gadow K (Ed) Kluwer Academic, Dordrecht, pp 21-48

Bremner J M (1965) Methods of soil analysis. Part 2. American Society of Agronomy

Brown S (2002) Measuring carbon in forests: current status and future challenges. Environmental Pollution 116:363-372

Brown S, Gaston G (1995) Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: Application to Tropical Africa. Environmental Monitoring and Assessment 38:157–168

Burdon R D (2005) The role of genetic improvement. New Zealand Institute of Forestry (Inc) Forestry Handbook, 4th Edition, Mike Colley (Ed) NZIF 318 pp

Burdon R D, Moore J M (1997) IUFRO: Genetics of radiata pine: Proceedings of Conference 1-4 December, Workshop 5, IUFRO Working Party *Pinus radiata* provenances and breeding, Rotorua (New Zealand) Forest Research Institute-Bulletin 1997, Number 203, 354 pp

Burdon R D, Carson M J, Shelbourne C J A (2008) Genetic improvement of *Pinus radiata* in New Zealand. Australian Forestry 71:263-279

Burk T E, Newberry J D (1984) A simple algorithm for moment-based recovery of Weibull distribution parameters. Forest Science 30:329−332

Burkhart H E (2003) Suggestions for choosing an appropriate level for modelling forest stands. In Amaro A, Reed D, Soares P (Eds) Modelling Forests Systems, CAB International. Wallingford, Oxfordshire, UK pp 3−10

Caldentey J (1989) Beziehungen zwischen Klimaelementen und der Produktivität von *Pinus radiata* Plantagen in Chile. Dissertation Forstwissenschaftliche Fakultät Ludwig-Maximilians-Universität. München, 131 pp

Campbell J B (2002) Introduction to Remote Sensing. The Guilford Press, New York

Canga E (2007) Crecimiento y producción de pinares regulares de *Pinus radiata* D. Don en Asturias. Phd Thesis. Universidad de Oviedo, Departamento de Biología de Organismos y sistemas

Cantero A, Espinel S, Sáenz D (1995) Un modelo de gestión para las masas de *Pinus radiata* en el País Vasco. Cuadernos de la Sociedad Española de Ciencias Forestales 1:193-198

Cao Q V (2004) Predicting parameters of a Weibull function for modelling diameter distributions. Forest Science 50:682−685

Cao Q V, Burkhart H E, Lemin R C (1982) Diameter distributions and yields of thinned loblolly pine plantations. School of Forestry and Wildlife Resources VPI and SU. Publication No. FSW-1-82

Carmean W H (1975) Forest site quality evaluation in the United States. Advances in Agronomy 27:209-267

Carmean W H (1972) Site index curves for upland oaks in the central states. Forest Science 18:109-120

Carreiras J M B, Pereira J M C, Pereira J S (2006) Estimation of tree canopy cover in evergreen oak woodlands using remote sensing. Forest Ecology and Management 223:45–53

Carson M J, Inglis C S (1988) Genotype and location effects on internode length of *Pinus radiata* in New Zealand. New Zealand Journal of Forestry Science 18:267-279

Carson S D, Kimberley M O, Hayes J D, Carson M J (1999) The effect of silviculture on genetic gain in growth of *Pinus radiata* at one-third rotation. Canadian Journal of Forest Research 29:1979-1984

Castedo-Dorado F (2004) Modelo dinámico de crecimiento para las masas de *Pinus radiata* D. Don en Galicia. Simulación de alternativas selvícolas con inclusión del riesgo de incendio. PhD Thesis. Escuela Politécnica Superior de Lugo. Universidad de Santiago de Compostela, 297 pp

Castedo-Dorado F, Álvarez J G (2000) Construcción de una tarifa de cubicación con clasificación de productos para *Pinus radiata* D. Don en Galicia basada en una función de perfil de tronco. Investigación Agraria Sistemas y Recursos Forestales 9:253-268

Castedo-Dorado F, Diéguez-Aranda U, Álvarez J G (2007) A growth model for *Pinus radiata* D. Don stands in north-western Spain. Annals of Forest Science 64:1−13

Castedo-Dorado F, Diéguez-Aranda U, Barrio M, Sánchez M, Gadow K v (2006) A generalized height-diameter model including random components for radiata pine plantations in northwestern Spain. Forest Ecology and Management 229:202−213

Castedo-Dorado F, Fernández-Manso A, Álvarez M F (2005) Tarifas de cubicación y curvas de calidad de estación para *Pinus radiata* D. Don en El Bierzo (León). In Actas del IV Congreso Forestal Español. Sociedad Española de Ciencias Forestales, Zaragoza

Castedo-DoradoF, Barrio M, Parresol B R, Álvarez J G (2005a) A stochastic height-diameter model for maritime pine ecoregions in Galicia (northwestern Spain) Annals of Forest Science 62:455−465

Castedo-Dorado F, Ruiz-Barrientos R, Fernández-Manso A, Castrosín R, Sarmiento-Maíllo L A (2004) Estudio de la calidad de estación utilizando modelos de intercepto de crecimiento en *Pinus radiata* D. Don en El Bierzo (León) Cuadernos de la Sociedad Española de Ciencias Forestales 18:147-152. Congreso de Modelización Forestal, 25-26 March, Palencia, Spain

Castilla G, Prieto A (1992) Desarrollo y utilización de un simulador de producción de madera para masas de *Pinus radiata* D. Don en el País Vasco, Madrid, Ministerio de Agricultura-INIA Serie Sistemas y Recursos Naturales VI (2):189-209

Cavanilles A (1858) Lequeitio en 1857, Madrid. In Martín Alegría J (Ed) 151 pp

Chauchard L M (2001) Crecimiento y producción de repoblaciones de *Pinus radiata* D. Don en el Territorio Histórico de Guipúzcoa (País Vasco). Tesis doctorales nº 40. Departamento de Agricultura y Pesca del Gobierno Vasco. 173 pp

Chen W, Chen J M, Price D T, Cihlar J (2002) Effects of stand age on net primary productivity of boreal black spruce forests in Ontario, Canada. Canadian Journal of Forest Research 32:833–842

Chen J M, Pavlic G, Brown L, Cihlar J, Leblanc S G, White H P, Hall R J, Peddle D R, King D J, Trofymow J A, Swift E, Van der Sanden J, Pellikka P K E (2002a) Derivation and validation of Canada-wide coarse resolution leaf area index maps using high-resolution satellite imagery and ground measurements. Remote Sensing of Environment 80:165–184

Cibula W, Zetka E, Rickman D (1992) Response of thematic mapper bands to plant water stress. International Journal of Remote Sensing 13:1869-1880

Cieszewski C J (2004) GADA derivation of dynamic site equations with polymorphism and variable asymptotes from Richards, Weibull and other exponential functions. University of Georgia PMRC-TR 2004-5

Cieszewski C J (2003) Developing a well-behaved dynamic site equation using a modified Hossfeld IV function $Y^3=(ax^m)/(c+x^{n-1})$, a simplified mixed-model and scant subalpine fir data. Forest Science 49:539−554

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

Cieszewski C J (2001) Three methods of deriving advanced dynamic site equations demonstrated on inland Douglas-fir site curves. Canadian Journal of Forest Research 31:165-173

Cieszewski C J, Bailey R L (2000) Generalized algebraic difference approach: theory based derivation of dynamic site equations with polymorphism and variable asymptotes. Forest Science 46:116−126

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

Cihlar J (2000). Land cover mapping of large areas from satellites: status and research priorities. International Journal of Remote Sensing 21:1093–1114

Clark D A, Brown S, Kicklighter D, Chambers J Q, Thomlinson J R, Ni J (2001) Measuring net primary production in forests: concepts and field methods. Ecological Applications 11:356–370

Clutter J L (1980) Development of taper functions from variable-top merchantable volume equations. Forest Science 26:117−120

Clutter J L, Fortson J C, Pienaar L V, Brister H G, Bailey R L (1983) Timber management: a quantitative approach. John Wiley and Sons Inc, New York

Cool L G, Zavarin E (1992) Terpene variability of mainland *Pinus radiata*. Biochemical Systematics and Ecology 20:133–144

Coops N C, Waring R H, Landsberg J J (1998) Assessing forest productivity in Australia and New Zealand using a physiologically-based model driven with averaged monthly weather data and satellite-derived estimates of canopy photosynthetic capacity. Forest Ecology and Management 104: 113-127

Coppin P, Bauer M (1996) Digital change detection in forest ecosystems with remote sensing imagery. Remote Sensing Review 13:207-234

Coppin P, Jonckheere I, Nackaerts K, Muys B, Lambin E (2004) Digital change detection methods in ecosystem monitoring: a review. International Journal of Remote Sensing 25:1565-1596

Corona P, Scotti R, Tarchiani N (1998) Relationship between environmental factors and site index in Douglas-fir plantations in central Italy. Forest Ecology and Management 110:195–207

Corral J J, Diéguez-Aranda U, Corral S, Castedo-Dorado F (2007) A merchantable volume system for major pine species in El Salto, Durango (Mexico). Forest Ecology and Management 238:118−129

Covell R R, McClurkin D C (1967) Site index of loblolly pine on Ruston soils in the southern Coastal Plain. Journal of Forestry 65:236-264

Cown D J (2005) Understanding and managing wood quality for improving product value in New Zealand. New Zealand Journal of Forestry Science 35:205–220

Cown D J (1997) New Zealand forest management and wood quality trends. In: Proceedings of the CTIA-IUFRO. Timber Management Toward Wood Quality and End-Product Value. International Wood Quality Workshop, Quebec City, Canada, August pp 18–22

Cremer K W (1998) Recovery of *Pinus radiata* saplings from tilting and bending. Australian Forestry 3:211–219

Cromer D A N, Pawsey C K (1957) Initial spacing and growth of *Pinus radiata*. Forestry and Timber Bureau Bulletin No 36. Canberra, Australia

Cubbage F, MacDonagh P, Sawinski J, Rubilar R, Donoso P, Ferreira A, Hoeflich V, Morales V, Ferreira G, Balmelli G, Siry J, Baez M N, Álvarez J (2007) Timber investment returns for selected plantations and native forests in South America and the Southern United States. New Forests 33:237-255

Curt T, Bouchaud M, Agrech G (2001) Predicting site index of Douglas-Fir plantations from ecological variables in the Massif Central area of France. Forest Ecology and Management 149:61-74

Curtis R O (1967) Height-diameter and height-diameter-age equations for second growth Douglas-fir. Forest Science 13:365−375

Daniel T W, Helms J A, Baker F S (1979) Principles of Silviculture. In 2nd Edn (Ed), McGraw-Hill, New York, 500 pp

Dans-del Valle F, Fernández de Ana-Magán F J, Romero-García A, Castro A, Molina-Rodríguez F, Rojo-Alboreca A, Sánchez-Rodríguez F (1999) Manual de selvicultura del pino radiata en Galicia. http://www.agrobyte.com/agrobyte/publicaciones/pinoradiata/indice.html

Danson B A, Curran P J (1993) Factors affecting the remotely sensed response of coniferous forest plantations. Remote Sensing of Environment 43:55-65

Defries R S, Belward A S (2000) Global and regional land cover characterization from satellite data: an introduction to the special issue. International Journal of Remote Sensing 21:893–916

Delmastro R, Díaz-Vaz J E, Schlatter J E (1981) Variabilidad de las características tecnológicas hereditarias del *Pinus radiata* (D.Don): Informe N° 3. Proyecto CONAF/PNUD/FAO/CHI/76/003. Informe de Convenio N° 43, Serie Técnica, Facultad de Ciencias Forestales, Universidad Austral de Chile, Valdivia, 187 pp.

Demaerschalk J (1972) Converting volume equations to compatible taper equations. Forest Science 18:241−245

DGCN (2000) Tercer Inventario Forestal Nacional 1997–2006: Galicia. Ministerio de Medio Ambiente. Dirección General de Conservación de la Naturaleza. Madrid

Diéguez-Aranda U, Castedo-Dorado F, Álvarez J G, Rojo-Alboreca A (2006) Dynamic growth model for Scots pine (*Pinus sylvestris* L.) plantations in Galicia (north-western Spain). Ecologial Modelling 191:225−242

Diéguez-Aranda U, Castedo-Dorado F, Álvarez J G, Rojo-Alboreca A (2006a) Compatible taper function for Scots pine (*Pinus sylvestris* L.) plantations in north-western Spain. Canadian Journal of Forest Research 36:1190−1205

Diéguez-Aranda U, Burkhart H E, Rodríguez-Soalleiro R (2005) Modelling dominant height growth of radiata pine (*Pinus radiata* D. Don) plantations in north-western Spain. Forest Ecology and Management 215:271−284

Dong J, Kaufmann R K, Myneni R B, Tucker C J, Kauppi P E, Liski J, Buermann W, Alexeyev. V, Hughes M K (2003) Remote Sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources and sinks. Remote Sensing of Environment 84:393–410

Drake N A, Mackin S, Settle J J (1999) Mapping vegetation, soils, and geology in semiarid shrublands using spectral matching and mixture modelling of SWIR AVIRIS imagery. Remote Sensing of Environment 67:12–25

Duncan J, Stow D, Franklin J, Hope A (1993) Assessing the relationship between spectral vegetation indices and shrub cover in the Jornada Basin, New Mexico. International Journal of Remote Sensing 14:3395–3416

Dyck W J, Beets P N (1987) Managing for long-term productivity. New Zealand Journal of Forestry 32:23-26

Dyck B, Thompson P (1999) Carter Holt Harvey’s Millennium Forestry. New Zealand Journal of Forestry 43:2-4

Dzierzon H, Mason E G (2006) Towards a nationwide growth and yield model for radiata pine plantations in New Zealand. Canadian Journal of Forest Research 36:2533-2543

Echevarría I (1942) Ensayo de tablas de producción del *Pinus insignis* en el norte de España. Boletines del IFIE nº 22, Madrid 67 pp

Eid T, Tuhus E (2001) Models for individual tree mortality in Norway. Forest Ecology and Management 154:69−84

Eklundh L, Hall K, Eriksson J, Ardö J, Pilesjö P (2003) Investigating the use of Landsat thematic mapper data for estimation of forest leaf area index in southern Sweden. Canadian Journal of Remote Sensing 29:349–362

Eldridge K G (1997) Genetic resources of radiata pine in New Zealand and Australia. In Burdon R D, Moore J M (1997) IUFRO: Genetics of radiata pine: Proceedings of Conference 1-4 December, Workshop 5, IUFRO Working Party *Pinus radiata* provenances and breeding, Rotorua (New Zealand) Forest Research Institute-Bulletin 1997, Number 203:26-41

Ellis P J, Thomas I L, McDonell M J (1978) Landsat II over New Zealand. Monitoring our resources from space. Ellis P J, Thomas I L, McDonell M J (Eds) New Zealand Department of Scientific and Industrial Research. Wellington. Bulletin 221, 450 pp

Falçao A (1997) Dunas-A growth model for the national forest of Leiría. In Proceedings of the IUFRO workshop "Empirical and process-based models for forest tree and stand growth simulation". Amaro A, Tomé M (Eds) Oeiras, Portugal, pp 145−153

Falçao A, Borges J G (2005) Designing decision support tools for Mediterranean forest ecosystems management: a case study in Portugal. Forest Science 62:751-760

Fang Z, Borders B E, Bailey R L (2000) Compatible volume-taper models for loblolly and slash pine based on a system with segmented-stem form factors. Forest Science 46:1−12

Fearnside P M (1996) Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil’s Amazon forest. Forest Ecology and Management 80:21–34

Fernández-Manso O, Quintano C, Fernández-Manso A, Dos Santos J R (2007) Cuantificación de parámetros forestales en masa de pino resinero sobre dunas continentales a nivel tranzón usando imágenes del sensor ASTER. In Anais do XIII Simpósio Brasileiro de Sensoriamento Remoto -SBSR- 21-26 April 2007, *Florianópolis*, Brasil, pp 1663- 1665

Fernández-Manso A, González J M, Ramírez J (2001) El pino radiata en la comarca del Bierzo: situación actual y propuestas de gestión. III Congreso Forestal Español, Granada. Mesa 5 pp 766−771

Fernández-Manso A, Sarmiento-Maíllo L A (2004) El pino radiata (*Pinus radiata*), Manual de gestión forestal sostenible. In Junta de castilla y león, Fondo Social Europeo y Fundación Biodiversidad (Eds) Depósito legal: BU-132-2004. 62 pp

Foody G M, Cox D (1994) Sub-pixel land cover composition estimation using a linear mixture model and fuzzy membership functions. International Journal of Remote Sensing 15:619-631

Foody G M, Boyd D S, Cutler M E J (2003) Predictive relations of tropical forest biomass from Landsat TM data and their transferability between regions. Remote Sensing of Environment 85:463–474

Forest research (2003) Atlas Cruiser. http://www.forestresearch.co.nz/default.asp

Forest Research Institute (1982) Monocultures- How vulnerable? New Zealand Forest Service, What's new in forest research. Nº 115

Franklin S E, Lavigne M B, Wulder M A, Stenhouse G B (2002) Change detection and landscape structure mapping using Remote Sensing. The Forestry Chronicle 78:618-625

Frazier J R (1981) Compatible whole-stand and diameter distribution models for loblolly pine. Unpublished PhD thesis. VPI and SU

Freitas S R, Mello M C S, Cruz C B M (2005) Relationships between forest structure and vegetation indices in Atlantic Rainforest. Forest Ecology and Management 218:353–362

Gadow K v, Hui G Y (1999) Modelling forest development. Kluwer Academic Publishers. Dordrecht, Netherlands

Gale M R, Grigal D F (1988) Performance of a soil productivity index model used to predict site quality and stand production. In Ek A R, Shifley S R, Burk T E (Eds) Forest growth modelling and prediction. Proceedings, IUFRO conference; 1987 August 23-27, Minneapolis, MN. North Central Forest Experiment Station Gen Tech Rep NC-120, pp 403-410

Gandullo J M (1997) Implicaciones térmicas de la topografía: ensayo de un parámetro termotopográfico. Investigación Agraria Sistemas y Recursos Forestales Vol 6 (1 y 2) Madrid

Gandullo J M (1985) Ecología vegetal. Fundación Conde del Valle Salazar. ETSIM. Madrid

Gandullo J M (1974) Ensayo de evaluación cuantitativa de la insolación en función de la orientación y de la pendiente del terreno. Anales INIA. Serie Recursos Naturales, I. Madrid

Gandullo J M, Sánchez-Palomares O (1994) Estaciones ecológicas de los pinares españoles. ICONA. Madrid

Gandullo J M, Bañares A, Blanco A, Castroviejo M, Fernández-Muñoz L, Sánchez-Palomares O, Serrada R (1991) Estudio ecológico de la laurisilva canaria. ICONA. Madrid

Gandullo J M, González-Alonso S, Sánchez-Palomares O (1974) Ecología de los pinares españoles IV. *Pinus radiata* D. Don. Ministerio de Agricultura, INIA, Madrid

García O (2003) Dimensionality reduction in growth models: an example. Forest biometry, Modelling and Information Sciences 1:1−15

García O (1994) The state-space approach in growth modelling. Canadian Journal of Forest Research 24:1894−1903

García O (1993) Stand growth models: Theory and practice. In Advancement in Forest Inventory and Forest Management Sciences. Proceedings of the IUFRO Seoul Conference, Forestry Research Institute of the Republic of Korea pp 22−45

García O (1988) Growth modelling – a review. New Zealand Forestry 33:14−17

García O (1983) A stochastic differential equation model for the height growth of forest stands. Biometrics 39:1059−1072

García S (1995) Atlas de León. La Crónica del Mundo 399 pp

Gastellu-Etchegorry J P, Martin E, Gascon F (2004) Dart: a 3D model for simulating satellite images and studying surface radiation budget. International Journal of Remote Sensing 25:73-96

Gerding V, Schlatter J E (1995) Variables del sitio de importancia para la productividad del *Pinus radiata* D. Don en Chile. Simposio IUFRO para Cono Sur Sudamericano sobre Manejo Nutritivo de Plantaciones Forestales. Valdivia, Chile

Gholz H L, Ewel K C, Teskey R O (1990) Water and forest productivity. Forest Ecology and Management 30:1–18

Gil J, García E, Rodríguez G (2001) Análisis discriminante, Madrid-Salamanca

Gil-Sotres F, Díaz de Bustamante J, Díaz-Fierros F (1977) Relaciones entre los factores edáficos y el crecimiento de *Pinus pinaster* Ait. y *Pinus radiata* D. Don en la península del Barbanza (Galicia). Boletín da Sociedade Galega de Historia Natural 1:167-207

Gitelson A A, Kaufman Y J, Merzlyak M N (1996) Use of a green channel in remote sensing of vegetation from EOS-MODIS. Remote Sensing of Environment 58:289–298

Goodale C L, Apps M J, Birdsey R A, Field C B, Heath L S, Houghton R A, Jenkins J C, Kohlmaier G H, Kurz W, Liu S, Nabuurs G J, Nilsson S, Shvidenko A (2002) Forest carbon sinks in the northern hemisphere. Ecologial Applications 12:891–899

Gordon A D (2005) Predicting log yield. New Zealand Institute of Forestry (Inc) Forestry Handbook, 4th Edition, Mike Colley (Ed) NZIF 318 pp

Grace J C, Carson M J (1993) Prediction of internode length in *Pinus radiata* stands. New Zealand Journal of Forestry Science 23:10-26

Grace J C, Pont D, Goulding C J, Rawley B (1999) Modelling branch development for forest management. New Zealand Journal of Forestry Science 29:391-408

Grace J C, Blundell W, Pont D (1998) Branch development in radiata pine- model outline and data collection. New Zealand Journal of Forestry Science 28:182-194

Gracia C, Sabaté S, López B, Sánchez A (2001) Presente y futuro del bosque mediterráneo: balance de carbono, gestión forestal y cambio global. In Zamora R y Puignaire F I (Eds) Aspectos funcionales de los ecosistemas mediterráneos. CSIC-AEET, Granada

Green K, Kempka D, Lackey L (1994) Using RS to detect and monitor land-cover and land-use change. Photogrammetric Engineering & Remote Sensing 60:331-337

Green R, Marshall P, Klinka K (1989) Estimating site index of Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) from ecological variables in southwestern British Columbia. Forest Science 35:50-63

Gregoire T G, Schabenberger O, Barrett J P (1995) Linear modelling of irregularly spaced, unbalanced, longitudinal data from permanent-plot measurements. Canadian Journal of Forest Research 25:137−156

Griffiths G H, Mather P M (2000) Remote sensing and landscape ecology: landscape patterns and landscape change. International Journal of Remote Sensing 21:2537-2539

Guerra J, Ganoso J, Schlatter V, Nespolo R (2005) Análisis de biomasa de raíces en diferentes tipos de bosques. Avances en la evaluación de *Pinus radiata* en Chile. Bosque 26:5-21

Hägglund B (1981) Evaluation of forest site productivity. Forestry Abstracts 42:515-527

Hall F G, Peddle D R, LeDrew E F (1995) Remote sensing of biophysical variables in boreal stands of *Picea mariana*. Proceedings of International Geoscience and Remote Sensing Symposium (IGARSS), Italy, Vol 2, pp 976-977

Halme M, Tomppo E (2001) Improving the accuracy of multisource forest inventory estimates by reducing plot location error – a multicriteria approach. Remote Sensing of Environment 78:321–327

Häme T, Salli A, Andersson K, Lohi A (1997) A new methodology for the estimation of biomass of conifer-dominated boreal forest using NOAA AVHRR data. International Journal of Remote Sensing 18:3211–3243

Hamel B, Bélanger N, Paré D (2004) Productivity of black spruce and Jack pine stands in Quebec as related to climate, site biological features and soil properties. Forest Ecology and Management 191:239-251

Harman H H (1976) Modern factor analysis. University of Chicago Press, Chicago. USA (traducción en Ed Saltés SA)

Heiskanen J (2007) Remote sensing of boreal land cover: estimation of forest attributes and extent. Phd Thesis, University of Helsinki, Finland

Heiskanen J (2006) Estimating aboveground tree biomass and leaf area index in a mountain birch forest using ASTER satellite data. International Journal of Remote Sensing 27:1135–1158

Hossfeld J W (1882) Mathematik für Forstmänner, Ökonomen und Cameralisten. Gotha, 4 Bd, pp 310

Huang S (2002) Validating and localizing growth and yield models: procedures, problems and prospects. In Amaro A, Reed D, Soares P (Eds) Workshop on reality, models and parameter estimation – the forestry scenario. Sesimbra (Portugal)

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, pp 271−293

Huete A R (1988) A Soil-Adjusted Vegetation Index (SAVI). Remote Sensing of the Environment 25:295-309

Huguenin R L, Karaska M A, Van Blaricom D, Jensen J R (1997) Subpixel classification of bald cypress and tupelogum trees in Thematic Mapper imagery. Photogrammetric Engineering & Remote Sensing 63:717–725

Hunter I R, Gibson A R (1984) Predicting *Pinus radiata* site index, from environmental variables. New Zealand Journal of Forestry Science 14:53-64

Hyyppa J, Hyyppa H, Inkinen M, Engdahl M, Linko S, Zhu Y H (2000) Accuracy comparison of various remote sensing data sources in the retrieval of forest stand attributes. Forest Ecology and Management 128:109–120

Ibáñez J J, Vayreda J, Gracia C (2002) Metodología complementaria al Inventario Forestal Nacional en Catalunya. In Bravo F, del Río M, del Peso C (Eds) El Inventario Forestal Nacional. Elemento clave para la gestión forestal sostenible

IPCC (2003) Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC National Greenhouse Gas Inventories Programme, Hayama, Japan pp 295

IPCC (2000) Land use, land use change and forestry. Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Jackson D S, Gifford H H (1974) Environmental variables influencing the increment of radiata pine (1). Periodic volume increment. New Zealand Journal of Forestry Science 4:3-26

Jalkanen A, Mäkipää R, Ståhl G, Lehronen A, Petersson H (2005) Estimation of the biomass stock of trees in Sweden: comparison of biomass equations and age-dependent biomass expansion factors. Annals of Forest Science 62:845–851

James R N (1990) Evolution of silvicultural practice towards wide spacing and heavy thinnings in New Zealand. pp13-20 In James R N and Tarlton G L (Eds) New Approaches to Spacing and Thinning in Plantation Forestry. Forest Research Institute Bulletin No. 151 pp 13-20

Jayawickrama K J S, Shelbourne C J A, Carson M J (1997) New Zealand's long internode breed of *Pinus radiata*. New Zealand Journal of Forestry Science 27:126-141

Kerr G (2000) The use of silvicultural systems to enhance the biological Diversity of plantation forests in Britain. Forestry 72:191-205

KimPhat N, Knorr W, Kim S (2004) Appropriate measures for conservation of terrestrial carbon stocks—analysis of trends of forest management in Southeast Asia. Forest Ecology and Management 191:283–299

Kininmonth J A, Whitehouse L J (1991) Properties and uses of New Zealand Radiata Pine (vol I, Wood properties). Kininmonth & Whitehouse (Eds) New Zealand Ministry of Forestry, Forest Research Institute, Rotorua

Klinka K, Carter R E (1990) Relationships between site index and synoptic environmental factors immature Douglas-fir stands. Forest Science 36:815–830

Koch N, Skovsgaard J P (1999) Sustainable management of planted forests: some comparisons between Central Europe and the United States. New Forests 17:11-22

Koivuniemi J, Korhonen K T (2006) Inventory by compartments. In Kangas A & Maltamo M (Eds) Forest inventory – methodology and applications, 271–278. Springer, Dordrecht

Kotze H (2003) A strategy for growth and yield research in pine and eucalipt plantations in Komatiland Forests in South Africa. In Amaro A, Reed D, Soares P (Eds) Modelling Forest Systems, CAB International, Wallingford, Oxfordshire, UK pp 75−84

Kozak A (2004) My last words on taper functions. The Forestry Chronicle 80:507−515

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

Krankina O N, Harmon M E, Cohen W B, Setter D R, Zyrina O, Duane M (2004) Carbon stores, sinks, and sources in forests of northwestern Russia: Can we reconcile forest inventories with remote sensing results? Climatic Change 67:257–272

Kumar S (2004) Genetic parameter estimates for wood stiffness, strength, internal checking, and resin bleeding for radiata pine. Canadian Journal of Forest Research 34:2601–2610

Kumar S, Burdon R D, Stovold G T (2008) Wood properties and stem diameter of *Pinus radiata* in New Zealand: Genetic parameter estimates of clonal and seedling material New Zealand Journal of Forestry Science 38:88–101

Kumar S, Gerber S, Richardson T E, Gea L D (2007) Testing for unequal parental contributions in using nuclear and chloroplast SSR markers in polycross families of radiata pine. Tree Genetics and Genomes 3:207-214

Labrecque S, Fournier R A, Luther J E, Piercey D (2006) A comparison of four methods to map biomass from Landsat-TM and inventory data in western Newfoundland. Forest Ecology and Management 226:129–144

Laclau P (2003) Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwestern Patagonia. Forest Ecology and Management 180:317–333

Laidler G J, Treitz P (2003) Biophysical RS of arctic environments. Progress in Physical Geography 27:44–68

Lambert M J, Turner J (1988) Interpretation of nutrient concentrations in *Pinus radiata* foliage at Belanglo state forest. Plant and Soil 108:237-244

Lamotte M (1971) Initiation aux methods statistiques en biologie. Masson. Paris

Lappi J (1997) A longitudinal analysis of height/diameter curves. Forest Science 43:555−570

Lasserre J P, Mason E G, Watt M S (2005) The effects of genotype and spacing on *Pinus radiata* D. Don corewood stiffness in an 11-year-old experiment. Forest Ecology and Management 205:375–383

Lavery P B (1986) Plantation forestry with *Pinus radiata* - review papers. Papers number 12. School of Forestry, University of Canterbury, New Zealand

Lea R D (2005) A comparison of forest change detection methods and implications for forest management. PhD Thesis, University of Missouri-Columbia, USA

Lefsky M A, Cohen W B, Spies T A (2001) An evaluation of alternate RS products for forest inventory, monitoring, and mapping of Douglas-fir forest in western Oregon. Canadian Journal of Forest Research 31:78–87

Lewis N B, Keeves A, Leech J W (1976) Yield regulation in south Australian *Pinus radiata* plantations. Bulletin No. 23. Woods and Forests Department, South Australia, 173 pp

López C A, Gorgoso J J, Castedo-Dorado F, Rojo-Alboreca A, Rodríguez R, Álvarez J G, Sánchez-Rodríguez F (2003) A height-diameter model for *Pinus radiata* D. Don in Galicia (Northwest Spain). Annals of Forest Science 60:237-245

Low A J (1964) Compression wood in conifers, a review of literature. Forestry Abstracts 25:35-43

Louw J H (1991) The relationship between site characteristics and *Pinus radiata* growth on the Tsitsikama Plateau, Southafrica. The Southern African Forestry Journal 158:37-45

Lu D (2006) The potential and challenge of remote sensing-based biomass estimation. International Journal of Remote Sensing 27:1297–1328

Lu D, Batistella M, Moran E, Mausel P (2004) Application of spectral mixture analysis to amazonian land-use and land-cover classification. International Journal of Remote Sensing 25:5345-5358

Lundqvist B (1957) On the height growth in cultivated stands of pine and spruce in northern Sweden. Medd Fran Statens Skogforsk 47:1−64

Lymburner L, Beggs PJ, Jacobson CR (2000) Estimation of canopy-average surface-specific leaf area using Landsat TM data. Photogrammetric Engineering & Remote Sensing 66:183–191

Mabvurira D, Maltamo M, Kangas A (2002) Predicting and calibrating diameter distributions of *Eucalyptus grandis* (Hill) Maiden plantations in Zimbabwe. New Forests 23:207−223

Maclaren J P (1993) Radiata pine grower's manual. Forest Research Institute Bulletin No. 184. New Zealand Forest Research Institute, New Zealand

Maclaren J P, Knowles R L (2005) Silviculture of radiata pine. New Zealand Institute of Forestry (Inc) Forestry Handbook, 4th Edition, Mike Colley (Ed) NZIF 318 pp

Maclaren J P, West G G (2005) Farm site effects. New Zealand Institute of Forestry (Inc) Forestry Handbook, 4th Edition, Mike Colley (Ed) NZIF 318 pp

Maclaren J P, Grace J C, Kimberley M O, Knowles R L, West G G (1995) Height growth of *Pinus radiata* as affected by stocking. New Zealand Journal of Forestry Science 25:73-90

Madrigal A, Toval G (1975) Tablas de producción de *Pinus radiata* en el País Vasco. Madrid, Dirección General de la Producción Agraria, Ministerio de Agricultura 77 pp

Madgwick H A I (1985) Dry matter and nutrient relationships in stands of *Pinus radiata*. New Zealand Journal of Forestry Science 15:324-336

Madgwick H A I (1983) Estimation of the oven-dry weight of stems, needles and branches of individual *Pinus radiata* trees. New Zealand Journal of Forestry Science 13:108-109

MAF (2007) A national exotic forest description as at April 2007. Ministry of Agriculture and Forestry, Wellington, 62 pp http://www.maf.govt.nz/forestry/resources/overview.htm.

Maltamo M, Puumalainen J, Päivinen R (1995) Comparison of Beta and Weibull functions for modelling basal area diameter distributions in stands of *Pinus sylvestris* and *Picea abies*. Scandinavian Journal of Forest Research 10:284−295

Martín-López J (2000) Comunidades vegetales en pinares y eucaliptales de la provincia de La Coruña: su relación con los parámetros de la plantación y con los tratamientos. PhD Thesis, Universidad de Santiago de Compostela, Spain

Maselli F (2004) Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multiyear NDVI data. Remote Sensing of Environment 89:423-433

Mason E G (1992) Decision-support systems for establishing radiata pine plantations in the central North Island of New Zealand. PhD Thesis, University of Canterbury, Christchurch, New Zealand

McDill M E, Amateis R I (1992) Measuring forest site quality using the parameters of a dimensionally compatible height growth function. Forest Science 38:409−429

McLeod S, Running S W (1988) Comparing site quality indices and productivity of ponderosa pine stands in western Montana. Canadian Journal of Forest Research 18:346-352

McNeill S J, Belliss S E (2002) Forest biomass estimation in New Zealand using full-polarisation SAR imagery. 24-28 June IGARSS 2002 Geoscience and Remote Sensing Symposium 2:1079-1081

McQuilkin R A (1976) The necessity of independent testing of soil-site equations. Soil Science Society of America Journal 40:783-785

Meng Q, Cieszewski C J, Madden M, Borders B (2007) A linear mixed-effects model of biomass and volume of trees using Landsat ETM+ images. Forest Ecology and Management 244:93-101

Menzies M I, Faulds T, Dibley M J (1992) Production of radiata pine cuttings for plantation forestry in New Zealand. Acta Horticulturae 319:359-364

Merganic J, Sterba H (2006) Characterisation of diameter distribution using the Weibull function: method of moments. European Journal of Forest Research 125:427−439

Merino A, Edeso J M (1999) Soil fertility rehabilitation in young *Pinus radiata* D. Don plantations from northern Spain after intensive site preparation. Forest Ecology and Management 116:83-91

Merino A, Balboa-Murias M A, Rodríguez R, Álvarez J G (2005) Nutrient exports under different harvesting regimes in fast-growing forest plantations in southern Europe. Forest Ecology and Management 207:325−339

Merino A, Rey C, Brañas J, Rodríguez-Soalleiro R (2003) Biomasa arbórea y acumulación de nutrientes en plantaciones de *Pinus radiata* D. Don en Galicia. Investigación Agraria Sistemas y Recursos Forestales 12:85-98

Miller W (2002) An overview of wood quality issues and their impact: a personal view. New Zealand Journal of Forestry 47:11-13

Monserud R A, Moody U, Breuer D W (1990) A soil site study for inland Douglas-fir. Canadian Journal of Forest Research 20:686-695

Montero G, Ruiz-Peinado R, Muñoz M (2005) Producción de biomasa y fijación de CO_2 por los bosques españoles. Monografías INIA: Serie Forestal, Madrid

Morisette J T, Privette J L, Justice C O (2002) A framework for the validation of MODIS Land products. Remote Sensing of Environment 83:77–96

Muñoz P (1985) Alternativas selvícolas en la producción de *Pinus radiata* D. Don. PhD Thesis. Escuela Técnica Superior de Ingenieros de Montes, Universidad Politécnica de Madrid, 185 pp

Muukkonen P, Heiskanen J (2007) Biomass estimation over a large area based on standwise forest inventory data and ASTER and MODIS satellite data: A possibility to verify carbon inventories. Remote Sensing of Environment 107:617–624

Nambiar E K S (1991) Management of forests under nutrient and water stress. Water, Air and Soil Pollution 54:209–230

Nelder J A (1962) New kinds of systematic designs for spacing experiments. Biometrics 18:283–307

Nicolás A, Gandullo J M (1966) Los estudios ecológicos selvícolas y los trabajos de repoblación forestal. IFIE. Madrid

Nilson T, Kuusk A, Lang M, Lukk T (2003) Forest reflectance modelling: theoretical aspects and applications. Ambio 32:535–541

Ninyerola M, Pons X, Roure J M (2005) Atlas Climático Digital de la Península Ibérica. Metodología y aplicaciones en bioclimatología y geobotánica. ISBN 932860-8-7. Universitat Autònoma de Barcelona, Bellaterra

Northway S M (1985) Fitting site index equations and other selfreferencing functions. Forest Science 31:233−235

Nowak D J (1993) Historical vegetation change in Oakland and its implications for urban forest management. Journal of Arboriculture 19:313-319

NZ Forest Owners Association (2003) New Zealand Forest Industry Facts & Figures 2003/2004, GPO Box 1208, Wellington, New Zealand

Oliver C D (1985) Silviculture and juvenile wood. In Juvenile wood, what does it mean to forest management and forest products?

Robertson D (Ed) Forest Products Research Society, Madison, WI, USA, pp 24-29

Ortega A, Montero G (1988) Evaluación de la calidad de las estaciones forestales. Revisión Bibliográfica. Madrid. Ecología 2:155-184

Pacheco C (1991) Evaluating site quality of even-aged maritime pine stands in northern Portugal using direct and indirect methods, Forest Ecology and Management 41:193–204

Padrón E, Navarro-Cerrillos R M (2007) Aboveground biomass in *Prosopis pallida* (Humb and Bonpl Ex Willd) H B K ecosystems using Landsat 7 ETM+ images. Revista Chilena de Historia Natural 80:43 – 53

Palahí M, Pukkala T, Trasobares T (2006) Modelling the diameter distribution of *Pinus sylvestris, Pinus nigra* and *Pinus halepensis* forest stands in Catalonia using the truncated Weibull function. Forestry 79:553−562

Palmer D J (2008) Development of national extent terrain attributes (TANZ), soil water balance surfaces (SWATBAL), and environmental surfaces, and their application for spatial modelling of Pinus radiata productivity across New Zealand. PhD Thesis, University of Waikato. Hamilton, New Zealand. 389 pp

Parresol B R (2003) Recovering parameters of Johnson's S_B distribution. USDA Forest Service. Res Pap SRS-31

Payn T, Clinton P (2005) The environmental footprint of New Zealand's plantation forests: nutrient fluxes and balances. New Zealand Journal of Forestry 50:17-22

Peddle D R, Johnson R L (2000) Spectral mixture analysis of airborne remote sensing imagery for improved prediction of Leaf Area Index in mountainous terrain, Kananoskis Alberta. Canadian Journal of Remote Sensing 26:177-188

Pellerin R F, Ross R J (2001) Chapter 2 - Transverse vibrational and longitudinal stress wave nondestructive evaluation methods. In Nondestructive Evaluation of Wood. Pellerin R F and Ross R J (Eds) Madison, WI, USA. Forests Products Society

Pérez-Crespo J, Sarmiento-Maíllo L A, Santamaría-Medel E, Sevillano-Marco E, Fernández-Manso A (2009) Áreas potenciales de *Pinus radiata* D. Don en El Bierzo (León). Actas del Congreso Forestal Nacional Español, 21-25 September, Ávila, Spain

Phua M H, Saito H (2003) Estimation of biomass of a mountainous tropical forest using Landsat TM data. Canadian Journal of Remote Sensing 29:429–440

Pinjuv G, Euan G, Mason A, Watt M S (2006) Quantitative validation and comparison of a range of forest growth model types. Forest Ecology and Management 236:37-46

Pinty B, Verstraete M M (1992) GEMI: a nonlinear index to monitor global vegetation from satellites. Vegetation 10:15-20

Pont D, Grace J C, Todoroki C (1999) Modelling the influence of radiata pine branching characteristics on visual timber grades. In Nepveu G (Ed) Proceedings of third workshop “Connection between silviculture and wood quality through modelling approaches and simulation softwares”. Publication Equippe de recherches sur la quality des bois. INRA-Nancy, France pp 63-71

Qin W, Gerstl S A W (2000) 3-D scene modelling of semi-arid vegetation cover and its radiation regime. Remote Sensing of Environment 74:145–162

Rautiainen M, Stenberg P (2005) Application of photon recollision probability in coniferous canopy reflectance simulations. Remote Sensing of Environment 96:98–107

Raymond C A, Muner A, Macdonald A C (1998) Non-destructive sampling for basic density in *Eucalyptus globulus* and *Eucalyptus nitens*. Appita 51:110–114

Rayner M E (1991) Site index and dominant height growth curves for regrowth karri (*Eucalyptus diversicolor* F. Muell.) in south-western Australia. Forest Ecology and Management 44:261-283

Reich P B, Grigal D F, Aber J D, Gower S T (1997) Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soil. Ecology 78:335–347

Reilly J J, Parkes E D, Ferguson I S (1975) The potential productivity of farmlands in the lower south coastal region of New South Wales for radiata pine plantations. Australian Forestry 38:233-244

Rey C (2000) Estimación de la biomasa arbórea en plantaciones de *Pinus radiata* D. Don y su relación con las propiedades del suelo. Proyecto fin de carrera. Escuela Politécnica Superior de Lugo. Universidad de Santiago de Compostela

Rey C, Brañas J, Rodríguez-Soalleiro R, Merino A (2001) Biomasa y acumulación de nutrientes en plantaciones de *Pinus radiata* D. Don del norte de España. Actas del III Congreso Forestal Español. Tomo 1:500-504

Reynolds M R (1984) Estimating the error in model predictions. Forest Science 30:454−469

Richards F J (1959) A flexible growth function for empirical use. Journal of Experimental Botany 10:290−300

Riesco-Muñóz G, Díaz-González J (2007) Características físicas de la madera de pino procedente de realeos en el noroeste de España. Maderas. Ciencia y tecnología 9:233-24

Rigueiro A, Mosquera R, Romero R (1998) Manual de sistemas silvopastorales. Monografías de Proyecto Columella, EPS, Lugo, Spain

Ripple W J, Wang S, Isaacson D L, Paine D P (1991) A preliminary comparison of Landsat Thematic Mapper and SPOT-1HVR multispectral data for estimating coniferous forest volume. International Journal of Remote Sensing 12:1971–1977

Robinson A P, Froese R E (2004) Model validation using equivalence tests. Ecological Modelling 176:349−358

Rodríguez J R, Álvarez M F, Asenjo A, Fernández-Manso A, Quintano C (2004) Inventariación de las masas de *Pinus radiata* D. Don en El Bierzo (León) empleando teledetección con imágenes multiespectrales de resolución media. Cuadernos de la Sociedad Española de Ciencias Forestales 19:163-168. I Jornadas de inventario y teledetección forestal, 25-26 March, Lleida, Spain

Rodríguez R, Sánchez-Rodríguez F, Gorgoso J, Castedo-Dorado F, López C, Gadow K v (2002) Evaluation standard treatment options for *Pinus radiata* plantations in Galicia (NW Spain). Forestry 75:273-284

Romanyà J, Vallejo V R (2004) Productivity of *Pinus radiata* plantations in Spain in response to climate and soil. Forest Ecology and Management 195:177−189

Rook D A, Corson M J (1978) Temperature and irradiance and the total daily photosynthetic production of the crown of a *Pinus radiata* tree. Oecologia (Berl.) 36:371–382

Rouse J W J, Haas R H, Schell J A, Deering D W (1973) Monitoring vegetation systems in the Great Plains with ERTS. In Third Earth Resources Technology Satellite-1 Symposium, 10–14 December 1973, Washington DC (Washington DC NASA) pp 309–317

Ruiz G, Schlatter J E (1985) Relación entre el índice de sitio, la elevación y la exposición en la Cordillera de Nahuelbuta. In *Pinus radiata* Investigación en Chile. Olivares B y Morales E (Eds) Universidad Austral de Chile, Valdivia. Volume 2, 51-65

Ruiz-de la Torre J (1979) Árboles y arbustos. Escuela Técnica Superior de Ingenieros de Montes, Madrid

Ryan T P (1997) Modern regression methods. John Wiley and Sons Inc, New York

Sa A C L, Pereira J M C, Vasconcelos M J P, Silva J M N, Ribeiro N, Awasse A (2003) Assessing the feasibility of sub-pixel burned area mapping in miombo woodlands of northern Mozambique using MODIS imagery. International Journal of Remote Sensing 24:1783–1796

Sánchez-Palomares O, Blanco A (1985) Un modelo de estimación del equivalente de humedad de los suelos. Revista Montes. Madrid

Sánchez-Palomares O, Rubio A, Blanco A (2004) Definición y cartografía de las áreas potenciales fisiográfico-climáticas de hayedo en España. Investigación Agraria Sistemas y Recursos Forestales. Fuera de serie 13-62

Sánchez-Palomares O, Sánchez-Serrano F, Carretero-Carrero M P (1999) Modelos y Cartografía de Estimaciones climáticas termopluviométricas para la España

Peninsular. INIA. Colección Fuera de Serie. 192 pp Madrid

Sánchez-Rodríguez F (2001) Crecimiento y producción de *Pinus radiata* en Galicia. PhD Thesis. Escuela Politécnica Superior, Universidad de Santiago de Compostela, Lugo. Spain

Sánchez-Rodríguez F, Rodríguez R, Rojo-Alboreca A, Álvarez J G, López C A, Gorgoso J J, Castedo-Dorado F (2003) Crecimiento y tablas de producción de *Pinus radiata* D. Don en Galicia. Investigación Agraria Sistemas y Recursos Forestales 12:65-83

Sánchez-Rodríguez F, Rodríguez-Soalleiro R, Español E, López C A, Merino A (2002) Influence of edaphic factors and tree nutritive status on the productivity of *Pinus radiata* D. Don plantations in northwestern Spain. Forest Ecology and Management 171:181-189

Sánchez-Rodríguez F, Álvarez-González J G, Rodríguez-Soalleiro R, Rojo-Alboreca A (1998) Resultados preliminareees del estudio de curvas de calidad de estación y de los factores ecológicos implicados en la productividad de *Pinus radiata* D. Don en Galicia (España). Primer Congreso IUFRO sobre Silvicultura en América Latina, Valdivia (Chile)

Sands R, Mulligan D R (1990) Water and nutrient dynamics and tree growth. Forest Ecology and Management 30:91–111

SAS Institute Inc (2004) SAS/ETS® 9.1 User's guide. Cary, NC: SAS Institute Inc USA

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

SAS-Institute (2000) SAS/STAT User's Guide: Version 8, vol 1–3. SAS Institute Inc, North Carolina, USA

Savill P, Evans J, Auclair D, Falck J (1997) Plantation silviculture in Europe. Oxford University Press, Oxford, 297 pp

Saunder J C, Booth T H, Turner J, Williams E R (1984) Some effects of site, particularly upper horizon soil on the growth of *Pinus radiata*. Australian Forest Research 14:27-36

Schlatter J, Gerding V, Oñate M I (1998) Characteristics and variability of sites with adult stands of *Pinus radiata* D.Don in granite soils of the VIII and IX Regions, Chile. Bosque 19:37-59

Schnute J (1981) A versatile growth model with statistically stable parameters. Canadian Journal of Fisheries and Aquatic Sciences 38:1128−1140

Scott C W (1961) Pino insigne (*Pinus radiata* D. Don), Roma: Publicaciones FAO, Estudios sobre selvicultura y productos forestales nº 14, 333 pp

Serrada R, Montero G, Reque J A (2008) Compendio de Selvicultura Aplicada en

España. Ministerio de Educación y Ciencia. Fundación Conde del Valle Salazar

Settle J J, Drake N A (1993) Linear mixing and the estimation of ground cover proportions. International Journal of Remote Sensing 14:1159–1177

Sevillano-Marco E, Fernández-Manso A (2009) Aplicaciones de un modelo dinámico de crecimiento en la gestión de masas de pino radiata en El Bierzo (León) Actas del Congreso Forestal Nacional Español, 21-25 September, Ávila, Spain

Sevillano-Marco E, Fernández-Manso A, Castedo-Dorado F (2009) Development and applications of a growth model for *Pinus radiata* D. Don plantations in El Bierzo (Spain). Investigaciones Agrarias Sistemas y Recursos Forestales 18:64-80

Sevillano-Marco E, Fernández-Manso A, Quintano C, Shimabukuro Y E (2009a) Biomass estimation of *Pinus radiata* (D. Don) stands in northwestern spain by unmixing CCD CBERS data. FRP E 1, Agricultural Applications, IEEE International Geoscience & Remote Sensing Symposium (IGARSS), 13-17 July, Cape Town, South Africa

Sevillano-Marco E, Fernández-Manso A, Quintano C, Shimabukuro Y E (2009b) Estimación de biomasa en *Pinus radiata* (D. Don) a partir de índices derivados de imágenes CCD-CBERS. Actas del Congreso de la Asociación Española de Teledetección. 23-26 September, Calatayud, Spain

Shabanov N V, Lo K, Gopal S, Myneni R B (2005) Subpixel burn detection in Moderate Imaging Spectroradiometer 500-m data with ARTMAP neural networks. Journal of Geophysical Research 110, D03111, doi: 10.1029/2004JD005257

Shelbourne C J A (1997) Genetic of adding value to the end-products of radiata pine. Proceedings of IUFRO 97 Genetics of Radiata Pine. IUFROConference 1–4 December and Workshop 5 December, Rotorua, New Zealand Forest Research Institue Bulletin 203:129-141

Shelbourne C J A, Burdon R D, Bannister M H, Thulin I J (1979) Choosing the best provenances of radiata pine for forest sites in New Zealand. New Zealand Journal of Forestry Science 24:288-300

Shepherd R W (1990) Early importations of *Pinus radiata* to New Zealand and distribution to Canterbury to 1885: implications for the genetic makeup of *Pinus radiata* stocks. Horticulture in New Zealand 1:28-35 and 33-38

Shimabukuro Y E, Smith J (1991) The least-squares mixing models to generate fraction images derived from remote sensing multispectral data. IEEE Transactions on Geoscience and Remote Sensing 29:16-21

Siemon G R, Wood G B, Forrest W G (1976) Effects of thinning on crown structure in radiata pine. New Zealand Journal of Forestry Science 6:57-66

Sims N C, Stone C, Coops N C, Ryan P (2007) Assessing the health of *Pinus radiata* plantations using remote sensing data and decision tree analysis. New Zealand Journal of Forestry Science 37:57-80

Sjolte-Jorgensen J (1967) The influence of spacing on the growth and development of coniferous plantations. International Review of Forestry Research 2:43-94

Smith D M, Larsen B C, Kelty M J, Ashton P M S (1996) The practice of Silviculture, 9th Edition, John Wiley & Sons Inc

Snedecor G W, Cochran W G (1984) Métodos estadísticos. CECSA. México D F

Snowdon P (1985) Alternative sampling strategies and regression models for estimating forest biomass. Australian Forest Research 15:353-366

Snowdon P, Jovanovic T, Booth T H (1999) Incorporation of indices of annual climatic variation into growth models for *Pinus radiata*. Forest Ecology and Management 117:187–197

Sorensson C T (2008) Improving the relevancy of breeding for wood quality in *Pinus radiata*. New Zealand Journal of Forestry Science 38:36-55

Sorensson C T (2002) Reflections on radiata pine genetic improvement by a clonal forester. New Zealand Journal of Forestry 47:29-31

Sorensson C T, Shelbourne C J A (2005) Clonal Forestry. New Zealand Institute of Forestry (Inc) Forestry Handbook, 4th Edition, Mike Colley (Ed) NZIF 318 pp

Sorensson C T, Nepveu G, Kimberley M (2002) Intra- and inter-tree modelling of wood stiffness of clears of age-10 radiata pine clones, and simulated response of stiffness to increased genetic selection intensity. In Proceedings Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software, Harrison Hot Springs, British Columbia, Canada, September 8–15

Spanner M A, Pierce L L, Peterson D L Running S W (1990) Remote sensing of temperate coniferous forest leaf area index. The influence of canopy closure, understory vegetation and background reflectance. International Journal of Remote Sensing 11:95–111

Stenberg P, Rautiainen M, Manninen T, Voipio P, Smolander H (2004) Reduced simple ratio better than NDVI for estimating LAI in Finnish pine and spruce stands. Silva Fennica 38:3–14

Suganuma H, Abe Y, Taniguchi M, Tanouchi H, Utsugi H, Kojima T, Yamada K (2006) Stand biomass estimation method by canopy coverage for application to remote sensing in an arid area of Western Australia. Forest Ecology and Management 222:75–87

Sutton W R J (1999) The need for planted forests and the example of radiata pine. New Forests 17:95–109

Thornthwaite C W (1948) An Approach to a rational classification of climate. Geography Review 38:55-94

Thornthwaite C W, Mater J R (1957) Instructions and tables for Computing Potential Evapotranspiration and Water Blances. Centerton. New Jersey

Thornthwaite C W, Mater J R (1955) The water balance. Climatology 8:1-104

Tombleson J D, Inglis C S (1988) Comparison of radiata pine shelterbelts and plantations. In Maclaren P (Ed) Proceedings of the Agroforestry Symposium. Rotorua 24-27 November 1986. New Zealand Forest Service. Forest Research Institute Bulletin No. 139. pp 261-278

Tomé M, Ribeiro F, Soares P (2001) O modelo Globulus 2.1. Relatorios Técnicocientíficos do GIMREF, nº1/2001. Universidade Técnica de Lisboa, Instituto Superior de Agronomía, Departamento de Engenharia Florestal, 69 pp

Tomppo E, Nilsson M, Rosengren M, Aalto P, Kennedy P (2002) Simultaneous use of Landsat-TM and IRS-1c WiFs data in estimating large area tree stem volume and aboveground biomass. Remote Sensing of Environment 82:156-171

Torres-Rojo J M, Magaña-Torres O S, Acosta-Mireles M (2000) Metodología para mejorar la predicción de parámetros de distribuciones diamétricas. Agrociencia 34:627−637

Trincado G V, Quezada P R, Gadow K v (2003) A comparison of two stand table projection methods for young *Eucalyptus nitens* (Maiden) plantations in Chile. Forest Ecology and Management 180:443−451

Trotter C M, Dymond J R, Goulding C J (1997) Estimation of timber volume in a coniferous plantation forest using Landsat TM. International Journal of Remote Sensing 18:2209-2223

Truman R A, Humphreys F R, Lambert M J (1983) Prediction of site index for *Pinus radiata* at Mullions Range State Forest, New South Wales. Australian Forest Research 13:207-215

Turvey N D (1983) Soil-type yield curves for *Pinus radiata* in Gippsland, Victoria. Australian Forestry 46:118-125

Turvey N D, Rudra A B, Turner J (1986) Characteristics of soil and productivity of *Pinus radiata* (D. Don) in New South Wales I. Relative importance of soil physical and chemical parameters. Australian Journal of Soil Research 24:95-102

USDA (1975) Soil Taxonomy. Agriculture Handbook nº 436. US Department of Agriculture. Washington DC

US Salinity Laboratory Staff (1954) Diagnosis and improvement of saline and alkaline soils. Soil conservation Service. US Department of Agriculture. Washington DC

Vanclay J K (1994) Modelling forest growth and yield. Applications to mixed tropical forests. CAB International. Wallingford, UK

Vanclay J K, Skovsgaard J P (1997) Evaluation forest growth models. Ecological Modelling 98:1−12

Vázquez A (2008) Structural attributes of three forest types in central Spain and Landsat ETM+ information evaluated with redundancy analysis. International Journal of Remote Sensing 29:5657–5676

Verbyla D L, Fisher R F (1989) An alternative approach to conventional soil-site regression modelling. Canadian Journal of Forest Research 19:179-184

Walkley A (1946) A critical examination of methods for determining organic carbon and nitrogen in soil. Journal of Agricultural Science 25:598-609

Walter H, Lieth H (1960) Klimadiagramm Weltatlas. Veb. Gustav Fischer. Jena

Wang G G (1995) White spruce site index in relation to soil, understory vegetation, and foliar nutrients. Canadian Journal of Forest Research 25:29–38

Wang G G, Klinka K (1996) Use of synoptic variables in predicting white spruce site index. Forest Ecology and Management 80:95-105

Watt M S, Moore J R, Facon J P, Downes G M, Clinton P W, Coker G, Davis M R, Simcock Robyn, Parfitt R L, Dando J, Mason E G, Bown H E (2006) Modelling the influence of stand structural, edaphic and climatic influences on juvenile *Pinus radiata* dynamic modulus of elasticity. Forest Ecology and Management 229:136-144

Watt M S, Coker G, Clinton P W, Davis M R, Parfitt R, Simcock R, Garrett L, Payn T, Richardson B, Dunningham A (2005) Defining sustainability of plantation forests through identification of site quality indicators influencing productivity. A national view for New Zealand. Forest Ecology and Management 216:51-63

Watt M S, Turner J A, Mason E G (2000) Genetic influence on second-log branching in *Pinus radiata*. New Zealand Journal of Forestry Science 30:315-331

Wessman C A, Bateson C A, Benning T L (1997) Detecting fire and grazing patterns in tall grass prairie using spectral mixture analysis. Ecological Applications 7:493–511

West P W (2007) Growing plantation forests. Springer-Verlag Berlin Heidelberg

Whiteside I D, Manley B R (1987) Radiata pine resource description by log-grade specification. In Kininmonth J P (comp) “Proceedings of the Conversion Planning Conference, Rotorua 8–11 April 1986”. Ministry of Forestry Forest Research Institute Bulletin No. 128 pp 27–38

Whyte A G D (1988) Radiata pine silviculture in New Zealand: its evolution and future prospects. Australian Forestry 51:185-196

Wielinga B, Raymond C A, James R, Matheson A C (2009) Effect of green density values on *Pinus radiata* stiffness estimation using a stress-wave technique. New Zealand Journal of Forestry Science 39:71-79

Wilcox P L, Carson M J (1989) Reduced initial stocking using improved radiata pine. In James R N, Tarlton G L (Eds) New approaches to spacing and thinning plantation forestry. Proceedings of IUFRO Symposium, Rotorua, New Zealand. Ministry of Forestry, Forest Research Institute Bulletin No. 151, pp 233-242

Will G M, Hodgkiss P D (1977) Influence of nitrogen and phosphorus stress on the growth and form of radiata pine. New Zealand Journal of Forestry Science 7:307-320

Wise R, Cacho O (2005) A bioeconomic analysis of carbon sequestration in farm forestry: a simulation study of *Gliricidia sepium*. Agroforestry Systems 64:237–250

Worrell R, Hampson A (1997) The influence of some forest operations on the sustainable management of forest soils: a review. Forestry 70:61-84

Wu H X, Ivkovic M, Gapare W, Matheson A C, Baltunis B S, Powell M B, McRae T A (2008) Breeding for wood quality and profit in radiata pine: a review of genetic parameters. New Zealand Journal of Forestry Science 38:56-87

Wulder M A, Skakun R S, Kurz W A, White J C (2004) Estimating time since forest harvest using segmented Landsat ETM+ imagery. Remote Sensing of Environment 93:179–187

Yang Y, Monserud R A, Huang S (2004) An evaluation of diagnostic test and their roles in validating forest biometric models. Canadian Journal of Forest Research 34:619−629

Zimmerman D L, Núñez-Antón V (2001) Parametric modelling of growth curve data: an overview (with discussion). Test 10:1−73

Zwolinski J, Bayley A D (2001) Research on planting stock and forest regeneration in South Africa, New Forests 22:59–74

TABLES AND FIGURES

Table 1. Summarised data corresponding to the sample of plots used for model development...... 26
Table 2. Summarised data corresponding to the sample of 41 fallen trees used for model development 26
Table 3. Descriptive statistics of ecological parameters........ 29
Table 4. Characteristics of the CBERS CCD and ASTER sensors data recording.......... 31

CHAPTER 1

Table 1.1. Base models and ADA/GADA formulations considered for dominant height and stand basal area growth modelling........ 37

CHAPTER 2

Table 2.1 Management regimes for radiata pine guidelines for local model simulation........ 55

CHAPTER 3

Table 3.1 Highest Pearson’s correlation coefficients obtained between *SI* and ecological parameters........ 78
Table 3.2 *SI* (dependent variable) linear regression models selected, independent variables and numeric statistics 80
Table 3.3 Ecological valances calculated for some ecological parameters describing the ecological behaviour of *Pinus radiata* D. Don in El Bierzo and comparison with the behaviour of the species in the rest of the country 83

CHAPTER 4

Table 4.1 Spectral Vegetation Indices (SVIs) used for model fitting 96
Table 4.2 Summarised data corresponding to the sample plots used for model development (n=40 plots) 97
Table 4.3 Tested regression models 101
Table 4.4 Top Pearson’s correlation coefficients (n=29 plots) between dependent variables (stand variables) and independent variables (single bands, vegetation indices and fraction images)... 104
Table 4.5 Selection of models, dependent and predictive variables (see Table 4.), parameters, numerical statistics (R^2, RMSE, and S%) calculated for data extracted from ASTER and CBERS images 105
Table 4.6 Numerical statistics (RMSEval, and S%val) corresponding to the validation data set of the models shown in Table 4.5........ 105

CHAPTER 5

Table 5.1 Mean values of main stem variables recorded in field inventory of the Nelder trial 126

Figure 1. Overall scheme, employed data sources and diagram of methodological processes involved in the study of *Pinus radiata* D. Don in El Bierzo 22
Figure 2. Area of study (El Bierzo, León, Spain)........ 23
Figure 3a. Bioclimatic diagram representative of the central plain in El Bierzo (Location Ponferrada) 24

Figure 3b. Bioclimatic diagram representative of the transitional highlands in El Bierzo (Location Villafranca del Bierzo) 24
Figure 4. Plan of the Nelder stocking design experiment used. Trees are planted at each spot..... 28

CHAPTER 1

Figure 1.1a Curves for site indices of 16, 20, 24 and 28 m at a reference age of 20 years overlaid on the trajectories of observed values over time (same tree or plot measurements joined by lines) 43
Figure 1.1b Pattern of residuals versus predicted values 43
Figure 1.2a Trajectories of observed and predicted stem number over time. Model projections for initial stocking densities of 400, 1200, 2000 and 2800 stems per hectare at 10 years. Same plot measurements joined by lines 44
Figure 1.2b Pattern of residuals versus predicted values 44
Figure 1.3a Stand basal area growth curves for stand basal areas of 15, 30, 45 and 60 m^2 ha^{-1} at 20 years overlaid on the trajectories of observed values over time. Same plot measurements joined by lines 44
Figure 1.3b Pattern of residuals versus predicted values 44
Figure 1.4 Plots of observed stand volume values against model-predicted values, from the model developed in this study. The solid line represents the linear model fitted to the scatter plot of data and the dashed line is the diagonal. R^2 is the coefficient of determination of the linear model 48
Figure 1.5 Plots of observed stand volume values against model-predicted values, from the Galician model (Castedo-Doradoet al. 2007). The solid line represents the linear model fitted to the scatter plot of data and the dashed line is the diagonal. R^2 is the coefficient of determination of the linear model 48

CHAPTER 2

Figure 2.1 Changes in basal area over the rotation for the two silvicultural schedules simulated... 56
Figure 2.2 Predicted diameter distribution at clearfelling in the two alternatives simulated............ 56
Figure 2.3 Volume mean annual increment (MAI) and current annual increment (CAI) for the silvicultural schedule corresponding to an initial stand density of 2500 stems per ha under two site conditions 56
Figure 2.4a Basal area (m^2 ha^{-1}) along the rotation (based on Rodríguez et al. 2002) 57
Figure 2.4b Basal area (m^2 ha^{-1}) over rotation (based on Dans-del Valle et al. 1999) 58
Figure 2.5a Basal area over rotation (m^2 ha^{-1}). *SI* 16 m at 20 years of age 58
Figure 2.5b Basal area over rotation (m^2 ha^{-1}). *SI* 26 m at 20 years of age 59
Figure 2.6 Volume mean annual increment (MAI) and current annual increment (CAI) (m^3 ha^{-1} $year^{-1}$) for 2126 stems ha^{-1} 59

CHAPTER 3

Figure 3.1 Diagram of data sources and methodological processes 71
Figure 3.2 Central habitat (LT-UT) and marginal habitat (LL-LT) and (UT-UL) of radiata pine stands in El Bierzo as regards the ecological parameters calculated. LT=lower threshold, LL=lower limit, M=mean, UL=upper limit, UT=upper threshold 72
Figure 3.3 Georeferenced ecological parameters in El Bierzo.......... 73

Figure 3.4 Central and marginal habitat of georeferenced ecological parameters in El Bierzo....... 74
Figure 3.5a Physiographic and climatic potential areas for *Pinus radiata* D. Don in El Bierzo........ 75
Figure 3.5b Sample of main potential areas for stands of *Pinus radiata* D. Don in El Bierzo.......... 76
Figure 3.6 Plots of standardized residuals against standardized predicted *SI* values for selected models 81
Figure 3.7 Plots of predicted values of *SI* provided by Models 1, 2, 3 and 4 versus observed *SI* values. *SI* (m, reference age 20 years). All models tend to overestimate *SI* 84

CHAPTER 4

Figure 4.1 Flow chart of data sources and methodological processes involved in stand variables assessment combining RS and field data 95
Figure 4.2 Flow diagram of data sources and methodological processes undertaken in the ASTER image analysis 99
Figure 4.3 Flow diagram of data sources and methodological processes undertaken in the CBERS image analysis 100
Figure 4.4 NIR band (*V3*) of ASTER image 103
Figure 4.5 Fraction images obtained by unmixing the original CBERS CCD image........ 103
Figure 4.6 Predicted stand variables values plotted against observed values 106
Figure 4.7 Selected sample of scatterplots (amongst the selected models that best performed and presenting a mean value of residuals around zero): predicted plotted against observed values of stand variables (*W, Ws, V*). *W* (Mg) M5, predictive variables *US/B1* (a), *W* (Mg) M5, predictive variables *SAVI/B1* (b). *Ws* (Mg) M5, predictive variables *US/B1* (c), *Ws* (Mg) M5, predictive variables *NDVI/B1* (d). *V* (m^3) M5, predictive variables *US/B1* (e), *V* (m^3) M5, predictive variables *NDVI/B1* (f)........ 109
Figure 4.8 Estimated stand basal area (m^2 ha^{-1}) in radiata stands in the area of study 110
Figure 4.9 Estimated volume (m^3 ha^{-1}) in radiata stands in the area of study 111
Figure 4.10 Estimated stem aboveground biomass (Mg ha^{-1}) in radiata stands in the area of study 111

CHAPTER 5

Figure 5.1 Diagram illustrating some categories of stem defects. These categories are part of a stem description system of common use in New Zealand (based on Gordon 2005)........ 127
Figure 5.2 Influence of stocking (stems ha^{-1}) and seedlot in growth (*h* and *d*) 128
Figure 5.3 Influence of slenderness (*h/d), d, h*, stocking and seedlot on standing tree velocity.... 130
Figure 5.4 Influence of stocking and seedlot on branching........ 131
Figure 5.5 Stem form defects by seedlot and stocking 132

ACRONYMS

ADA: Algebraic Difference Approach
ANOVA: analysis of variance
ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer (sensor)

BAI: Base-Age Invariant

c: cuttings
CAI: Current Annual Increment
CAR: continuous time autoregressive error structure
CBERS: Chinese-Brazilian Earth Resources Satellite (satellite)
CCD: Charge-Coupled Device (CCD) CBERS (sensor)

DA: Discriminant Analysis
DART: Discrete Anisotropic Radiative Transfer
DTM: Digital Terrain Model

FLAASH: Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes

GADA: Generalizad Algebraic Difference Approach
GEMI: Global Environmental Monitoring Index
GIS: Geographic Information Systems/SIG: Sistemas de Información Geográfica
GNDVI: green difference vegetation index
GPS: Global Positioning System
GxE: Genotype and Environment interaction

INPE: Instituto Nacional de Pesquisas Espaciais (Brasil)

MAI: Mean Annual Increment
MFN: National Forestry Map/Mapa Forestal Nacional
MOE: Modulus Of Elasticity

NASA: National Aeronautics and Space Administration
NDMI: Normalized Difference Moisture Index
NDVI: Normalized Difference Vegetation Index
NIR: near infrared

PCA: Principal Component Analysis
PSP: Permanent Sample Plots/red de parcelas permanentes

R^2: coefficient of determination
RMSE: Root Mean Square Error
RS: Remote Sensing/ TD: teledetección
RS: Relative Spacing index

s: seedlings
S%: percent standard erro*r*
SAVI: Soil Adjusted Vegetation Index
SI: site index/índice de sitio
SMA: spectral mixture analysis
SR: Simple Ratio
SVI (SVIs): Spectral Vegetation Index (spectral vegetation indices)
SWIR: Short Wave Infrared Radiometer

TIR: Thermal Infrared radiometer

UTM: Universal Transverse Mercator

VNIR: Visible and Near Infrared Radiometer

Stand variables

C: total carbon stock per hectare
Cs: stem carbon stock per hectare
D_g: quadratic mean diameter
D_0: dominant diameter
G: stand basal area
N: number of trees per hectare
H: dominant height
H_m: mean height
t: age
V: stand volume
Vh: stand volume per hectare
W: aboveground biomass
Wh: aboveground biomass per hectare
Ws: stem aboveground biomass
Wsh: stem aboveground biomass per hectare

Stem variables

blcl: number of branches in the lowest branch cluster
clm: number of branch clusters per metre
dcl: estimated diameter of the largest branch of the lowest branch cluster
d: stem diameter at breast height

d_g: square mean diameter
h: stem height

Physiographic parameters

Alt: altitude
Slo: slope
Ss: superficial stoniness
Tti: thermotopograhic index

Climatic parameters

Anr: annual rainfall
Spr: spring rainfall
Smr: summer rainfall
Atr: autumn rainfall
Wr: winter rainfall
Mat: mean annual temperature
Max: mean maximums warmest month
Min: mean mimimums coldest month
Osc: oscillation
Etp: sum of potential evapotranspiration
Sup: water surplus
Def: water shortage
Hi: hydric index
Dl: draught length

Edaphic parameters

D: upper horizons depth
Fef: fine earth fraction
Snd: sand
Sli; silt
Cly: clay
Ccc: cementation capacity coefficient
Sic: silt impermeability coefficient
Eh: equivalent humidity
Per: permeability
Wrc: water retention capacity
Om: organic matter
Pha: total acidity
Phe: exchange acidity
N: superficial nitrogen
CN: C/N relationship
P: phosphorus
Ca: calcium
Mg: magnesium

Edaphoclimatic parameters

Retp: maximum real evapotranspiration
Pd: physiologic draught
Sd:calculated soil drainage