

Knowledge and experiences for
the development of sustainable
silvopastoral systems
in heathlands in Asturias

Raquel Benavides Calvo
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“Experiencias y conocimientos para el desarrollo de sistemas
silvopastorales sostenibles en brezales en Asturias”

Memoria para optar al grado de Doctor

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1. Resumen amplio

Introducción

Una gran proporción de la superficie de la Península Ibérica está cubierta por matorral, superándose el millón de hectáreas, tan sólo, en las comunidades cantábricas (Ministerio de Agricultura y Medio Rural y Marino, 2008). En Asturias el matorral se distribuye en un total de 212.147 ha, siendo los brezales el 21% de la superficie total (Álvarez et al., 2004). Los brezales son formaciones arbustivas cuyo origen está vinculado a la deforestación y otras actividades del hombre a lo largo de los siglos, como el aclarado del bosque, introducción de ganado, quemas o recogida de leñas (Calvo et al., 2002; Webb, 1998). Estas comunidades dominadas por varias especies de brezos que cubren amplias zonas de la Europa atlántica, sobre todo en zonas de suelos pobres y ácidos (Webb, 1998). En la actualidad, su área de distribución en Europa se está viendo reducida drásticamente debido al abandono de las prácticas ganaderas tradicionales y a su sustitución por sistemas intensivos y a la eutrofización (Diemont et al., 1996; Webb, 1998). Esta situación ha promovido su inclusión en la lista de hábitats de interés comunitario para su conservación recogida en la Directiva Hábitats (92/43/EEC). Sin embargo, en el norte de la Península Ibérica, los brezales están en expansión, como resultado del abandono de las actividades agrícolas y ganaderas desde los años 50, especialmente en zonas de suelos poco fértiles y erosionables donde la sucesión hacia los bosques está limitada por las características del suelo (poca fertilidad, escasez de profundidad del perfil...) y los frecuentes incendios. Son en definitiva zonas consideradas marginales.

La búsqueda de la sostenibilidad de estos territorios pasa por la aplicación de nuevas políticas y planes territoriales, así como de gestiones de usos del suelo que permitan alcanzar una serie de metas, tanto económicas, como sociales y ambientales. Y esto sólo se puede realizar desde un enfoque sistémico (Bertomeu García, 2007), es decir, con un profundo análisis de la situación socioeconómica de la zona en particular, y desde la disponibilidad de conocimientos relativos a distintos ámbitos que contribuyan al desarrollo de sistemas agrarios (pastorales, silvopastorales, forestales, conocimientos del suelo) y que supongan la aplicación

de nuevas técnicas y/o la introducción de nuevos componentes en los sistemas tradicionales.

Los sistemas silvopastorales son sistemas mixtos que permiten un aprovechamiento del medio más eficiente, y pueden ser la respuesta para preservar estas áreas rurales en abandono e infrautilizadas (Rigueiro-Rodríguez et al., 2005b). No obstante, en el entorno en el que nos encontramos, el noroeste peninsular, los estudios referentes a estos sistemas son bastante recientes y no son todavía muy numerosos (Mosquera-Losada et al., 2006; López-Díaz et al., 2007; Rigueiro-Rodríguez et al., 2007), en comparación con los existentes para los sistemas silvopastorales de la España Mediterránea.

Otro de los aspectos que debemos considerar para el desarrollo de sistemas silvopastorales sostenibles en estas zonas de baja productividad, tal como se plantea, es el conocimiento de la gestión y comportamiento de los herbívoros domésticos. Los animales presentan diferentes conductas de pastoreo según sus adaptaciones eco-fisiológicas, y por tanto aprovecharán de diferente manera los recursos existentes (Hofmann, 1989; Illius & Gordon, 1993). Esto se traduce en distintos grados de competencia o complementariedad que podrán ser gestionados para un aprovechamiento más eficiente.

La demanda de diferentes objetivos en la gestión del territorio requiere a su vez la mayor información multidisciplinar posible sobre el medio. A este respecto, los avances en Sistemas de Información Geográficos (SIG/GIS), en teledetección y en técnicas geoestadísticas permiten aumentar nuestras posibilidades de análisis y paliar las dificultades que la heterogeneidad temporal y espacial provocan cuando se trabaja a escala de paisaje. La modelización de variables ecológicas puede ayudarnos a caracterizar y evaluar un determinado territorio, además pueden servir como datos de entrada para desarrollar otros tipos de modelos (ecológicos, hidrológicos o productivos). Por otra parte la modelización y simulación permiten evaluar el impacto que determinadas actuaciones pueden causar sobre el medio (Tappeiner et al., 1998) o las implicaciones que distintas estrategias pueden acarrear (Bravo & Díaz-Balteiro, 2004; Rodríguez Soalleiro et al., 2004).

Por todo ello, el objetivo genérico del presente trabajo es la **puesta en valor de territorios marginales y abandonados, ocupados por brezales, del noroeste de la Península Ibérica, en concreto de Asturias**. Para ello se

desarrollan cuatro líneas de trabajo complementarias en cuanto a su contenido y metodología, que se concretan en los objetivos parciales expuestos a continuación:

1. Revisión de las experiencias y los conocimientos de los efectos del arbolado en el pasto en sistemas silvopastorales de áreas templadas. Experiencias en Nueva Zelanda.
2. Análisis socioeconómico y de recursos disponibles en la Comarca del Occidental-interior de Asturias, deprimida y dominada por formaciones de matorral.
3. Gestión pastoral en brezales-tojales parcialmente mejorados
 - a. Comportamiento del vacuno y del ovino en pastoreo mono-específico o mixto con caprino y su efecto en la dinámica vegetal del brezal-tojal
 - b. Estudio de la conducta de pastoreo de rumiantes domésticos en un brezal-tojal manejados en pastoreo mixto.
4. Análisis de herramientas y modelos para la planificación territorial.
 - a. Análisis de diferentes técnicas geoestadísticas para el desarrollo de modelos de predicción de variables climáticas en una zona montañosa.
 - b. Propuesta de un modelo para estimación de la productividad potencial forestal en Asturias.

Revisión de los sistemas silvopastorales en zonas templadas: efectos sobre el pasto de árboles caducifolios vs. perennifolios. Experiencias en Nueva Zelanda

Introducción

Dentro de las zonas templadas, Nueva Zelanda es un país pionero en el estudio de los sistemas silvopastorales. Desde los años 80 se han llevado a cabo gran cantidad de experimentos, en sistemas silvopastorales con *Pinus radiata* D. Don (pino radiata o insigne) y con *Populus* spp (chopos). La similitud entre el clima neozelandés y el asturiano (templado y húmedo) y su gran producción científica, precisamente con especies arbóreas y pastables presentes en Asturias, son los principales motivos de esta recopilación y revisión de información, con

vistas a que nos pueda servir de referencia al plantear sistemas silvopastorales sostenibles.

El origen de los sistemas silvopastorales con el pino radiata se halla en plantaciones de producción maderera, donde se permitía la entrada de ganado cuando el crecimiento del pasto era suficiente. De esta manera se reducía la competencia entre el pasto y los árboles (Hawke & Knowles, 1997), al tiempo que se aprovechaba ese pasto para obtener sistemas más diversificados y más rentables (Fenton, 1972, citado por Knowles, 1991). El comienzo de la utilización de frondosas, en este caso de crecimiento rápido, ha estado, sin embargo, orientado a otra realidad importante del campo en Nueva Zelanda: el control de la erosión. La ganadería es un pilar fundamental de la economía neozelandesa (Wilkinson, 1999), sin embargo su productividad potencial está limitada en muchas ocasiones por la erosión (Douglas & Trustrum, 1986; Hicks, 1992, 1995). Una de las principales medidas tomadas para su prevención desde los años 60 y 70 fue la plantación de árboles a densidades bajas en las granjas (Pollock et al., 1994, Mead, 1995; New Zealand Poplar Commission, 1995), en especial de chopos (*Populus* spp.) y sauces (*Salix* spp.). El interés por este tipo de árboles se ha reavivado en la actualidad porque que además de estabilizar el terreno con su rápido crecimiento, tienen un aceptable valor nutritivo para el ganado (Wilkinson, 1999).

El objetivo de este capítulo es por tanto revisar los efectos que el arbolado plantado a densidades bajas ejerce sobre las características del medio (microclima y propiedades del suelo) y, consecuentemente sobre el pasto (calidad y cantidad), haciendo distinción entre especies perennifolias (*Pinus radiata*) y caducifolias (*Populus* spp. y *Salix* spp.).

Efectos sobre el medio

Efectos sobre el microclima

Uno de los principales y más evidentes efectos que provoca el arbolado es la disminución de la luz que llega al suelo limitando la productividad del pasto. Esta limitación dependerá de la edad de la masa (Guevara-Escobar, 1999; Guevara-Escobar et al., 2007), de la distancia al tronco del árbol (Peri et al., 2002b), de la exposición (Douglas et al., 2001, 2006b), y sobre todo, del espaciamientos entre los

árboles (Wall et al., 1997a, 1997b) y del tipo de especie, no sólo por la arquitectura particular de cada uno (altura, ángulo de las ramas, área foliar, etc.) sino también por la variación estacional de su follaje (Power et al., 2001). A este respecto, el punto de extinción del pasto con especies caducifolias como los chopos se estimó en torno al 85% de fracción de cabida cubierta en Nueva Zelanda (McElwee & Knowles, 2000), mientras que para una conífera como el pino radiata se estimó en un 67% (Knowles et al., 1997).

La competencia por el agua es otro factor importante en zonas templadas (Peri et al., 2002a), sobre todo si existe sequía estival. Con la existencia de árboles, parte del agua de lluvia es interceptada y se evapora (Guevara-Escobar et al., 2000), por lo que el agua que llega al suelo dependerá del tamaño de la copa (edad y especie) y la densidad del arbolado. El contenido de agua en el suelo, además está muy influenciada por la estación y la intensidad de las lluvias, así como el tipo de suelo (textura y profundidad) y la topografía. Cuando las lluvias superan la demanda evaporativa, el tipo de cobertura no influye en el contenido de agua en el suelo (Yanusá et al., 1995). Sin embargo cuando hay déficit, el contenido de agua disminuye más bajo la cubierta arbórea (McIvor et al., 2003), salvo que nos encontremos en situaciones de gran estrés donde entonces la cubierta arbórea puede proteger de una evaporación excesiva como ocurre en ambientes mediterráneos más secos (Joffre & Rambla, 1988).

El arbolado reduce la velocidad del viento, y consecuentemente su efecto desecante y mecánico (Percival et al., 1984b; Hawke & Wedderburn, 1994), y además amortigua las temperaturas extremas, elevando las mínimas en invierno, y reduciendo las máximas en verano por la menor radiación que llega al suelo.

Efectos en las propiedades del suelo

Los resultados obtenidos con diversos estudios han mostrado efectos muy distintos, según nos encontremos con especies de coníferas o de frondosas, sin olvidarse que todo estará influenciado por el tipo de suelo y el clima específicos (Wall et al., 1997b). El pH y los macronutrientes encontrados en el suelo parecen incrementarse cuando nos encontramos en masas de frondosas (Guevara-Escobar et al., 2002; Douglas et al., 2006b; Wall, 2006), mientras que en plantaciones de pino radiata se ha detectado un pH y un contenido de nutrientes menores en las capas superficiales del suelo (Davis & Lang, 1991; Alfredsson et al., 1998; Chang

et al., 2002), siendo más destacable a mayor densidad y edad del arbolado. Por otra parte, parece que bajo arbolado disminuye el contenido de N y C orgánico en el suelo (Giddens et al., 1997), mientras que incluyendo la capa superior de materia orgánica, el contenido total de C es superior debido a la hojarasca de los árboles (Parfitt et al., 1007). El menor contenido de N y C orgánico parece deberse a mayores tasas de mineralización y nitrificación bajo el arbolado (debido a las mejores condiciones que crea), de manera que tan pronto se mineralizan, éstos son absorbidos rápidamente por las plantas o se lava en forma de nitritos en el caso del N.

Efectos sobre el pasto

Los efectos que el arbolado ejerce sobre el pasto herbáceo son consecuencia directa de las modificaciones que éste ejerce sobre el suelo y el ambiente (microclima).

Efectos sobre la productividad

Es la estructura de la cobertura (edad y espaciamiento) un factor decisivo para la productividad del pasto herbáceo. Durante los 3-5 primeros años del arbolado, los efectos sobre la producción de pasto son prácticamente inapreciables (Pollock et al., 1994; Guevara-Escobar, 1999). No obstante, los efectos dependerán del terreno ocupado por los nuevos árboles (y por tanto dependerá de la densidad inicial), y del grado de aplicación de herbicidas para eliminar competencia de las herbáceas con las plántulas. En esta fase parece incluso más relevante el efecto que el pasto ejerce sobre el crecimiento de las plántulas que viceversa (Percival et al., 1984a).

Los árboles jóvenes en densidades inferiores a 100 pies ha⁻¹ pueden mejorar las condiciones ambientales, compensando la falta de luz, y favoreciendo un incremento de la producción de pasto (Hawke, 1991; Hewson, 1993). Sin embargo, a medida que los árboles van creciendo, la competencia por los recursos aumenta y la producción de pasto disminuye. Eso sí, parece que el efecto causado por los árboles caducifolios es menor que el producido por los perennifolios. Descensos de la productividad en torno a un 10-20% se han registrado con chopos jóvenes (primera mitad de la rotación) a una densidad de 100 pies ha⁻¹ (New Zealand Poplar Commission, 1995; McIvor et al., 2003; Douglas et al., 2006a), mientras

que con pino radiata se estimó en torno al 13% con una densidad de 50 pies ha⁻¹ y del 20-40% con 100 pies ha⁻¹ (Hawke, 1991; Cossens & Crossan, 1995). Cuando se aumenta la densidad del arbolado o la edad (ya en la segunda mitad de la rotación, por encima de los 15 años), la reducción del pasto aumenta drásticamente en ambos casos (Guevara-Escobar et al., 1997; Cossens & Hawke, 2000; Douglas et al., 2001) hasta alcanzar el punto de extinción.

Los restos de podas y la hojarasca, también influyen al cubrir el pasto (Kellas et al., 1995). Las acículas caídas tardan más en descomponerse que la hojarasca de las frondosas, por lo que cubren durante más tiempo el pasto, intensificando todavía más el descenso de la producción del mismo (Percival & Knowles, 1988).

Por otra parte, en sistemas con frondosas, las diferencias estacionales y la posición con respecto al árbol pueden influir mucho sobre el crecimiento del pasto. El pasto localizado al norte (zonas soleadas en el hemisferio sur) recibe mucha más luz que la orientada al sur (zona de sombra), y por tanto registra acumulación de pasto mayor (Douglas et al., 2001). El pasto que se sitúa algo más alejado del tronco, en los huecos que deja la cobertura de las copas, también presenta mayor productividad (Wall, 2006). Además en ciertas épocas del año, cuando han perdido o todavía no han desarrollado el nuevo follaje (otoño y principios de primavera), reciben mayor cantidad de luz que permite mayores crecimientos si el resto de condiciones ambientales son favorables (temperatura y disponibilidad de agua).

Efecto sobre la calidad del pasto

El diferente grado de tolerancia a la sombra que demuestran las distintas especies es clave para comprender el cambio en la calidad del pasto herbáceo bajo una masa arbolada. La composición botánica cambia bajo las copas, haciéndose más marcada cuanto mayor es la edad y la densidad del arbolado. En términos generales, se registra un descenso en el contenido de leguminosas, en especial del trébol, y en el contenido de raigrás (Hawke, 1991; Douglas et al., 2006a), al tiempo que se incrementa la materia muerta (Gilligham, 1984; Guevara-Escobar et al., 2007). La proporción de otras gramíneas parece que también aumenta, como muestran estudios llevados a cabo con *Holcus lanatus* L. (Crowe & McAdam, 1992b; Wall, 2006), *Dactylis glomerata* L. (Miller et al., 1996; Douglas et al., 2001)

y *Poa annua* L. (Crowe & McAdam, 1992b; Guevara-Escobar, 1999) debido a su mayor tolerancia a la sombra, a su desarrollo fenológico y crecimiento invernal.

Estos cambios conllevan a un descenso del valor nutricional del pasto, con menor contenido de carbohidratos solubles y mayor en fibras.

Orientaciones futuras

El silvopastoralismo continuará siendo una disciplina importante en Nueva Zelanda dentro del paisaje ganadero, debido a la multifuncionalidad y la conveniencia, reconocida por los propios ganaderos, de los árboles en las granjas. Los planteamientos actuales sobre las líneas de investigación futura se centran en torno a un mayor conocimiento de la efectividad del arbolado para el control de la erosión, la gestión del tamaño y la forma de los árboles para maximizar la producción, la utilización de especies autóctonas, su papel en la captura del carbono, la diversificación de la producción y mejora de la renta y el impacto de los sistemas silvopastorales sobre la biodiversidad del medio.

Descripción de la situación socioeconómica y agraria en la zona de estudio

Descripción de la zona de estudio

Cada vez está más presente, dentro de la comunidad científica, la importancia que el panorama socioeconómico tiene a la hora de gestionar un territorio (Agnolletti & Anderson, 2000; Bertomeu García, 2007). Por lo tanto, una vez realizada la revisión bibliográfica y recopilada la información sobre los sistemas silvopastorales en regiones templadas, es fundamental centrarnos en la realidad social, económica y en los recursos humanos y físicos disponibles en área en el que trabajamos.

La zona de estudio se sitúa en la comarca agroganadera del occidente-interior asturiano (Figura 1.), tiene una superficie de 2.109 km² (20% de la total asturiana) y está formado por 11 concejos: Allande, Cangas del Narcea, Degaña, Grandas de Salime, Ibias, Illano, Pesoz, San Martín de Oscos, Santa Eulalia de Oscos, Taramundi y Villanueva de Oscos. Se caracteriza por un relieve abrupto, una superficie de pastos y praderas en torno al 20%, una superficie forestal alta

(68,4%), en la que se incluye una importantísima proporción de matorral (el 31% de la misma), y una gran riqueza natural, con diferentes tipos de espacios protegidos.

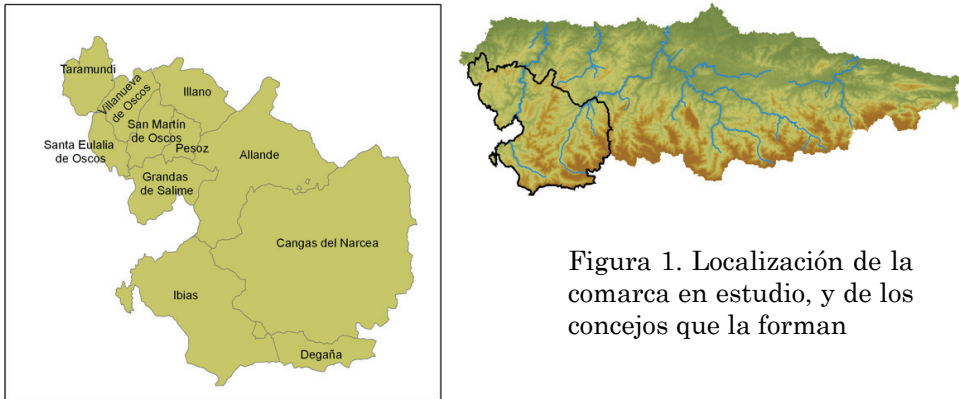


Figura 1. Localización de la comarca en estudio, y de los concejos que la forman

Análisis demográfico

En la actualidad sólo el 2,3% de la población asturiana vive en esta comarca (INE, 2007), y es que se trata de una zona muy despoblada que vio mermar su población a partir de los años 60, cuando se produjo un fuerte movimiento de la población rural asturiana hacia la zona central de la región (más industrializada). Este flujo que continúa en la actualidad (SADEI, 2007e), junto con otro flujo hacia otras provincias españolas, como Madrid, Castilla y León y Canarias, aunque a menor ritmo. Es cierto, que desde finales de los 90 la migración procedente del extranjero ha aumentado mucho en Asturias creando un saldo positivo. Aún así, Asturias es una de las regiones españolas que menos inmigrantes recibe y la comarca en estudio, a su vez, es de las zonas asturianas que menos inmigración atrae con sólo el 1,6% del total asturiano, lo que no ha conseguido compensar los saldos negativos de la migración interna.

La pirámide poblacional de esta zona muestra una población envejecida con pocos jóvenes, tan sólo con un 9,2% de la población menor de 15 años, y con un índice de envejecimiento de 450,5, (casi 5 personas mayores de 65 años por cada joven menor de 15), lo que duplica el valor medio regional (222,1) y cuadruplica el valor nacional (117,4). Además existe un desequilibrio entre la población adulta femenina y masculina, siendo ésta superior en más de 5 puntos de media, y con

algunos valores locales realmente preocupantes superando los 18 puntos de diferencia, como en el caso de Ibias e Illano.

Esta estructura poblacional determina los movimientos naturales de la población (número de nacimientos, defunciones y matrimonios que tienen lugar en una población determinada). Después del *baby boom* de los años 70, España se convirtió en uno de los países de Europa con menor tasa de natalidad (EUROSTAT, 2006), lo que también se reflejó en Asturias y en la comarca. En los últimos 25 años, la edad media de maternidad en Asturias aumentó en casi 4 años y el número de hijos por mujer disminuyó de 2,4 a 0,8 en 1998. Los datos del 2006 muestran una tasa de natalidad de un 4,4‰ en la comarca (por debajo de la tasa provincial, 7,2‰), mientras que la mortalidad aumentó un 25% desde 1990, situándose en el 14,2‰ (frente al 11,4‰ asturiano) (SADEI, 2007f). Estos valores altos de mortalidad y bajos de natalidad son consecuencia del envejecimiento de la población y del desequilibrio entre la población masculina y la femenina, junto con el aumento de la participación de la mujer en el mercado laboral, el problema de la vivienda y la precariedad laboral.

Otra característica de la población de la comarca, es el bajo nivel de formación académica. Esta zona incluye los concejos asturianos con mayor proporción de población analfabeta, y con más de la mitad de la población mayor de 16 años sin estudios (escolarización menor a 5 años) o con estudios primarios. Tan sólo el 4,6% tiene estudios universitarios. Este factor es clave porque limita las oportunidades laborales, la movilidad social y el desarrollo de un área

Nivel de renta

Una de las causas de abandono de esta región, puede deberse a que nos encontramos en una de las regiones más pobres de Asturias (SADEI, 2007g). En el 2004 la renta media anual disponible por habitante (11.453€) fue un 14,1% más baja que la media Asturiana (13.326€). De hecho, algunos de sus concejos han registrado durante años las rentas más bajas de toda Asturias. Las excepciones de la comarca son Cangas del Narcea, Ibias y Degaña, que superan el 90% de la renta media regional, debido a que presentan una cierta actividad industrial (como la minería) y un desarrollo del sector servicios mayor que el resto de concejos.

Estadísticas laborales

El análisis del Mercado de Trabajo (SADEI, 2005a) muestra una tasa de actividad (proporción de población mayor de 16 años que trabaja o busca trabajo) del 43%, lo cual está por debajo de la media regional. Esto puede deberse a que es una región con gran cantidad de jubilados, prejubilados por la mina y de mujeres que trabajan en las explotaciones familiares sin darse de alta en la Seguridad Social ni en la Oficina de Empleo. Sin embargo, la tasa de población ocupada (87,3%) supera a la media regional, debido probablemente a esa migración tan importante hacia otras zonas más desarrolladas. La evolución del empleo también refleja esa pérdida de población, disminuyendo el empleo existente entre 1990 y 2006 en un 36,7%.

El número de desempleados también ha descendido durante ese periodo (INEM, 2006). Destaca que en esta región el paro femenino ha sido tradicionalmente menor que el masculino, al contrario de lo que ha sucedido en el resto de la provincia y del país. Aunque esto parece deberse, como ya comentamos antes, a la presencia de mujeres que trabajando en las explotaciones familiares y en los hogares no se registran en la Oficina de Empleo.

Sectores económicos

El peso relativo que tiene un sector económico en la economía regional se puede medir mediante tres variables: el número de trabajadores que emplea, las empresas incluidas en el sector y la producción (VAB¹). Teniendo en cuenta estas tres variables, el sector servicios es el que presenta mayor importancia en la región con una aportación al VAB comarcal del 51,5% (SADEI, 2007g), un número de trabajadores que suponen en 43,5% de los trabajadores que viven en la comarca (SADEI, 2005a) y con el 75,6% de las empresas censadas en la comarca (Cámara de Comercio de Oviedo, 2006). Sin embargo, este peso dista mucho del peso que este sector alcanza a nivel regional y nacional. Por otro lado, el sector primario, muy marginal en el contexto nacional, adquiere gran importancia en esta zona, contribuyendo con el 10,4% al VAB comarcal, y con el 27,6% de los

¹ Valor Añadido Bruto a precios básicos es un buen indicador para medir la importancia económica de un sector, y se define como la diferencia entre el valor de la producción y el valor que los productores reciben de los compradores por cada unidad de bien o servicio producido, descontando los impuestos sobre los productos y sumando las subvenciones a los productos.

trabajadores. Por lo que se confirma que nos encontramos en una zona rural muy dependiente de las actividades agrarias.

Sector Primario

La principal rama de este sector en Asturias es la ganadería, más adecuada que la agricultura considerando su compleja orografía, con un 85,7% de la producción total agraria. Esto se refleja en la comarca, de manera que tan sólo el 2,3% de la superficie agraria está destinada a zonas de cultivo (SADEI, 2004), mientras que el 83% de la superficie agraria incluye pastos permanentes y zonas de matorral.

Asturias, por motivos históricos y topográficos, presenta explotaciones de tamaño menor a la media española (93,2% de las explotaciones son menores de 20 ha). La comarca, en el contexto asturiano se caracteriza por presentar una fragmentación mayor de las explotaciones, con un número de parcelas medio por explotación en torno a 27,5, y por presentar una superficie agraria útil dentro de las explotaciones (formada por las tierras labradas más los pastos permanente) mayor a la media regional, lo que puede considerarse como un mayor aprovechamiento de la superficie agrícola con respecto a la media asturiana.

La mayoría de las explotaciones son propiedades privadas (77,7%), aunque existe una parte importante de tierras comunales, especialmente cuando se tiene en cuenta sólo la superficie agraria útil (22,8%). La mayoría de las explotaciones en esta comarca son explotaciones familiares, donde la mano de obra familiar supone el 97,2% del trabajo anual total. Del trabajo restante (no familiar) el 78% es mano de obra fija, frente al 61% de mano de obra temporal que se registra en España en su conjunto.

El principal ganado existente en esta región es el ganado vacuno (80%). En particular, vacuno de carne de la raza local *Asturiana de los Valles* con un 77% del total del vacuno, y al que le sigue el vacuno de leche. Destaca la poca presencia de la otra especie autóctona de vacuno, *Asturiana de las Montañas*, y la escasa presencia de otros rumiantes (ovejas y cabras). En general, estas explotaciones familiares, se caracterizan por un número de animales por explotación pequeño, por tratarse de sistemas no intensivos.

Sector Secundario

La comarca presenta un pequeño grado de industrialización comparado con otras zonas de Asturias. La industria emplea al 17,9% de los trabajadores de la comarca (SADEI, 2005a), y se concentra en unos pocos concejos que elevan al 29,2% la aportación de esta actividad al VAB comarcal (SADEI, 2007g), compensando la total inexistencia de industria en otros concejos. La actividad industrial se localiza en Degaña e Ibias (extracción de carbón), Taramundi (por la tradicional fabricación de cuchillos y navajas) y Grandas de Salime (por la presencia de industrias dedicadas al sector alimenticio, sobre todo lácteo).

Por otra parte la construcción, con un 11% de los trabajadores de la comarca (SADEI, 2005a) y un aporte a la economía comarcal en torno al 14,3% (SADEI, 2007g), sí está presente en todos concejos. En los últimos años se ha producido un crecimiento de este sector en la comarca como en el resto del país, aunque en este caso está más ligado a la mejora de las infraestructuras que está sirviendo de base al crecimiento de otros sectores como el turístico, y está incrementado la calidad de vida de los habitantes de esta zona.

Sector Terciario

Como ya comentamos, es la actividad económica con mayor peso dentro de la economía comarcal y, al contrario que la industria, está sufriendo una evolución positiva en los últimos años. Aunque en general, esta actividad económica se caracteriza por la poca diversificación y por la falta de muchos servicios.

En la comarca en estudio, este sector se caracteriza por estar formado principalmente por el comercio con el 47% de los negocios de la comarca (Cámara de Comercio de Oviedo, 2006). La mayoría de estas empresas se dedican al comercio al por menor, y destaca el porcentaje de establecimientos dedicados a la alimentación, bebidas y tabaco, pero sobre todo los establecimientos no especializados, donde se incluyen las tiendas de productos mixtos: alimenticios, droguería, ferretería, textil, etc. El turismo se considera otro subsector muy importante dentro del sector terciario. Produce un efecto multiplicador tanto en la producción, como en el empleo y en la renta de la región, no sólo por el efecto directo de la actividad en sí misma, sino porque además provoca un esfuerzo en la maquinaria necesaria que supera el valor de la producción del sector. El turismo

experimenta un continuo crecimiento que se manifiesta en el aumento de la oferta turística de los últimos años, especialmente de alojamientos rurales, tanto en Asturias como en la comarca (SITA, 2007).

Gestión pastoral en comunidades de brezal-tojal

Introducción

Los brezales en Asturias tienen gran importancia, dado que ocupan el 21% de su superficie (Álvarez et al., 2004). Sin embargo, la productividad que presentan es baja, principalmente por el escaso el valor nutritivo que las plantas leñosas dominantes tienen para el ganado (Hodgson & Eadie, 1986; Osoro et al., 2007a). De ahí que en la actualidad se apueste por la transformación de las zonas más favorables del brezal implantando pastos herbáceos para así cubrir las necesidades nutricionales del ganado. También, suelen practicarse desbroces periódicos para permitir una mayor presencia de herbáceas y limitar temporalmente la invasión total del matorral y, a su vez, disminuir también el riesgo de incendios. Sin embargo, el beneficio que tales actuaciones conllevan, dependerán de la gestión pastoral que se realice de estos recursos (especies, raza, tipos de rebaño, cargas ganaderas, etc.).

La conducta de pastoreo varía de unas especies a otras debido a las diferentes adaptaciones eco-fisiológicas (tamaño, anatomía de la boca, capacidad digestiva, etc.) y por tanto, su aprovechamiento de los recursos disponibles (Hofmann, 1989; Illius & Gordon, 1993). El ganado vacuno apenas consume plantas leñosas, por lo que prácticamente su dieta esta basada en herbáceas. Por el contrario, los pequeños rumiantes, como las ovejas y las cabras, son capaces de seleccionar los brotes de las plantas leñosas cuando la disponibilidad del pasto herbáceo es reducida o limitante.

El grado de complementariedad entre las distintas especies afectará la eficiencia de utilización, la productividad y la sostenibilidad del sistema, ya que un alto nivel de solapamiento en las dietas conlleva una alta competición por los mismos recursos (Wright & Connolly, 1995). Sin embargo, los niveles de solapamiento pueden variar de acuerdo a las distintas especies, densidades o épocas del año (Bullock, 1995), y con una apropiada gestión de las diferentes especies se puede lograr un mayor aprovechamiento de los recursos, como parece

ocurrir con el uso complementario de cabras en brezales-tojales parcialmente mejorados pastados por ovejas o vacas (Allan & Holst, 1996).

Para el estudio de la gestión pastoral en brezales-tojales parcialmente mejorados se realizaron dos experimentos:

Experimento 1: Se estudió la conducta de vacuno y ovino de acuerdo al tipo de rebaño (rebaño monoespecífico *vs.* mixto con caprino), y su efecto sobre la dinámica vegetal.

Experimento 2: Se estudió el comportamiento de los rumiantes (vacuno, ovino y caprino) en pastoreo mixto con sus crías.

Material y métodos

Ambos experimentos tuvieron lugar en una finca experimental localizada en el concejo de Illano (comarca occidental-interior de Asturias), en la sierra de San Isidro. La vegetación natural está compuesta por matorrales, especialmente brezo (*Calluna vulgaris* L. (Hull.) y *Erica* spp.) y tojo (*Ulex gallii* Planch.). Las implantaciones de pastos herbáceos se establecieron mediante roturación, fertilización y siembra de raigrás inglés (*Lolium perenne* L.) y trébol blanco (*Trifolium repens* L.).

Los animales utilizados fueron vacas de la raza Asturiana del Valle, ovejas de raza Gallega y Latxa, y cabras de raza Cachemere, todas con sus crías.

Experimento 1

El experimento se llevó a cabo en 8 parcelas previamente desbrozadas, y con un tercio de su superficie mejorada, agrupadas en 2 bloques. Dentro de cada bloque, 4 tratamientos: vacuno solo (CA), vacuno con caprino (C+G) a una proporción 1:7, ovino solo (SA) y ovino con caprino 1:1 (S+G), a cargas de 1,1 vaca ha¹ (ó 1,5-1,7 terneros añojos) y 10 hembras adultas de ovino/caprino ha⁻¹. Estos tratamientos se mantuvieron durante la estación de pastoreo (abril-mayo hasta octubre-noviembre), desde 2002 hasta 2005. En los años 2006 y 2007, en un bloque se sustituyó una parcela de SA por caprino solo.

Se tomaron datos de conducta cada 15 min durante 2 días consecutivos en 2003, 2005, 2006 y 2007. En mayo del 2003 y 2004, se analizó la composición de la dieta de los animales mediante la técnica de los *n*-alcanos (Oliván & Osoro, 1999), y se analizó el valor nutritivo de los componentes de la vegetación. Al comienzo de la estación de pastoreo, desde 2002 a 2006, se hicieron controles de la cubierta

vegetal para analizar la dinámica del brezal-tojal con datos de cobertura, altura y biomasa en los distintos tratamientos, y en 2006 también se muestreó en las jaulas de exclusión (control). Se tomaron también datos de altura del pasto implantado a lo largo de las estaciones de pastoreo desde 2002-2005. Finalmente, en mayo del 2006 se examinó el rebrote del tojo en las zonas mejoradas.

La información derivada de los diferentes controles se analizó estadísticamente en busca de diferencias entre manejos, entre especies y a lo largo del tiempo, utilizando el programa SAS (SAS, 2001).

Experimento 2

En una única parcela de brezal-tojal de 22,3 ha, con un 24% del total de la superficie con pasto mejorado, se introdujeron 6 vacas, 42 ovejas y 42 cabras, todas con sus crías, durante la estación de pastoreo (de mayo a diciembre) de dos años, 2003 y 2006.

En el 2003, se tomaron datos de composición botánica de la zona de matorral y de la mejorada, se estimó mensualmente la composición química de los componentes principales de la vegetación (brezo, tojo, herbáceas en la zona de matorral, y raigrás y trébol en la mejorada). La conducta de pastoreo se registró cada 15 min durante dos días consecutivos, en seis ocasiones durante la estación, y se analizó la selección de la dieta de cada especie mediante la técnica de los *n*-alcanos, en 5 ocasiones durante la estación de pastoreo del 2006. Además, de manera mensual se pesaron los animales, se apuntó su condición corporal, y se tomaron del recto muestras de heces para estimar la cantidad de parásitos gastrointestinales (conteo fecal).

Las datos se analizaron estadísticamente mediante análisis de varianzas con el programa STATISTICA 6.0 (StatSoft Inc, 2001).

Resultados

Experimento 1

El valor nutritivo de los componentes vegetales fue significativamente distinto de unos a otros ($p < 0,001$), presentando el mayor contenido de proteína el trébol, y el mayor contenido de lignina (ADL) las leñosas (brezo y tojo).

En la zona mejorada, la altura del pasto descendió significativamente a lo largo de la estación de pastoreo ($p < 0,001$), obteniéndose una altura media durante la estación mayor ($p < 0,01$) en las parcelas con vacuno (7,7 cm) que en las de ovino

(6,4 cm). Además, en las parcelas con ovejas no se detectó presencia de rebrotes de tojo, y en las parcelas con vacuno la presencia del caprino redujo dicho rebrote de un 7% (CA) a un 0.5% (C+G).

Los análisis de conducta, mostraron que las cabras pastaron durante más tiempo que el vacuno y el ovino (595, 550 y 512 min día⁻¹, respectivamente; $p < 0,05$), aunque el tipo de rebaño también influyó, dedicando más tiempo a pastar cuando se encontraban en rebaños mixtos ($p < 0,001$). Por otra parte, las cabras pastaron más tiempo en la zona de matorral ($p < 0,001$) con una proporción de 0.68 del tiempo de pastoreo, mientras que el ovino y el vacuno dedicaron el 0.35 y el 0.19, respectivamente. El tiempo de pastoreo en la zona mejorada varió también de acuerdo con el tipo de rebaño ($p < 0,05$), dedicando ambas especies, ovino y vacuno, mayor tiempo en rebaños monoespecíficos.

Se detectaron diferencias significativas ($p < 0,001$) en la selección de tojo y herbáceas en función de la especie animal. Las cabras presentaron una proporción de tojo en sus dietas de 0,28, mientras que en el ovino y vacuno apenas supuso un 0,07 y 0,02. La proporción de especies herbáceas detectada en la dieta de vacuno fue de 0,95, en el ovino de 0,89 y de 0,68 en el caprino.

Los tratamientos provocaron diferencias en la dinámica vegetal que se recogen en la Tabla 1.

En términos generales puede decirse que a lo largo del experimento se ha producido un aumento de la cobertura, altura y biomasa del tojo ($p < 0,001$), siendo especialmente destacable en los rebaños monoespecíficos. El en caso de la altura, ésta fue además significativamente mayor en las parcelas de vacuno frente a las de ovino ($p < 0,01$). Por el contrario, la cobertura de herbáceas y materia muerta descendió a lo largo del experimento en ambos casos con una significación de $p < 0,001$. La interacción entre el factor año y el manejo, muestra que este descenso a lo largo del experimento, fue más acusado en rebaños monoespecíficos para ambos elementos ($p < 0,05$).

La comparación con las jaulas de exclusión (controles), mostró un aumento significativo de la cobertura, altura y biomasa del tojo en las parcelas no pastadas, sobre todo en comparación con los rebaños mixtos; mientras que cobertura de herbáceas y materia muerta fue menor en estos controles.

Tabla 1. Efectos de la especie animal principal (Sp), del manejo (M) y del año (Yr) en la cobertura vegetal, altura del tojo y fitomasa del brezal-tojal (2002-2006). Tratamientos: vacuno solo (CA), vacuno con caprino (C+G), ovino solo (SA) y ovino con caprino (S+G)

Especie (Sp)	Vacuno		Ovino		SEM	Significaciones					
	CA	C+G	SA	S+G		Sp	M	Sp x M	Yr	Yr x Sp	Yr x M
Cobertura (%)											
Tojo	48,2	45,6	47,1	33,0	6,79	ns	ns	ns	***	ns	**
Brezo	10,9	2,7	0,8	5,4	2,75	ns	ns	*	ns	*	*
Herbáceas	16,5	25,2	28,3	37,2	4,65	+	ns	ns	***	ns	*
Materia muerta	23,3	25,6	22,0	22,6	2,70	ns	ns	ns	***	ns	*
Suelo desnudo	1,1	0,9	1,8	1,9	0,65	ns	ns	ns	ns	ns	*
Altura del tojo (cm)	14,2	10,6	11,0	8,6	1,14	*	*	ns	***	**	***
Fitomasa (kgDMha⁻¹)											
Tojo	11914	8242	12980	7559	2279	ns	+	ns	***	ns	*
Brezo	2045	735	294	891	609	ns	ns	ns	ns	+	+
Herbáceas	4221	4629	3132	4695	748	ns	ns	ns	ns	ns	ns
Total	18180	13605	16406	13145	1631	ns	+	ns	***	ns	*

+ $P < 0,1$; * $P < 0,05$; ** $P < 0,01$; *** $P < 0,001$; ns no significativo ($P > 0,1$). SEM indica error estándar de la media. La interacción Yr x L x M fue no significativa con todas las variables.

Experimento 2

De manera similar al primer experimento, el valor nutritivo del pasto mejorado superó el de la vegetación natural, con un mayor contenido de proteína y menor de fibra (NDF, ADF). También la altura del pasto mejorado descendió significativamente a lo largo de la estación de pastoreo en ambos años ($p < 0,05$).

De nuevo, las cabras pastaron durante más tiempo que las otras dos especies, especialmente en verano, con una media diaria de 720 min día⁻¹. El tiempo que las cabras pastaron en la zona de matorral fue de nuevo mayor al del ovino y el vacuno. Mientras éstas últimas dedicaron más del 70% de su tiempo de pastoreo a la zona mejorada, el caprino permaneció más del 50% del tiempo en la zona de matorral. Las proporciones de tiempo en la zona mejorada variaron con el avance de la estación, especialmente en el caso del vacuno, mientras que el ovino apenas se vio afectado. El análisis de la dieta volvió a demostrar que el vacuno y el ovino seleccionaron activamente la vegetación herbácea (principal componente de su dieta en toda la estación de pastoreo) y rechazaron el tojo. La dieta de las cabras varió en mayor medida con la estación, disminuyendo la proporción de herbáceas seleccionadas de 0,69 en julio a 0,16 en noviembre, y con una

proporción de tojo mayor que en las otras especies, en particular al principio y al final de la estación de pastoreo. El contenido de brezo en las dietas fue en aumento a lo largo de la estación de pastoreo en las tres especies. Con todo esto, se estimó un mayor solapamiento entre el ovino y el vacuno, que con el caprino, aunque en general el solapamiento fue disminuyendo a medida que avanzaba la estación.

Los cambios en la producción animal (peso vivo) se muestran en la Tabla 2. En términos generales se puede afirmar que tanto la especie como la estación afectan significativamente a la productividad animal. Se observa una productividad total similar entre el vacuno y ovino en primavera, mientras que el verano fue significativamente más favorable para los pequeños rumiantes. Durante el pastoreo en primavera-verano, la producción total (madres + crías) mayor se obtuvo con el ganado ovino (1110 g día⁻¹ por unidad ganadera -UGM-), seguido del vacuno (990 g día⁻¹ por UGM), y el menos productivo fue el caprino (857 g día⁻¹ por UGM). Considerando la estación total (de mayo a diciembre), la menor producción fue registrada con el vacuno, seguida del caprino y, de nuevo con los mejores resultados, el ovino (con 647, 667, 975 g día⁻¹ por UGM, respectivamente).

Tabla 2. Cambio diario del peso vivo (PV) por unidad ganadera (UGM) en las crías (terneros, cabritos y corderos) y en las madres lactantes (vacas, ovejas y cabras) en brezales parcialmente mejorados durante dos estaciones de pastoreo (de mayo a diciembre).

Año (Y)	2003			2006			Significaciones		
	V	O	C	V	O	C	Sp	Y	Sp x Y
PV inicial en crías (kg UGM ⁻¹)	228	96	57	50	77	71	***	***	***
Variación de PV (g día ⁻¹ por UGM)									
Primavera	1295	1335	713	737	1362	677	***	**	**
Verano	591	919	717	626	264	403	ns	***	***
Total	904	1082	715	676	665	525	***	***	*
PV inicial en madres (kg UGM ⁻¹)	590	305	263	462	288	264	***	**	**
Variación de PV (g día ⁻¹ por UGM)									
Primavera	1159	437	282	421	447	402	***	**	***
Verano	6	468	360	-556	-227	-57	***	***	*
Otoño	-540	-71	-124	-455	2	-216	***	ns	**
General	-26	156	98	-260	45	-4	***	***	ns

V: vacuno, O: ovino; C: caprino. * $P < 0,05$; ** $P < 0,01$; *** $P < 0,001$; ns no significativo ($P > 0,1$).

Los parásitos gastrointestinales aumentaron con la estación de pastoreo, y además este incremento fue mayor en las cabras.

Discusión

En ambos experimentos, los análisis bromatológicos mostraron que el valor nutritivo de los componentes de estas comunidades de brezal-tojal era bajo, y como cabía esperar, menor al valor nutritivo del pasto implantado, como ya se había descrito en estudios anteriores (Hodgson & Eadie, 1986; Celaya et al., 2007b). Esto ratifica la conveniencia de establecer zonas mejoradas en brezales para que el ganado alcance sus requerimientos alimenticios (Maxwell et al., 1986; Osoro et al., 1999).

La conducta de pastoreo y la selección de dieta ponen en evidencia en ambos estudios, que el vacuno selecciona básicamente vegetación herbácea rechazando los componentes del matorral, lo que concuerda con la información obtenida en trabajos previos (Aldezabal, 2001; Celaya et al., 2007b). Ello se debe a la limitación del vacuno para seleccionar eficientemente los brotes verdes, dada su anatomía buco-dental, a pesar de su mayor capacidad para digerir alimentos más fibrosos (mayor tiempo en tracto digestivo) (Illius & Gordon, 1993). Al contrario, los pequeños rumiantes son capaces de utilizar las leñosas cuando disminuye la disponibilidad de pasto mejorado, aunque existen diferencias entre ambas especies (Lu, 1988; Narjisse, 1991; Allan & Holst, 1996). El ovino es capaz de mantenerse con alturas de pasto muy bajas (Osoro et al., 1999a, 2002; Celaya et al., 2007a), como muestran las respuestas del ovino a las alturas medias tan bajas del primer experimento, comparado con las parcelas pastadas por el vacuno. Además se ha observado que el ovino pasta con mayor intensidad sobre los pastos implantados de raigrás-trébol que el caprino (Grant et al., 1984) mientras que el caprino selecciona el tojo en mayor proporción, tanto en el caso de *Ulex europaeus* (Clark et al., 1982; Radcliffe, 1985, 1986) como en el de *U. gallii* (Celaya et al., 2007b).

Del primer experimento además, se infiere que existen diferencias en la conducta de las distintas especies según pastan solas o en rebaños mixtos, aumentando el tiempo de pastoreo en éste último caso. En otro estudio realizado en la misma finca se obtuvo un resultado similar para el caprino (Osoro et al., 2000a), aunque la conducta del ovino apenas se vio alterada por la presencia de caprino ni la dinámica vegetal de la vegetación natural.

Aunque a largo plazo los brezos puedan llegar a dominar la composición florística de estas formaciones de matorral (Celaya et al., 2007a), después de

perturbaciones como un desbroce o una quema, el tojo compite de manera más eficaz en los primeros años (Stokes et al., 2003; Jáuregui et al., 2007). Esto concuerda con este experimento, donde aparece un incremento del tojo en todos los tratamientos, incluido en los controles. Aunque no se observaron diferencias significativas entre las parcelas de vacuno y ovino, la altura del tojo aumentó más en las parcelas de vacuno a lo largo del experimento, así como el porcentaje de brezo (en términos de cobertura y fitomasa). Ya se ha comentado la menor capacidad del vacuno para consumir los brotes verdes de los arbustos, y esto ocurre particularmente en el caso de los brezos, como por ejemplo *Calluna vulgaris* (Oliván & Osoro, 1998).

En cuanto al tipo de manejo, los efectos a lo largo del primer experimento sobre la vegetación fueron más claros. El pastoreo mixto con caprino, frenó más eficazmente el aumento del matorral que el pastoreo monoespecífico, sobre todo en el caso del tojo, lo que a su vez permitió un mayor desarrollo de las herbáceas. Esto concuerda con los resultados de otros estudio en la misma finca experimental, donde el tojo aumentó más después de tres años en parcelas sólo con ovino, comparado con parcelas manejadas con pastoreo mixto de ovino y caprino (Celaya et al., 2007a).

En ausencia del pastoreo, la acumulación de fitomasa casi alcanzó los 40 t DM ha⁻¹ a los 5 años de haber desbrozado, y con un 92% del total de biomasa de tojo. En el trabajo de Celaya et al. (2007a) se obtuvieron cantidades de 18,5 t DM ha⁻¹ con un 46% de tojo después de 5 años sin pastoreo tras el desbroce. Estas diferencias podrían deberse a distintos niveles de fertilidad en el suelo, a distintas condiciones climáticas o a la capacidad distinta de rebrotar tras desbroces sucesivos.

En el experimento 2, donde las tres especies pastan juntas, se observa un menor solapamiento existente entre el caprino y el vacuno o el ovino que entre el vacuno y el ovino. Este hecho ya se constató en el anterior experimento y en otros trabajos, aunque bajo condiciones distintas (Lechner-Doll et al., 1995; Aldezabal, 2001), indicando una menor competencia interespecífica entre cabras y otras especies de herbívoros, y por lo tanto, un mayor aprovechamiento de recursos heterogéneos (Wright & Connolly, 1995).

El análisis de la productividad de cada especie animal, mostró que la relación entre las variaciones de peso y la estación de pastoreo fueron resultado

de la variación en la disponibilidad del pasto, la capacidad de ingestión y la conducta de pastoreo de los distintos animales en cada situación. De hecho, Wright y Whyte (1989) ya mostraron que las vacas lactantes logran un máximo de ingestión y de producción cuando la altura del pasto es de unos 8 cm, y se reducen significativamente cuando la altura disminuye hasta los 4-5 cm. Sin embargo, las ovejas en lactación pueden maximizar las ganancias de peso con pasto de 5-6 cm de altura (Orr et al., 1990; Osoro et al., 2002), siendo capaces de mantener su peso corporal con alturas de pasto de 4.0 cm. En el caso de las manejadas en comunidades vegetales naturales, las ovejas no lactantes mantienen su peso con un pasto de hasta sólo 2 cm de altura media (Osoro et al., 2000a).

La capacidad de ingestión de los animales viene determinada por el tamaño corporal y los requerimientos nutricionales (Fitzhugh, 1978). Illius y Gordon (1993) señalaron que los herbívoros de pequeño tamaño generalmente requieren más energía en relación al tamaño de su sistema digestivo que los de mayor tamaño, y por tanto, necesitan seleccionar componentes vegetales de mayor calidad. Por otro lado, los animales de mayor tamaño, al tener un aparato digestivo mayor, retienen durante más tiempo los alimentos en el tracto intestinal digiriéndolos más y mejor. Pero a pesar de esta ventaja, el vacuno no es capaz de mantener la ingestión en este tipo comunidades (brezales) debido a su limitada capacidad para seleccionar los brotes verdes y la limitada ingestión de hierba cuando la altura del pasto herbáceo desciende por debajo de los 5-6 cm.

El conteo fecal de huevos de parásitos ha señalado que las cabras son más susceptibles a la parasitosis por nematodos gastrointestinales que el ovino y el vacuno. Esto parece estar relacionado con el desarrollo inmunitario de cada especie y de su nivel nutricional. Las cabras desarrollan poco los niveles de inmunidad dada su tendencia a seleccionar material leñoso en sus dietas. Por este motivo es aconsejable administrarles tratamientos antihelmínticos para su manejo en pastoreo, tanto a las madres como a las crías (Hoste et al., 2008). Aun así, los valores obtenidos en las cabras manejadas en pastos mejorados, sin brezo disponible, son mucho mayores (Osoro et al., 2007b).

Conclusiones

A partir de estos experimentos se concluye que el ganado ovino es la especie que presenta mejores rendimientos en un brezal-tojal parcialmente mejorado, a lo

largo de toda la estación de pastoreo. Sin embargo, los resultados indican que el caprino complementa bien al ovino con un uso más eficiente de la vegetación natural disponible, incluso alcanzando niveles de producción similares al de las vacas con cría con paridera en primavera. En definitiva, los rebaños mixtos de ovino y caprino serían los más aconsejables para el manejo eficiente de este tipo de comunidades vegetales y para alcanzar sistemas sostenibles desde el punto de vista de producción animal y de uso de los recursos.

Herramientas para la planificación territorial

Introducción

Además del conocimiento del comportamiento de los herbívoros domésticos, para el desarrollo de sistemas silvopastorales resulta esencial el uso de herramientas para estimar el potencial productivo de estos territorios. Es evidente que las características del suelo, las condiciones climáticas y la topografía difieren significativamente de unas zonas a otras. En nuestra zona de estudio, encontramos extensiones muy erosionadas con suelos pedregosos y/o poco profundos, con pendientes muy pronunciadas, muy expuestos a condiciones climáticas adversas, etc., que condicionan la producción vegetal y, muy particularmente, la forestal. Por lo tanto, se trata de desarrollar herramientas y modelos que permitan estimar con cierta fiabilidad el potencial para la producción vegetal y forestal de estos territorios infrautilizados.

La temperatura es uno de los principales datos de entrada para sistemas de caracterización y evaluación territorial, y para muchos modelos hidrológicos y ecológicos. Estos modelos utilizan la temperatura para evaluar procesos como la evapotranspiración, la descomposición de la materia orgánica del suelo y la productividad vegetal (Dodson & Marks, 1997). Sin embargo, este tipo de variables no son fáciles de obtener ya que son medidas en puntos discretos: las estaciones meteorológicas. Como resultado se han desarrollado diferentes métodos de interpolación para generar mapas regionales a partir de datos puntuales, basándose en la continuidad de la temperatura y en su dependencia con la altitud (Barry & Chorley, 1987; Lutgens & Tarbuck, 1995) y posición geográfica (Goodale et al., 1998). Éstos pueden ser simples modelos matemáticos como la triangulación, el inverso de la distancia, polígonos de Thiessen, o modelos más

complejos como la regresión multivariante (Sánchez-Palomares et al., 1999; Ninyerola et al., 2000, 2005) y los modelos geoestadísticos (Hudson & Wackernagel, 1994; Ishida & Kawashima, 1993).

Por otra parte, los gestores del territorio hoy en día afrontan grandes retos como la necesidad de mantener la productividad del campo frente a una población mundial que no para de crecer, al tiempo que los recursos naturales están amenazados por el cambio climático, la desertificación, la contaminación ambiental o los incendios forestales, mientras que otros territorios son infrautilizados. Por todo ello, los bosques han adquirido un significado clave como refugio de biodiversidad, en la captura de C y como lugar recreo, pero a su vez han de tener una productividad que ayude a fijar y sustentar una población rural, en definitiva, han de integrarse en sistemas sostenibles. Incluir estas líneas en la investigación del mundo forestal implica la necesidad de buscar estimaciones más precisas de biomasa, de productividad potencial forestal y de tasas de crecimiento de los bosques (Tickle et al., 2001), así como de modelizaciones a diferentes escalas (paisaje, monte, rodal, etc.) y que a ser posible, tengan una fácil aplicabilidad para los gestores. A este respecto, un profundo conocimiento de la productividad forestal de un territorio es esencial para desarrollar planes y políticas forestales y de uso del suelo (Lansberg, 2003).

El objetivo de un primer trabajo (*Estudio 1*) es comparar diferentes modelos de predicción de temperaturas medias, en una región montañosa como es Asturias, en los meses de temperatura más extremos (enero y agosto) y con la única información adicional de la altitud. Se valoraron la bondad de diferentes aproximaciones geoestadísticas mediante una validación cruzada y se compararon con modelos multivariantes ya existentes. En concreto, estos modelos nos han permitido predecir las variables climáticas necesarias para estimar la productividad potencial forestal de Asturias, a través de un índice geocéntrico: el índice de Paterson (*Estudio 2*). De manera que con la ayuda de las técnicas geoestadísticas y a través de un GIS se revisó este índice tradicional de productividad potencial, aplicándolo a una zona montañosa como es Asturias, y por primera vez se compararon estos datos potenciales con datos reales de producción.

Material y métodos

Estudio 1

Los datos de partida son las temperaturas medias, de una serie de 30 años, de enero y agosto, registrados en las estaciones meteorológicas pertenecientes al Instituto Nacional de Meteorología localizadas en la provincia de Asturias y alrededores, y un modelo digital de elevaciones (DEM).

La Geoestadística comprende un conjunto de técnicas y estimadores que sirven para analizar y predecir valores de una variable que se distribuye en el espacio de manera continua. Estas técnicas han sido descritas amplia y rigurosamente en la literatura científica (Isaaks & Srivastava, 1989, Cressie, 1993). Las técnicas empleadas en este estudio fueron un *Ordinary Kriging* (OK) en el plano XY, y un OK con anisotropía zonal en el eje Z (OKxyz), un *Ordinary Kriging with External Drift* (OKED) y dos variantes del *Universal Kriging* (UK1 y UK2). A excepción de la primera, estos métodos utilizan una variable auxiliar para la estimación, en este caso la altitud (DEM). Todas estas técnicas, pasan por 3 pasos fundamentales: un estudio de la estructura espacial de la variable a través del semivariograma experimental (media de las varianzas entre pares de datos separados por una distancia determinada); el *kriging* propiamente dicho o predicción en los puntos no muestreados mediante estimadores que actúan de manera similar a los estimadores de regresión lineal, pero que además cumplen las condiciones de varianza mínima y son no sesgados; y por último, una validación cruzada que permita obtener dos estadísticos (Cressie, 1993): el Error Medio Normalizado (EMN) y la Raíz del Error Medio Normalizado al Cuadrado (REMNC) para conocer la bondad de nuestro ajuste.

Finalmente se compararon los errores de predicción de cada uno de los modelos con el error medio (EM) y el error medio absoluto (EMA) para comparar los distintos modelos, incluidos dos trabajos previos realizados con regresiones multivariantes en la Península Ibérica: uno de Sánchez-Palomares et al. (1999) (R1) y otro de Ninyerola et al. (2000) (R2).

Estudio 2

Se utilizó una variante del índice de Paterson (Paterson, 1956), revisado para la Península Ibérica con una corrección debida a la litología (Serrada, 1976;

Sánchez Palomares & Sánchez Serrano, 2000), para hallar la productividad potencial forestal (P):

$$P = C \cdot 5,3 \cdot \log\left(\frac{VfPG}{A12}\right) - 7,4 \quad [1] \qquad f = \frac{2500}{n + 1000} \quad [2]$$

Donde C es la corrección litológica (para lo que se utilizó un mapa de litología de Asturias 1:25.000), V es la temperatura media mensual del mes más cálido, A es la diferencia de la temperatura media máxima del mes más cálido y la temperatura media mínima del mes más frío, P es la precipitación anual, G es la duración del período vegetativo en meses, y f es el factor de insolación propuesto por Gandullo (1994) [2], siendo n el número de horas de sol al año. El número de horas se halló como una variante del modelo desarrollado por Kumar et al. (1997) para modelizar la radiación solar mediante un programa implementado en un GIS, y el resto de parámetros se estimaron aplicando las distintas técnicas geoestadísticas (*Estudio 1*) para modelizar las temperaturas medias y las precipitaciones mensuales.

A continuación se compararon los valores obtenidos con datos de productividad obtenidos a partir del III Inventario Forestal Nacional, y se analizaron los factores que contribuyen a las diferencias entre la productividad real y potencial.

Resultados

Estudio 1

Tras aplicar las 5 técnicas geoestadísticas, se obtuvieron los diferentes modelos (Figura 2 y 3) con sus errores estimados (Tabla 3).

Se observa un gradiente progresivo de temperaturas más frescas según nos desplazamos desde la línea de la costa hacia el sur (hacia las montañas). Comparando los modelos derivados de las distintas técnicas, se aprecian grandes diferencias entre el OK y el resto de técnicas que tienen en cuenta la altitud como variable auxiliar. Estas diferencias fueron mayores en invierno, cuando la correlación entre la temperatura media y la altitud es mayor.

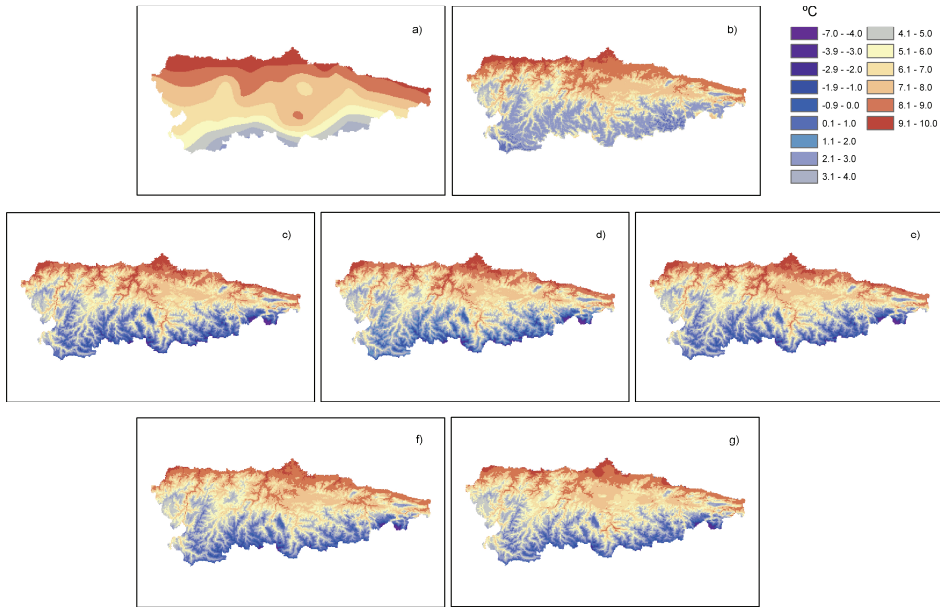


Figura 2. Modelos para la estimación de la temperatura media de enero: a) OK, b) OKxyz, c) OKED, d) UK1, e) UK2, f) R1, g) R2

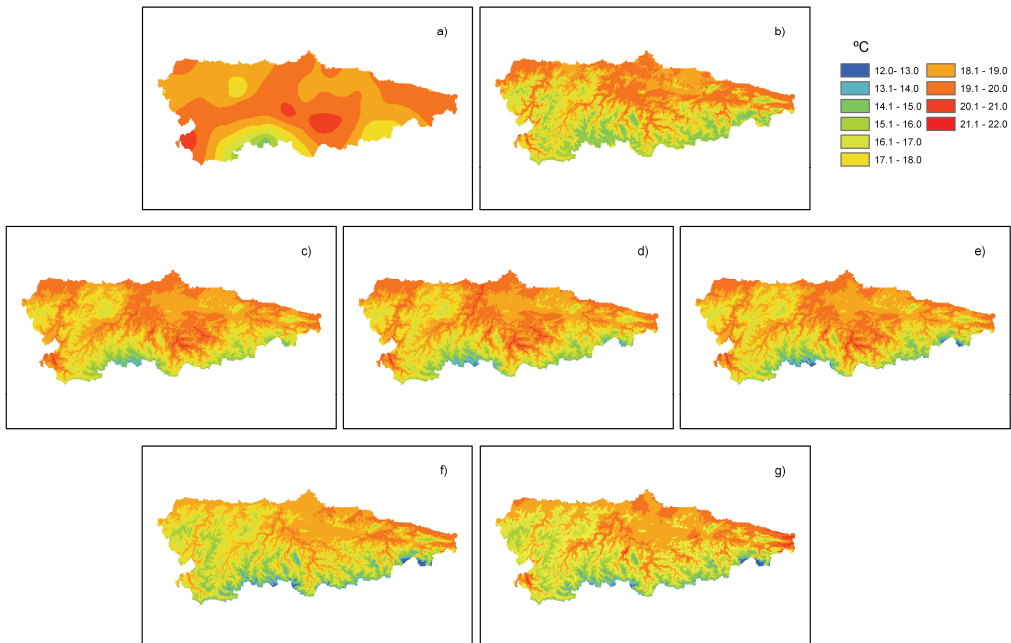


Figura 3. Modelos para la estimación de la temperatura media de agosto: a) OK, b) OKxyz, c) OKED, d) UK1, e) UK2, f) R1, g) R2

Tabla 3. Estadísticos resultantes de la validación cruzada: error medio normalizado (EMN) y raíz del error medio normalizado al cuadrado (REMNC), así como el error medio (EM) y el error medio absoluto (EMA), para las 5 técnicas geoestadísticas y los dos modelos multivariantes de Sánchez Palomares et al. (1999) (R1) y de Ninyerola et al. (2000) (R2)

		EMN	REMNC	Con todas las estaciones		Estaciones por encima de 600 m	
				EM	EMA	EM	EMA
Enero	OK	0,025	0,737	0,052	0,731	-0,386	0,788
	OK _{xyz}	0,003	0,320	0,018	0,668	0,100	0,678
	OKED	0,017	0,994	0,024	0,774	0,094	0,841
	UK1	0,011	0,996	0,020	0,791	0,026	0,881
	UK2	0,009	0,875	0,018	0,778	0,006	0,846
	R1			-0,087	0,796	-0,305	0,952
	R2			0,070	0,377	-0,029	0,147
Agosto	OK	0,016	1,190	0,029	0,788	-0,518	1,022
	OK _{xyz}	0,008	1,136	0,009	0,567	-0,012	0,638
	OKED	0,028	1,181	0,032	0,624	-0,225	0,762
	UK1	0,030	1,156	0,033	0,617	-0,111	0,734
	UK2	0,026	0,955	0,032	0,608	-0,055	0,755
	R1			0,232	0,640	0,025	0,552
	R2			-0,024	0,240	-0,096	0,152

Estudio 2

Al aplicarse el algoritmo [1], con los parámetros climáticos modelizados y el factor de corrección litológica revisado previamente, se obtuvo el modelo de productividad potencial forestal de la Figura 4a.

El análisis de varianza realizado con la producción obtenida en parcelas seleccionadas del III IFN (con las principales especies forestales de la región, con una fracción de cabida cubierta superior al 15%) mostró que en las zonas interiores y media montaña, el rango de producción no se diferenciaba significativamente de los rangos establecidos por el modelo de productividad potencial ($p < 0,05$), mientras que sí lo hacía en las zonas de costa y en una zona de alta montaña.

El análisis de correlaciones identificó los factores que influyeron en esta disparidad entre la productividad real para y la potencial, en concreto el tipo de especie (de crecimiento rápido *vs.* lento) ($\rho = -0.602^{**}$), la edad ($\rho = -0.537^{**}$) y sobre todo la densidad ($\rho = 0.803^{**}$), en definitiva factores de gestión. Además, existe una relación positiva entre especies de crecimiento rápido, clases diamétricas

bajas (edad de la masa joven) y densidades elevadas. De ahí, que en las zonas de costa donde hay más especies de crecimiento rápido, en especial *Eucalyptus globulus* Labill., es donde los valores reales superan los potenciales, mientras que en la única zona donde sólo se inventariaron especies de crecimiento lento con los criterios establecidos (zona montañosa), la productividad real quedó por debajo de la estimada como potencial.

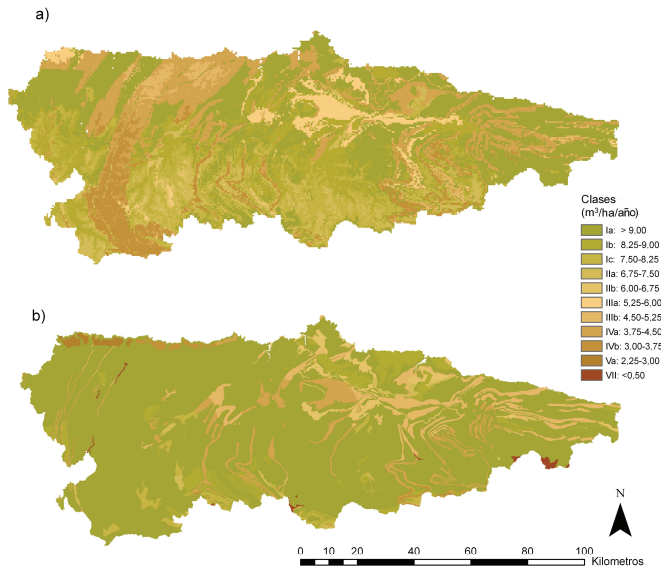


Figura 4. a) Modelo de productividad potencial forestal, b) Modelo de productividad potencial forestal por Sánchez Palomares y Sánchez Serrano (2000).

Discusión

Estudio 1

En términos generales, los estadísticos EMN y REMNC confirmaron que la predicción de los modelos son aproximadamente insesgados y que la predicción del error es bastante buena, dado que EMN se aproxima a 0 y REMNC a 1 (Cressie, 1993).

En este trabajo se aprecia que las predicciones para agosto presentan en general errores menores que las predicciones en invierno, lo que concuerda con los resultados obtenidos en otros estudios (Rolland, 2002). Así mismo, aparece diferente correlación entre la temperatura y la altitud en ambos meses, lo que también se ha observado en otros trabajos (Hudson & Wackernagel, 1994; Dodson & Mark, 1997). Por tanto no es sorprendente que los modelos que introducen la altitud como variable auxiliar den lugar a predicciones más exactas, porque como se sabe, la altitud juega un importante papel en los cambios espaciales climáticos

en zonas montañosas (Stoutjesdijk & Barkman, 1992). En este caso, tomando las estimaciones en zonas de montaña (altura por encima de los 600m) se aprecia como las técnicas que utilizan la altitud (OKED, UK1 y UK2) presentan errores de predicción menos sesgado (EM menor) que OK, probablemente debido a la menor existencia de datos (estaciones meteorológicas) en altitudes mayores, pero al incluir la variabilidad en el eje Z (OKxyz), parece resolverse el problema, obteniéndose los mejores resultados con esta técnica geoestadística en términos de errores absolutos. El modelo de regresión R1 mostró un fuerte sesgo suavizando las temperaturas extremas, mientras que el modelo R2 mostró las mejores predicciones en términos de error absoluto. Sin embargo, este último presentó estimaciones más sesgadas que OKxyz y UK2.

Estudio 2

El modelo obtenido con las nuevas técnicas, comparado con el modelo anterior de Sánchez Palomares & Sánchez Serrano (2000) (Figura 4.b.), presenta un mapa más detallado de la productividad potencial ya que utiliza datos litológicos a una escala más precisa. Además, el modelo anterior no ha tenido en cuenta el gradiente altitudinal que se da en la modelización de las variables climáticas, conociendo la importancia que éstas tienen sobre el crecimiento vegetal (Lansberg & Waring, 1997; Ni 2004).

Este modelo basado en el índice de Paterson, ha sido tradicionalmente de gran ayuda para los gestores de las masas forestales en la Península. Su incorporación a la toma de decisiones es un importante logro al que muchos modelos aspiran y no consiguen (Battaglia & Sands, 1998). Pero a pesar de su utilidad demostrada, su validación es una tarea complicada debido a la falta de conocimientos o datos adecuados para verificar la productividad potencial. Es difícil separar los efectos de la densidad, la edad, la estructura de la masa, la especie y el medio sobre los datos de crecimientos por parcelas, en especial cuando es una masa mixta o irregular (Milner et al., 1996). Además, la estimación de variables ecológicas en zonas montañosas como la nuestra suele ser más compleja que en zonas llanas, incluidas las características edáficas que pueden estar muy alejadas de las esperadas según la litología.

La existencia de una correlación significativa entre nuestro modelo y los datos del inventario ($\rho=0.203^{**}$), reflejan que nuestro modelo estima de manera aceptable las productividades potenciales del medio. Sin embargo, la pequeña

varianza explicada refleja las dificultades para predecir la productividad real a partir de la potencial.

Conclusiones

Del primer estudio se concluye que las técnicas geoestadísticas pueden ser utilizadas con una precisión aceptable para la modelización de variables climáticas continuas como la temperatura, especialmente el *Ordinary Kriging* estimado en los ejes XYZ con anisotropía en la dirección del eje Z. Todo ello a pesar de tener una fuente de datos iniciales escasa, dispersa e irregular, como ocurre en zonas montañosas, y de una manera más sencilla que otros métodos multivariantes que requieran un gran esfuerzo computacional y de tiempo.

Del segundo estudio se concluye que con la utilización de nuevas técnicas (geoestadísticas, GIS) puede obtenerse un mapa mejorado de productividad potencial basado en un índice tradicional. Además, a pesar de sus limitaciones, este modelo permite definir las áreas de producción a escala regional independientemente de la existencia de árboles, de las características de las especies existentes y la gestión que se esté llevando a cabo, así como evaluar el estado actual de las masas forestales. En definitiva, un modelo muy útil para la toma de decisiones de los gestores en la planificación territorial.

Discusión General

Con la ayuda de las nuevas técnicas, se ha obtenido un modelo de productividad potencial forestal para Asturias. Es un modelo que a pesar de sus limitaciones permite definir áreas en función de la producción y, que a su vez, pueden ser de gran ayuda para la planificación territorial.

De esta manera, se propone una gestión principalmente forestal para aquellas zonas con mayor productividad forestal, sin olvidarse de la búsqueda de su sostenibilidad y de la conservación de la biodiversidad. Es importante que se utilice la especie y el método de gestión adecuados, desde un punto de vista productivo y ambiental. La introducción de ganado en estas masas forestales, puede utilizarse para reducir la competencia con el estrato herbáceo cuando las plantaciones sean jóvenes, siempre y cuando el daño del ganado sobre la plantación esté controlado; o también puede tener lugar tras aclareos u otras prácticas selvícolas que permitan mayor crecimiento del pasto. Por otra parte,

estos territorios tan productivos, coinciden en gran medida con aquellos que presentan una topografía más suave y a menor altitud, por lo que también pueden ser aprovechados por cultivos, en especial, forrajeros.

En zonas con alguna limitación para el crecimiento de arbolado se propone el uso de sistemas silvopastorales como estrategias de gestión. De manera que, según disminuye la potencialidad forestal, un aumento del uso ganadero puede suponer un aprovechamiento más eficiente y productivo de los recursos, para ello se requiere un control de la cubierta forestal (desarrollo de copas, densidad) para asegurar un determinado crecimiento del pasto. Estos sistemas pueden ser muy diversos según la especie animal, su manejo (raza, carga ganadera, tipo de rebaño, etc.), los árboles utilizados y su estructura (espaciados regularmente, en mosaico, en bosquetes, en plantaciones lineales, etc). Todo ello dependerá de los objetivos de la producción y del medio en el que nos encontremos.

En aquellas zonas donde la productividad forestal sea baja, se plantea la ganadería como principal actividad productiva y como herramienta de gestión del paisaje. En concreto, en Asturias, muchas de estas zonas menos fértiles o con suelos poco profundos, coinciden con el área de extensión de los brezales. Los resultados de nuestros experimentos han mostrado el diferente comportamiento de pastoreo de los rumiantes domésticos, cuyo manejo adecuado puede llevar a una eficiente gestión de estos recursos naturales. En concreto, parece que es el ganado ovino la especie con mejores resultados productivos en brezales-tojales parcialmente mejorados. Si además son manejados en pastoreo mixto con caprino, el manejo será más eficiente y el más aconsejable para alcanzar sistemas sostenibles desde el punto de vista de producción animal y de uso de los recursos en estas comunidades.

Finalmente, las zonas con severas limitaciones productivas deben ser manejadas principalmente con estrategias de conservación, de manera que cualquier sistema productivo debe estar supeditado a contribuir con su conservación.

Conclusiones Finales

1. La zona de estudio es un ejemplo de área rural desfavorecida en abandono. La gente joven emigra en busca de más y mejores oportunidades, con el consiguiente envejecimiento y menor preparación de la población que queda.

2. La región en estudio tiene una tradición ganadera que ha supuesto durante siglos una continua deforestación de muchas áreas. En la actualidad, con el abandono de las actividades agrarias, estas zonas están siendo ocupadas por matorral (especialmente brezales), que a su vez, aumentan el riesgo de incendios y de erosión.
3. Los sistemas silvopastorales se presentan como una buena opción para una gestión sostenible. La elección de la especie animal y del sistema de producción dependerán del medio y de los objetivos prioritarios de la explotación. La gestión de la cobertura forestal (especie/clon adecuados, densidades bajas y podas o trasmoches) también tiene una gran importancia en el buen desarrollo del sistema.
4. Durante los 5 primeros años tras la plantación de los árboles, los efectos sobre el pasto herbáceo son casi imperceptibles, independientemente de la especie.
5. Durante la primera parte de la rotación, si se mantienen densidades de arbolado bajo, los efectos sobre el pasto herbáceo serán pequeños. Aun así, los efectos de los árboles caducifolios parecen ser menores, o más retrasados que los que provocan los perennifolios. Por ejemplo se estimaron descensos en la producción del pasto con la presencia chopos del 10-20%, y de 20-40% con pino radiata, ambos a 100 pies ha⁻¹.
6. Con incrementos en la densidad y/o la edad del arbolado (segunda mitad de la rotación), la reducción en la producción del pasto se agudiza drásticamente, especialmente con coníferas, cuyas acículas caídas contribuyen al descenso del crecimiento del pasto.
7. Si el grado de sombra aumenta, también se detectan cambios en la composición del pasto, produciéndose una pérdida de la calidad al disminuir la cantidad de leguminosas como el trébol y algunas gramíneas como el raigrás; e incrementándose la materia muerta y otras gramíneas de menor valor nutritivo como el holco.
8. Para el desarrollo de sistemas sostenibles, se confirma la recomendación de establecer áreas de pasto mejorado (implantado) en los brezales para que los animales en producción cubran sus necesidades nutricionales.
9. Se detectaron diferencias en la conducta de pastoreo de las tres especies de ganado estudiadas. El vacuno y el ovino mostraron una clara preferencia por

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- el pasto mejorado, mientras que el caprino exhibió una alta capacidad de utilización del matorral.
10. La presencia de cabras puede por tanto llevar a un mayor control de la invasión del matorral (disminuyendo la acumulación de biomasa), posibilitando a su vez una mayor presencia de herbáceas.
 11. El ganado ovino presentó la mayor producción a lo largo de toda la estación de pastoreo, manteniendo ganancias de peso a pesar de la reducción en la disponibilidad del pasto a lo largo de la estación.
 12. Dada la complementariedad entre el caprino y el vacuno u ovino, los rebaños mixtos pueden ofrecer una buena alternativa para una gestión más eficiente de los recursos del medio. En concreto, los rebaños mixtos de ovino y caprino, son la opción más eficiente y productiva en brezales parcialmente mejorados con la implantación de pastos.
 13. A pesar de la escasez, irregularidad y dispersión de los datos, los modelos obtenidos con técnicas geoestadísticas presentan una precisión aceptable para modelizar la temperatura en zonas montañosas. En especial, aquellos que utilizaron la altitud como variable auxiliar, como el *Ordinary Kriging* con anisotropía en el eje Z.
 14. La modelización de variables ecológicas a través de estas técnicas pueden resultar muy útiles para el desarrollo de otros modelos más complejos. En este caso, el uso de estas técnicas junto con la utilización de SIG, han servido para mejorar un modelo de productividad potencial forestal utilizado tradicionalmente por los gestores forestales.
 15. Este modelo es muy útil para la planificación territorial ya que permite definir zonas con mayor potencial productivo, independientemente de la gestión que se esté llevando en la actualidad, y además puede servir de referencia para evaluar el estado actual de la masa.
 16. El problema de la producción sostenible en áreas marginales y tan heterogéneas como las estudiadas ha de ser abordado necesariamente desde un enfoque multidisciplinar y un profundo conocimiento del medio.

2. Summary

An important proportion of the countryside of the Northern Iberian mainland is covered by shrublands. In particular, 212,147 ha of the surface of Asturias are covered by this type of vegetation, most of them (21% of the total surface area) are heathlands (Álvarez et al., 2004), ericaceous shrubs mainly originated by human activity over the centuries such as forest clearances, grazing introduction, burning, turf cutting and firewood gathering (Calvo et al., 2002; Webb, 1998).

Nowadays, heathlands in Northern Spain are actually widespread (Díaz, 1998) as a consequence of the underutilisation of the resources. The abandonment of agricultural and livestock managements since the 1950s has led to this spread of heathlands, particularly where the land is more infertile and erodible and where the succession to forests is restricted by soil thickness and fertility, as well as by frequent fires. Hence, many of these shrublands comprise rural areas in state of abandonment with low productivity, thus marginal or less-favoured areas.

The search for sustainability of these less-favoured areas requires a multidisciplinary approach with new land use strategies or plans in order to manage these large and underutilised areas. Therefore, a wide knowledge of different topics (soil, pastoral, silvopastoral, forestry, socioeconomic analysis) is required, involving the incorporation of new techniques or components into the planning and management of agrarian systems in order to attain the desired environmental and economic objectives.

Bearing this in mind, the general objective of this work is **to place a renewed value on these less-favoured and abandoned lands covered by heathlands in the Northwestern Spain, specifically in Asturias**. Particularly, four main complementary topics will be focused in this thesis in order to achieve this main target:

1. Review of silvopastoralism in temperate regions: effects of evergreen and deciduous trees on pasture dynamics. Experiences in New Zealand.

New Zealand is a pioneer country in the study of silvopastoral systems in temperate regions, with prolific scientific production in relation to the introduction of wide-spaced trees on farms, mainly *Pinus radiata* and *Populus* spp.

2. Analysis of the current socio-economic and agrarian scenario.

An understanding of the socio-economic scenario in the study area is crucial, especially in the so-called less-favoured areas. We need to know about the financial and human resources as well as the characteristics of the population and the land (structure of farms).

3. Pastoral management in heath and gorse communities.

To develop sustainable silvopastoral systems in such less-favoured areas covered by heathlands, it is essential to understand the grazing behaviour of domestic herbivores and their overlap. In this respect, two trials have been carried out in order to better understand:

- The grazing behaviour and performance of cattle and sheep when are managed under single grazing *vs.* under mixed grazing with goats in partially improved heath and gorse communities.
- The grazing behaviour of domestic ruminants: cows, ewes and does grazing all together in partially improved heathlands.

4. Tools for land use planning.

Another key aspect in the development of silvopastoral systems is the utilisation of tools to assess the productive potential of land as well as for the land use planning. It is evident that the characteristics of sites will differ significantly from one site to another and may limit the vegetal production, including forest productivity. For this reason, the last chapter comprises two studies in which the usefulness of different models and tools for estimating vegetal production in these abandoned and underutilised areas is evaluated:

- Different geostatistical techniques are compared to check their usefulness in modelling ecological variables. In particular, they are tested using a climate variable related to plant productivity: air temperature.
- These previously tested techniques are used to model the inputs required in order to spatially estimate the (potential) site productivity of forested areas, based on a geocentric index.

3. General Introduction

A large proportion of the countryside of the Iberian mainland is covered by shrublands, exceeding the million of hectares only in the Cantabrian provinces (Ministerio de Agricultura, Medio Rural y Marino, 2008). In particular, 212,147 ha of the surface of Asturias are covered by this type of vegetation. Most of these are heathlands (21% of the total surface area) (Álvarez et al., 2004), ericaceous shrubs mainly arising as a result of human activity over the centuries such as forest clearances, the introduction of grazing, burning, turf cutting and firewood gathering (Calvo et al., 2002; Webb, 1998). Heathlands cover large areas of the Atlantic regions of Western Europe with acidic and poor soils (Webb, 1998). During the last century, in most of the natural distribution area, heathland areas have decreased dramatically, mainly due to the replacement of traditional livestock farming with intensive systems (overgrazing, agricultural transformation) (Thompson et al., 1995; Alonso, 2004; Britton et al., 2005) and eutrophication (Diemont et al., 1996; Webb, 1998). In contrast, heathlands in Northern Spain are actually widespread (Díaz, 1998) as a consequence of the underutilisation of resources. The abandonment of agricultural and livestock managements since the 1950s has led to this spread of heathlands, particularly where the land is more infertile and erodible and where the succession to forests is restricted by soil thickness and fertility, as well as by frequent fires. Hence, many of these shrublands comprise rural areas in state of abandonment with low productivity, thus marginal or less-favoured areas.

Land use strategies or plans need to be implemented in order to manage these large and underutilised areas, in a sustainable way. Therefore a varied mix of financial, social and environmental goals must invariably to be set out. The new plans should contribute to increase the standard of living of their inhabitants in these areas, generating employment, labour opportunities, increasing the income level and improving services, etc. However, landscape and environmental aspects should be also considered. Due to the large accumulation of biomass in these underutilised communities, the likelihood of wildfires increases significantly, especially since these shrublands are characterised by high

combustibility and flammability (Núñez-Regueira et al., 1996; Marquínez et al., 2003). This is becoming a serious problem, particularly in hilly areas as recurrent fires leave the soil unprotected against erosion, with high environmental and economical losses (Ministerio de Medio Ambiente, 2007). Moreover, this situation poses a serious threat to the conservation of the natural resources and in turn, to the rural development in these marginal, less-favoured areas (Hadjigeorgiou et al., 2005).

Rural managers are faced with an increasingly complex decision making environment, particularly in these communities characterised by low productivity (Mosquera-Losada et al., 2000; Osoro et al., 2007a). The search for sustainability in these less-favoured areas requires a systemic approach (Bertomeu García, 2007) with a wide knowledge of different topics (soil, forestry, pastoral, silvopastoral systems, socioeconomic scenario) that involves the incorporation of new techniques or components into the planning and management of agrarian systems in order to attain the desired environmental and economic objectives.

Silvopastoral rationale

Silvopastoral systems are multipurpose systems aimed towards achieving an increased and more efficient use of resources. Thus, such systems may save rural areas from abandonment and enhance profits from the land (Rigueiro-Rodríguez et al., 2005b), two objectives implicit in the definition of sustainability. These systems provide additional benefits to those afforded by one-objective systems. Apart from the evident environmental externalities, such as the aesthetic improvement of farm landscapes, the provision of a tool for fire prevention, the increase in structural and biological biodiversity, consolidation of erosion-prone hill country, and both shade and shelter (and consequent welfare) for livestock, the economic impact of these diversified systems is arguably the most important reason for their adoption by farmers and land owners. Economic studies have inferred financial benefits (in comparison with monocultures) only with appropriate tree species and managements programs, such as those carried out in the southern United States by Grado et al. (2001) and Husak et al. (2002), or in New Zealand by Thorrold et al. (1997).

Silvopastoral systems have been widely studied in the Mediterranean part of Spain. 'Dehesas' are thousand-year-old silvopastoral systems that have

attracted the attention of scientists due to their significance in terms of biodiversity as well as their cultural and economic importance (González Bernáldez et al., 1969; Marañón, 1986; Puerto & Rico, 1988; Joffre & Rambal, 1993; Gallardo et al., 2000; Moreno et al., 2007). However in the Atlantic regions of Spain, scientific interest in silvopastoral systems is quite recent, and the number of trials is very limited. Some forest grazing trials were developed in the Basque Country (Albizu et al., 2000, 2001) to evaluate the effect of fertilization on pasture production beneath *Pinus radiata* stands. However, the most extensive research on the topic has been carried out in Galicia. This research has mainly focused on grazing forest under fast growing species such as pine (*Pinus radiata* D. Don, *Pinus pinaster* Ait.) and eucalyptus stands (*Eucalyptus globulus* Labill.), which are the most extensive plantations in Galicia, managed at high stocking rates to maximise pulp and timber production. Trials have been conducted to evaluate the effect of livestock on the understorey biomass with the aim of reducing the risk of forest fires in such woodlands (Rigueiro-Rodríguez et al., 2005a). Other experiments have been more concerned with the effects of fertilization effects on pasture productivity under these plantations (Mosquera-Losada et al., 2006; López-Díaz et al., 2007; Rigueiro-Rodríguez et al., 2007). Therefore, other avenues of investigation, already explored in other regions, have not as yet been developed in this area, such as the introduction of wide-spaced trees to non-wooded grazing areas in order to provide fodder, shade/shelter, erosion control and quality timber purposes (Dupraz & Newman, 1997; Hawke & Knowles, 1997; Douglas et al., 2006a).

Pastoral management

In a farming context, heathland dynamics must be appraised in conjunction with an adequate knowledge of livestock performance and management. Due to the aforementioned low productivity of heathlands (Mosquera-Losada et al. 2000; Osoro et al., 2007a) caused by the poor nutritive value of the dominant woody species for grazing livestock, several studies have suggested that by establishing adjacent areas of improved pasture, usually of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), to meet the nutritional requirements of livestock, the total yields in heathlands can be increased (Hodgson & Eadie, 1986; Osoro et al., 1999). Furthermore, in some

heathland areas, controlled burning or mechanical clearing is carried out to reduce the encroachment of woody plants such as heather species (*Erica* spp, *Calluna vulgaris*) and gorse (*Ulex* spp), thus increasing the presence of herbaceous species and helping prevent bush fires (Calvo et al., 2002; Jáuregui et al., 2007). However, the benefit of such investment procedures will depend on the posterior grazing management (livestock species and breed, single or mixed grazing, stocking rate, etc.).

Animal species display different foraging behaviour due to their different eco-physiological adaptations (mouth and dental anatomy, digestive capacity, etc.), and therefore their ability to exploit the available plant resources varies (Hofmann, 1989; Illius & Gordon, 1993). Many trials in which the grazing habits of cattle have been analysed, have shown that they hardly consume woody plants (Aldezabal, 2001; Celaya et al., 2007b). In contrast, small ruminants like sheep or goats are able to select more efficiently the green shoots of these shrubs, complementing their diet when the availability of green herbaceous pasture is reduced (Grant et al., 1984; 1987). Nevertheless, differences between sheep and goats can be appreciated. Sheep are able to graze on very short swards without reducing the level of intake below their maintenance needs (Osoro et al., 2000c) whereas goats are browser species that utilise woody plants at a higher degree than the former (Lu, 1988; Narjisse, 1991).

In addition, the levels of complementarity between the domestic ruminant species in their grazing behaviour will affect the productivity and sustainability of the systems, particularly in these heterogeneous resources. Other studies have already suggested the complementary use of goats in order to increase the effective utilisation in partially improved heathlands grazed by cattle or sheep (Allan & Holst, 1996), i.e. reducing the encroachment of shrubs and controlling the re-growth of invasive plants like gorse (Radcliffe, 1985; Celaya et al., 2007a), as well as diversifying the production.

Therefore, the utilisation of different animal species and different types of flock management may promote different vegetation dynamics that will affect subsequent animal performance and the sustainability of extensive grazing systems for meat production.

Implementation of spatial modelling in decision support

The demand for multiple objective land use planning requires that sufficient information be made available to the rural land managers to enable them to explore the options and the impacts of alternative land use strategies (Matthews et al., 1999). It is obvious that the characteristics of soils, the climate, the topography, etc. differ significantly from one site to another and may limit the vegetal production, and therefore the agrarian systems, including stockbreeding, forestry or silvopastoral systems. In this respect, advances in computer technology, particularly in relation to Geographic Information Systems (GIS), remote sensing and statistics, have increased the scopes of spatial data analysis and ameliorated the difficulties imposed by temporal and spatial heterogeneity across landscapes.

Spatially modelled ecological variables (temperature, rainfall, soil characteristics, vegetation, etc) can be very useful as inputs to the different site evaluation and characterisation systems, as well as hydrological, ecological and productive models. They can also be useful to assess the impact of human actions on the landscape (Tappeiner et al., 1998) or the implications of different management strategies (Bravo & Díaz-Balteiro, 2004; Rodríguez Soalleiro et al., 2000). However, these variables are not always easy to obtain because they appear as measurements at discrete points (samplings). Consequently, many different methods, indices and algorithms implemented in GIS are currently being developed to model and predict the spatial distribution of these variables and generate regional maps from point data, supporting land use planning and aiding rural managers to make appropriate decisions.

4. Objectives

The general objective of this work is **to place renewed value on these less-favoured and abandoned lands in Northwest Spain, specifically in Asturias, covered by heath and gorse communities.** With this main objective in mind, this thesis will particularly focus on four main complementary topics:

5. Review of silvopastoralism in temperate regions: effects of evergreen and deciduous trees on pasture dynamics. Experiences in New Zealand.

New Zealand is a pioneer country in the study of silvopastoral systems in temperate regions, with prolific scientific production in relation to the introduction of wide-spaced trees on farms, mainly *Pinus radiata* and *Populus* spp. Scientists are also managing to convince farmers to implement all the scientific improvements to the systems and increase production on the farms, thus providing the necessary feedback to facilitate improvements to the systems and increase production on the farms. Despite the lack of subsidies, New Zealand farms are examples of productive agrarian systems, due to their important contribution to the state economy.

Therefore, it is clearly of great interest to review the work of the New Zealanders. Their knowledge could prove extremely valuable, particularly if one considers the similarity between the New Zealand climate and that of Northern Spain as well as the fact that the main species they used are also present in Spain.

6. Analysis of the current socio-economic and agrarian scenario.

An understanding of the socio-economic scenario in the study area is crucial. We need to know about the financial and human resources as well as the characteristics of the population and the land (structure of farms).

Knowledge of other markets and opportunities is also important when trying to manage land use, especially in the so-called less-favoured areas.

7. Pastoral management in heath and gorse communities.

To develop reliable and sustainable silvopastoral systems in such less-favoured areas covered by heathlands, it is essential to understand the grazing behaviour of domestic herbivores and their overlap. In this respect, two trials have been carried out in order to better understand:

- The grazing behaviour and performance of cattle and sheep when are managed under single grazing *vs.* under mixed grazing with goats in partially improved heath and gorse communities.
- The grazing behaviour of domestic ruminants: cows, ewes and does grazing all together in partially improved heathlands.

8. Tools for land use planning

Another key aspect in the development of silvopastoral systems is the utilisation of tools to assess the productive potential of land as well as for the land use planning. It is evident that the characteristics of sites will differ significantly from one site to another and may limit the vegetal production, including forest productivity. For this reason, the last chapter comprises two studies in which the usefulness of different models and tools for estimating vegetal production in these abandoned and underutilised areas is evaluated:

- Different geostatistical techniques are compared to check their usefulness in modelling ecological variables. In particular, they are tested using a climate variable related to plant productivity: air temperature.
- These previously tested techniques are used to model the inputs required in order to spatially estimate the (potential) site productivity of forested areas, based on a geocentric index.

5. Silvopastoralism in New Zealand: review of effects of evergreen and deciduous trees on pasture dynamics

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Abstract

Complex interactions between livestock, trees and pasture occur in silvopastoral systems. Between trees and pasture, competition for soil resources (nutrients and water) occurs, becoming especially relevant when one of them is in scarce supply. Trees reduce light and water reaching the understorey layers according to tree density and canopy size. However, they may ameliorate extreme climatological values (reducing wind speed and evapotranspiration, and alleviating extreme temperatures), and improve soil properties, for example, deciduous tree litter may contribute to increased pH and soil nutrient concentrations. During tree establishment, there are generally negligible effects on pasture, irrespective of tree type. However, there is a decline in pasture production and nutritive value under shade with increasing tree age and higher stocking rate. Under the same conditions, deciduous trees affect pasture later (extinction point of pasture occurs at 85% of canopy closure) than evergreen trees (about 67% for *Pinus radiata* D. Don). This is mainly because deciduous trees have a leafless period that enables pasture recovery, and their litter smothers pasture less intensely because of its relatively fast decomposition. Silvopastoral studies conducted in New Zealand are reviewed to discuss these effects, and differences in the effects of evergreen and deciduous trees are shown using the

examples of *P. radiata*, and *Populus* and *Salix* spp., respectively, which exist in many temperate countries. Future research needs are outlined.

Keywords: Botanical composition; Management; Pasture responses; Shade; Soil properties; Yield.

Introducción

New Zealand is a pioneering country in the study of silvopastoral systems (syn. agroforestry, 2-tier farming) in temperate regions. These systems were first recognised in 1969 as a potentially profitable land use, and since then, many trees of several species have been established on farms (Hawke & Knowles, 1997).

Silvopastoral systems originated as a component of forestry management. Livestock were introduced in the early stages of establishment of plantations (mostly with *Pinus radiata* D. Don; common name radiata pine) for sawlog regimes, to utilise the pasture growing beneath trees (Hawke & Knowles, 1997). Simultaneously, competition between the new tree seedlings and weeds was controlled (Hawke & Knowles, 1997), financial returns were obtained earlier from the livestock enterprise than from forestry, and the land use and production could be more efficient and diversified (Fenton et al., 1972, quoted by Knowles, 1991). Currently, more than 1.6 million ha in New Zealand are planted with *P. radiata* (Ministry of Agriculture and Forestry, 2006). These stands are pruned and thinned in order to obtain good quality timber, and when stocking rates are low, pasture production increases and silvopastoralism is possible. During the 1980s and 1990s, numerous studies were conducted to determine the effects of this evergreen tree species on the micro-environment and pasture characteristics within silvopastoral systems (Percival et al., 1984a; Percival & Knowles, 1988; Hawke & Wedderburn, 1994).

The economy of New Zealand is mainly underpinned by livestock grazing of developed pastures (Wilkinson, 1999). On pastoral hill country, in particular, soil erosion can severely limit pasture production which affects the potential area of grazing land, and threatens the sustainability of pastoral farming enterprises on affected landscapes (Douglas & Trustrum, 1986; Hicks 1992; Hicks, 1995). It is estimated that about 28% of New Zealand's land area requires significant soil conservation measures (Mead, 1995), and in a number of areas supporting pasture, wide-spaced conservation tree planting is the preferred technique

(Pollock et al., 1994; Mead, 1995; New Zealand Poplar Commission, 1995). During the 1960s and 1970s, over 2 million *Populus* spp. (poplar) were planted in erosion control schemes, but this planting rate declined later because of the increased emphasis towards introducing *P. radiata* (Wilkinson, 1999). There has been renewed interest in *Populus* crops, together with *Salix* spp. (willow) and other species (Wall et al., 1997a; Guevara-Escobar, 1999; Power et al., 2001; Douglas et al., 2006a) because of their suitability for establishing in the presence of grazing livestock (with protection) on unstable hillsides with pasture covers. *Populus* spp. are easy to propagate vegetatively, grow rapidly, have extensive root systems, are tolerant of flooding, and their foliage is of acceptable nutritive value to grazing livestock (Wilkinson, 1999).

The choice between using evergreen (*P. radiata*) or deciduous (*Populus* spp. and *Salix* spp.) trees in agroforestry systems depends largely on the primary objectives of the farm business and its characteristics and enterprise mixes, although other factors such as vista enhancement, effects on macro- and micro-fauna, and personal preferences may also be influential. This paper reviews the literature on the effects of widely spaced (approximately under 200 stems per hectare) evergreen and deciduous trees on the environment (microclimate and soil properties) and pastures (yield and quality) in silvopastoral systems, and identifies knowledge gaps and areas for future research. It focuses on systems in New Zealand, but includes some literature from elsewhere to show similarities and differences in approaches, and to support statements on some aspects such as environmental effects and responses.

Effects of trees on the environment

The presence of trees in grasslands alters the local environment (Percival et al., 1984b; Hawke & Wedderburn, 1994; Guevara-Escobar et al., 2002, 2007; Douglas et al., 2006b). The effects on microclimate caused by both evergreen and deciduous trees follow the same trends because they are related to the physical existence of trees, although they can vary in intensity according to the different characteristics of the species. Conversely, in the case of soil properties, attributes may change dramatically with species because they are more related to the chemical properties of the tree debris.

Effects on the microclimate

Light

One of the main factors affecting the productivity of pasture in silvopastoral systems is light interception by the trees, above all when water and soil nutrients are freely available (Ong et al., 1996; Power et al., 2001). This has been widely corroborated, both with *P. radiata* stands (Anderson & Batini, 1979; Hawke & Knowles, 1997) and with *Populus* trees (McElwee & Knowles, 2000; Guevara-Escobar et al., 2007). A reduction in the quantity and quality of light directly affects the physiological processes of plants, decreasing pasture carbohydrate manufacture and net dry matter production (Sanderson et al., 1997; Wall et al., 1997b; Peri et al., 2007). However, a reduction in light does not lead to a proportional decrease in vegetative growth because compensatory responses occur in plant morphology and biochemistry (Solangaarachchi & Harper, 1987; Wall et al., 1997b). The production of more chlorophyll per leaf, the development of fewer leaves, but thinner and larger (increasing leaf area), and longer stems, petioles and internodes, are some of the changes found in shaded plants.

The intensity of light under trees depends on their spacing (Wall et al., 1997a, 1997b) because increasing tree density results in increasing shading. Hence, the light transmitted in a stand of *P. radiata* aged 7 years was 81% of that in open pasture (without trees) at 100 stems per hectare (sph), and 69% at 300 sph (Anderson & Moore, 1987). A reduction in solar radiation was also recorded beneath stands of other coniferous species such as *Picea sitchensis* (Bong.) Carr. with figures ranging from 68.9% to 22.7% of the solar radiation in open pasture at 156 sph and 625 sph, respectively (Sibbald et al., 1991). Similarly, Wall (2006) showed an inverse relationship between the radiation that passes directly through canopy gaps between widely spaced *Populus* and different stand density indices tested, especially the canopy closure ratio (the percentage of shaded points under a canopy).

The canopy structure of trees is another relevant factor in competition for light. It varies with tree age and species, although silvicultural treatments (pruning and thinning operations) may partially modify it. During tree establishment, canopy structure of *Populus* spp. has negligible effect on intercepted light (Guevara-Escobar, 1999; Guevara-Escobar et al., 2007) and in *P.*

radiata stands at different stocking rates, structure has minimal effect on solar radiance reaching the understorey during the first four years (Anderson & Moore, 1987). Wall (2006) found a higher percentage of incident photosynthetically active radiation (PAR) under *Populus* aged 5 years than under trees aged 25-30 years, because as trees grow, the overall interception by their crowns increases and less solar radiance reaches the understorey. Furthermore, light penetration varies with different species or clones because of their different architecture: height, size of the crown, branch numbers and distribution, foliar density, leaf area and angle, reflectance characteristics (De Reffye et al., 1995; McAdam, 1996), and because of seasonal variation in foliation (evergreen *vs.* deciduous species). In an experiment to determine the impact of shading duration on pasture growth (Power et al., 2001), an effective advantage in pasture yield recovery of deciduous trees over evergreen species occurred when the leaf-free period was longer than 4 months. Consequently, the extinction point (threshold where pasture plants can not compensate for the lack of light and are excluded by trees) estimated in New Zealand for a deciduous species such as *Populus* is 85% of canopy closure (McElwee & Knowles, 2000) compared with 67% for *P. radiata* (Knowles et al., 1997).

Significant differences in light distribution pattern occur between different distances from the tree trunk and between tree aspects e.g. north *vs.* south, and consequently in silvopastoral systems, understorey plants experience fluctuations in irradiance from full sun to shade (Peri et al., 2002b). For deciduous trees, differences also vary with season because leaves are considered to be responsible for approximately 69% of shaded area (McElwee & Knowles, 2000). In trials conducted in wide-spaced *Populus*-pasture systems, during winter, canopy closure without leaves measured at different densities did not exceed 50%, and the relationship between PAR transmission and canopy closure reduced at the centre of a vertically projected gap (Wall, 2006). In summer, Douglas et al. (2001) recorded a reduction in solar radiance of 31% beneath *Populus* at 25-100 sph (aged 8-11 years), compared to open pasture, while in winter, the reduction was 9%. In this experiment, it was also found that the south side (shaded side in southern hemisphere) received 14% less solar radiation than the north side. Similar trends were recorded by Gilchrist et al. (1993), McElwee and Knowles (2000), and Douglas et al. (2006b).

Water

In temperate regions, competition for water is usually the other main factor that limits pasture growth (Peri et al., 2002a), particularly in places with droughts in summer, when highest temperatures and incident radiance are recorded. Soil water deficits result in a reduction in dry matter yield of forages primarily by limiting leaf area development, and photosynthesis is reduced because of stomatal closure (Sanderson et al., 1997). The relationship between rainfall, soil water content (SWC), water uptake by plants, and evapotranspiration, is complex and varies seasonally.

When trees are present, less rain falls on the understorey because some of it is intercepted by tree canopies and it partly evaporates (Guevara-Escobar et al., 2000; Douglas et al., 2001; McIvor et al., 2003). Thus, the percentage of rainfall reaching the pasture understorey depends largely on tree stocking rate and crown size. Rainfall received has been 34%, 24%, 10% and 6% lower beneath *Populus* stands at 37 sph (aged 29 years), 25-100 sph (8-11 years), 44-16 sph (15 years) and 156 sph (6 years), respectively, compared to open pasture.

Soil water content is affected by season (Yanusa et al., 1995; Guevara-Escobar et al., 1997; Douglas et al., 2006b). When rainfall exceeds evaporative demand, SWC is not or hardly affected by ground cover (Yanusa et al., 1995). However, when evapotranspiration increases during summer, ground cover may significantly influence SWC. A number of studies have shown that soil beneath trees has lower water content than soil beneath open pasture (Giddens et al., 1997; Douglas et al., 2001; Peri et al., 2001; McIvor et al., 2003), and the latter has lower water content than bare ground (Chang et al., 2002). This is probably because of water uptake by the plants and the plant's contribution to higher drainage through improved soil physical characteristics e.g. higher porosity from root exploration. Conversely, beneath unevenly spaced mature *Populus*, SWC was higher or similar in the 0-300 mm stratum compared to open pasture (Guevara-Escobar et al., 2000). Despite the higher water use of the mature trees, this result may be because of the positive effect of tree shade reducing evapotranspiration. This is supported by findings in Australia and in the Spanish dehesa (with higher mean temperature and lower rainfall than New Zealand) where SWC was higher under stands of *P. radiata* (0-100 mm depth) and evergreen oaks (0-1500 mm depth), respectively, than under open pasture. This was possibly because open

pasture experienced more severe soil water deficits than pasture growing under trees (Anderson & Batini, 1979; Joffrey & Rambal, 1988).

Water holding capacity of the soil is affected by factors such as soil type (texture), topography (slope) and depth. The latter factor can be important in silvopastoral systems because tree species normally develop deeper root systems than pasture and this may vary with SWC within the soil profile. Thus, during the growing season, it was found that SWC at 200-800 mm depth beneath *Populus* was lower than beneath open pasture (McIvor et al., 2003). Near the surface, SWC is also strongly related to climatic conditions. For example, the content at 0-100 mm depth under *P. radiata* was lower than that at 100-200 mm depth during summer because of high evapotranspiration coupled with less precipitation (Clinton & Mead, 1990; Gautam, 1998; Chang et al., 2002).

Other variables may influence SWC such as tree species, their competitive ability (for example, because of deeper or shallower root systems (Yanusa et al., 1995; Miller et al., 1998)), and the relative position of measurements with respect to tree trunk and aspect (Stout & McMahon, 1961; Guevara-Escobar et al., 1997; Douglas et al., 2001).

Wind

When wind speed is high, plants may suffer physical damage because of the collision between neighbouring leaves (Wall et al., 1997b), and anatomical changes occur, such as an insufficient pre-winter hardening and the development of thinner cuticles, and thicker, shorter and fewer leaves. Moreover, wind may produce changes in the local environment for example, increase evapotranspiration, reduce relative humidity and modify temperature (Skidmore et al., 1972; Eastham & Rose, 1988; Bird, 1998). Consequently, there can be an increased vulnerability to water stress, and a decrease in the yield of highly exposed plants.

The presence and contribution of trees is widely stated to reduce the adverse effects of wind because they produce a physical barrier. Wind is an important feature of New Zealand's climate (Radcliffe, 1983) and several studies have focused on the performance of shelterbelts over crops. Some of them have also analysed the effects of various densities of evergreen trees (*P. radiata*) on reducing wind in space-planted tree-pasture systems. In a stand aged 8-11 years,

a spacing of 400 sph reduced average annual wind run by 78% compared with at 0 sph, and spacings of 100 and 200 sph reduced wind run by 44 and 45%, respectively (Percival et al., 1984b; Hawke & Wedderburn, 1994). A similar trend was found in Australia in a 300 sph stand aged 7 years where wind run was 69% of that in open pasture (Anderson & Moore, 1987). Apart from stand density, differences in wind speed and wind flow can be attributed to tree species and management, porosity of the crowns, seasonal variation in leafiness, and to their siting and tree height (Hawke & Dodd, 2003).

Temperature

Temperature is an important factor affecting pasture production because it affects the physiological processes of plants such as photosynthesis, respiration, and germination. It varies with latitude, distance to the sea, altitude and the orographic layout at a large scale, but it can also vary locally, depending on wind run, soil type, micro-relief, aspect and shading. Shade of both evergreen and deciduous trees induces similar changes on soil and air temperature at ground level because they behave as a barrier against the wind and the incident radiance. In *P. radiata* stands aged 8-11 years, soil temperature at 200 sph measured at 300 mm depth was 0.7-1.5°C cooler than at lower stocking rates (0-100 sph), with the greatest differences in summer and spring (Percival et al., 1984b; Hawke & Wedderburn, 1994). In a 7-year old stand, differences in soil temperature were detected but varied only with sampling date (Chang et al., 2002). In mature *Populus*-pasture systems, with canopy closure, soil temperatures were 0.6-3.3°C lower compared to open pasture (Guevara-Escobar et al., 1997, 2007; Guevara-Escobar, 1999). The north side (sunny side in southern hemisphere) of young *Populus* at 24-400 sph was 1.1°C warmer than the south side (shaded side) at 100 mm soil depth, primarily because it received greater global irradiance (Douglas et al., 2001, 2006b). For young trees of evergreen and deciduous species, no significant differences in soil temperature have been found at low tree stocking rates e.g. < 30 sph for *Populus* (Douglas et al., 2001) and < 100 sph for *P. radiata* (Hawke & Wedderburn, 1994).

Reducing wind speed may raise the minimum temperature under trees, making seasonal variations less relevant and reducing extreme conditions. For example, grass minimum temperatures increased under *P. radiata* and this was

more obvious in winter and spring (Percival et al., 1984b; Hawke & Wedderburn, 1994). On wet days the effect of wind run reduction can be more pronounced and the minimum temperature can increase 2 or 3°C. Percival et al. (1984a) found that while the temperature under *P. radiata* trees was warmer at night, it was cooler during the day.

Effects on soil properties

In New Zealand, studies have recorded the effects on soil properties when trees are introduced into improved pastures. Most of these studies involve *P. radiata*-pasture systems (Hawke & O'Connor, 1993; Alfredsson et al., 1998; Amatya et al., 2002), but there is an increasing interest in the effects of other tree species such as *Populus* and *Salix* (Wall et al., 1997a; Douglas et al., 2006b). Soil property changes vary between species, and with climate and soil type (Wall et al., 1997b).

pH

Soil pH is markedly affected by tree species because it depends largely on the chemical characteristics of the litter. The pH of soil beneath *Populus* stands is higher than that of soil in open pasture and this trend is more evident in mature stands with larger canopies (Guevara-Escobar, 1999; Guevara-Escobar et al., 2002; Douglas et al., 2006b; Wall, 2006). Furthermore, the influence of trees on soil pH extends across the inter-tree gap because the litter does not remain just under the trees. Thus, as Wall (2006) suggested, wide-spaced stands of *Populus* could be used for bioremediation for controlling soil acidification.

Conversely, for *P. radiata* trees, numerous studies have found lower pH in the upper layers of the soil beneath trees than in adjacent pastures, irrespective of understorey species or stocking rate (Davis & Lang, 1991; Hawke & O'Connor, 1993; Giddens et al., 1997; Parfitt et al., 1997; Alfredsson et al., 1998; Cossens & Hawke, 2000; Chang et al., 2002). This outcome often increases with tree age and tree stocking rate as well. Results from a trial conducted by Hawke and O'Connor (1993) showed a decline in soil pH at densities above 50 sph, but it really became evident from a tree age of 13 years at 400 sph or from an age of 18 years at 200 sph. The different effects of evergreen and deciduous trees on soil pH probably arise from the disparate chemical and physical characteristics of their litter, and

their associated different contributions and decomposition rates (Taylor & Parkinson, 1988).

Carbon and Nitrogen

These elements are major constituents of plant and soil organic matter, and they play a fundamental role as nutrients. Consequently, numerous experiments to appraise them have been carried out in silvopastoral systems. It has been widely accepted that there is an increase in carbon (C) and nitrogen (N) mineralization under trees compared to open pastures (Giddens et al., 1997; Parfitt et al., 1997; Amatya et al., 2002), particularly near the surface. This may be caused by the higher contribution of organic matter (litter and dead roots) and the modified environmental conditions beneath trees, such as temperature and drying and rewetting cycles.

Decreases in soil N and organic C (expressed as g 100g⁻¹, g kg⁻¹ of soil and kg ha⁻¹) have been detected in the mineral soil (0-200 mm depth) when *P. radiata* is established in open pasture (Davis, 1995; Giddens et al., 1997; Parfitt et al., 1997; Yeates et al., 1997). However, C storage may be balanced by an accumulation of organic C in the surface litter layer (Parfitt et al., 1997), provided by the litter and tree biomass (an important C pool). Likewise, trials conducted with mature *Populus* by Guevara-Escobar et al. (2002) showed higher soil C pools and N content (t ha⁻¹) in open pasture than in a *Populus*-pasture system; meanwhile, the estimated C accumulated in topsoil and plants during the lifetime of the *Populus*-pasture system seems to exceed that in the open pasture system. These results have special relevance in relation to recent concerns about the need for C sequestration.

The low N content beneath non-leguminous trees may be explained by several reasons, including enhanced mineralization and nitrification (Parfitt et al., 1997). It is suggested that as soon as mineral N is produced in the mineralization process, it is rapidly absorbed by plants (accumulation of N in vegetation) or leached. Consequently, the C:N ratio normally increases under trees (Giddens et al., 1997).

Other macronutrients

Similar or higher contents of exchangeable cations have been found beneath *Populus* than in open pasture (Guevara-Escobar, 1999; Guevara-Escobar et al., 2002; Douglas et al., 2006b; Wall, 2006). Under mature *Populus* (> 29 years), concentrations of Ca, K, Mg and Na (kg ha^{-1}) were respectively 41%, 116%, 64% and 21% higher than adjacent open pastures (Guevara et al., 2002). Higher concentrations (kg ha^{-1}) of N, P and K (increments of 19%, 65% and 55%, respectively) were also found in *Populus* stands compared to stands of *Eucalyptus hybrid*, with different interplanted grass crops (Singh et al., 1989). The positive effect of broadleaved trees on soil fertility has also been reported for other temperate silvopastoral systems (Young, 1997), such as dehesas with Holm-oaks in Mediterranean Europe or North American oak savannas (McPherson, 1997; Gallardo, 2003; Moreno et al., 2007).

In contrast, an overall trend is a lower concentration of bases in soils beneath conifers (evergreen), although the proportions vary dramatically depending on soil type. Thus, Alfredsson et al. (1998) estimated mean reductions under *P. radiata* in the availability of Ca, K and Mg of 31.4%, 44.8% and 37.4%, respectively, at 450 sph compared to open pasture soils. They also found similar results under fir stands (*Pseudotsuga menziesii* (Mirb.) Franco). Hawke and O'Connor (1993) reported similar trends, and also noted that decreased availability of cations beneath trees compared with in open pasture seems more pronounced as the trees age and with increasing stocking rate. However, different results have been obtained in other studies. For example, relatively high concentrations have been found beneath trees for K and Mg (Davis & Lang, 1991), and Na and Mg (Giddens et al., 1997; Parfitt et al., 1997). The authors suggested that these responses were likely because of the known deposition of sea-salts on the canopies (study sites were near the sea) and subsequent deposition in the soil with rainfall leaching, and nutrient absorption by the tree roots from deeper layers of soil, and its incorporation to the nutrient cycling, returning to the soil surface via litterfall and canopy throughfall.

Trends for phosphorous (P) concentration are less clear because of the generally extended use of fertilisers that mask actual P concentration, high variation in soil type and analysis methods for P, and nutrient transfer through stock movement (Davis & Lang, 1991; Giddens et al., 1997). Higher

concentrations of exchangeable aluminium (me 100g⁻¹) and sulphate-sulphur (mg kg⁻¹) have been detected under *P. radiata* and other conifers than beneath open pasture, although the latter seems to be because of the characteristics of the site and the interaction between vegetation type and tree age (Davis & Lang, 1991; Giddens et al., 1997; Cossens & Hawke, 2000). The concentration of aluminium usually increases as the soil pH decreases.

Other properties

Limited studies have described the physical and biological properties of soils in silvopastoral systems, and none have shown evidence of changes in soil physical properties. The analysis of 28 paired-sites conducted by Davis and Condron (2002) showed that bulk density at 0-100 mm soil depth was similar beneath *P. radiata* during the first rotation, and adjacent pasture. Similar soil texture and physical properties were also found between open pasture and a mature, wide-spaced *Populus*-pasture system (Guevara-Escobar, 1999; Guevara-Escobar et al., 2002).

Key biological properties of soil are frequently the invertebrate populations living under the surface and the density of roots. Earthworm, nematode and grass grub populations decline with the establishment of tree crops (Percival et al., 1984b; Giddens et al., 1997; Parfitt et al., 1997; Yeates et al., 1997), although these changes seem to be more closely associated with the decrease in pasture growth. The opposite trend was found in the study conducted by O'Meara (1995), where a significant number of earthworms were observed under *P. radiata* compared with the adjacent pasture, suggesting that other variables can be influential or limiting.

The number of soil invertebrates was determined in a silvoarable system with rows of *Populus* trees spaced at 14 m x 3 m (Park et al., 1994). More invertebrates were located within 1 m of the trunk, being 1.5 to 2.5-fold greater than in the soil under the crop. It was suggested that rows of trees improve soil properties by contributing more organic matter and modifying the microclimate that affects the detritus process. In contrast, Guevara-Escobar (1999) found similar or lower activity of earthworms in a mature *Populus*-pasture system than in open pasture, although it might have been caused by variation in seasonal patterns.

The role of roots is related to their organic matter contribution when they die, and this is especially important in C and N cycling when the above ground biomass is removed (Schroth, 1995; Wall et al., 1997b). Roots are supposed to improve the physical characteristics of soils, but hitherto no published data are available in silvopastoral systems. Recent New Zealand studies have determined the distribution of roots of spaced *Populus* trees in hill pastures, with implications for their likely contribution to slope stabilisation (McIvor et al., 2003; 2008).

Effects on pasture

The effects of trees on the pasture understorey are the direct consequence of the extent to which they modify the microclimate and soil properties. The quantity and quality of pastures beneath trees are useful indicators of the sustainability of farms, because they significantly influence both economic performance (farm output) and resource status (Lambert et al., 1996). Thus, they need to be appraised according to tree stand characteristics so that farmers can optimise the resources through appropriate species selection and efficient management of tree density and size.

Effects on pasture productivity

Competition for resources, mainly light, results in decreased herbage production (Gillingham, 1984; Percival et al., 1984b; Percival & Hawke, 1985; Hawke, 1991; Bird et al., 1994; Wall et al., 1997a; Douglas et al., 2006a; Guevara-Escobar et al., 2007). This negative relationship between pasture productivity and light transmission to the understorey has been recorded in different studies with both evergreen and deciduous trees. In *P. radiata*, a negative and curvilinear relationship existed between relative pasture production and the sum of the crown lengths per hectare and mean crown length per tree (Percival & Knowles, 1988). A significant negative linear relationship ($R^2 \approx 0.89$) was determined between pasture production and estimated canopy closure (inferred from the basal area), with an extinction point at 67% (Knowles et al., 1997). For *Populus* plantations, a curvilinear relationship between pasture production and canopy closure was modelled and the predicted extinction point occurred later than for *P. radiata*, at 85% of canopy closure (McElwee & Knowles, 2000). The authors suggested that the reason for differences between species in extinction point was

that *Populus* spp., which have a season without leaves, tend to allow more light through the canopy for a given level of canopy closure, or that non-light-related competition is greater under *P. radiata* stands than *Populus* stands. A trial conducted in Northwest Spain, with similar climatic conditions to New Zealand, compared pasture production under 3 evergreen species with that under 3 broadleaved species. Higher yields were achieved under the broadleaved species because of their lack of foliage at the beginning of spring promoting increases in pasture production, their lower production of litter year round, and their slower growth (particularly diameter growth) (Rozados-Lorenzo et al., 2007).

Canopy cover: tree density and age effects

It is recommended that the spacing of trees within a silvopastoral system should be between 100 and 200 sph (The New Zealand Poplar Commission, 1995). During the first 3-5 years of tree establishment, evergreen and deciduous trees generally have negligible effects on pasture because their tree crowns are small (Hawke, 1991; Pollock et al., 1994; Goh et al., 1996; Guevara-Escobar, 1999; Guevara-Escobar et al., 2007), although it depends on the growth rate of the tree species (Rozados-Lorenzo et al., 2007) and the initial stocking rate. Hewson (1993) suggested that the establishment of trees on pasture would not unduly suppress grass growth using stocking rates less than 400 sph. At this stage, competition with weeds or the reduction of area due to herbicide applications may have more effect on pasture growth (Percival et al., 1984a; Pollock et al., 1994); even the effect of the understorey on tree growth may be more important than vice versa. The edible dry matter yield of *Populus* and *Salix* established recently decreased by 20% when there was no weed control (Sulaiman, 2006). A significantly higher growth of *P. radiata* was also recorded on bare ground compared with different pasture species beneath the trees (Pollock et al., 1994; Chang et al., 2002), reaching an increment in volume of up to 34% and 29% more than those trees grown with *Medicago sativa* L. and *Dactylis glomerata* L. pastures, respectively (Peri et al., 2002a). Pasture species can also affect tree growth at the initial establishment stage, because of their different competitive abilities. The most competitive pastures are *M. sativa*, *Phalaris aquatica* L. and *D. glomerata*, which result in smaller tree growths than those attained with *Trifolium* spp. and

Lolium perenne L. pastures (Pollock et al., 1994; Peri et al., 2002a; Chang et al., 2003; Chang and Mead, 2003).

Young trees may enhance pasture production because they can improve some environmental attributes, offsetting partially the light reduction at the understorey level (Percival et al., 1984a; Percival & Hawke, 1985; Wall et al., 1997). A large silvopastoral trial conducted at Tikitere in the North Island of New Zealand showed that pasture yield beneath a 3 year-old stand of *P. radiata* at 50 sph was even higher than in open pasture (116% of that with no trees) (Hawke, 1991). Tree shade may help to reduce evapotranspiration in late summer when water stress is high, as a trial by Douglas et al. (2001) reported, with higher pasture production on the shaded side of young *Populus* trees (8-11 years old) than on the sunny side in late summer. Trees may also favour pasture growth by reducing surplus water in damp situations (Hewson, 1993), and controlling hill erosion (Hicks, 1992). Miller et al. (1996) showed that pasture production under *Salix* spp. (aged 6-10 years) at 400 sph was similar to that on unstable, unplanted earthflows, and it was higher than on eroded sites.

Numerous studies have shown that when trees grow and light penetration and soil temperature start to decline, tree effects on pasture occur (Wall et al., 1997b), and tree age and stocking rate influence when these effects are detected. Understorey growth in *Populus*-pasture systems appears higher than in younger *P. radiata* silvopastoral systems at similar stocking rates (Guevara-Escobar, 1999), and for the same species, differences at similar tree age and stocking rate may be because of different soil fertility and climatic conditions. In both cases, it seems that during the first mid-rotation (trees aged 10-15 years) no significant effects occur at tree densities less than 100 sph. For deciduous trees, a decrease of 10-15% in pasture production occurred beneath *Populus deltoides* × *nigra* 'Veronese' aged 5-7 years and spaced 8 m x 8 m (156 sph) (McIvor et al., 2003), and a reduction of 22-24% was estimated beneath *Populus* aged 8 and 10 years at 200 and 100 sph, respectively (New Zealand Poplar Commission, 1995; Douglas et al., 2006a). With *Salix* trees at 400 sph and aged 6-10 years, annual pasture dry matter production was about 40% less than for open pasture (Miller et al., 1996). For *P. radiata* trees, North Island trials showed that pasture beneath a stand of 11 year-old trees at 80-105 sph had a sheep carrying capacity of about 95% of that for open pasture (Cossens & Hawke, 2000). For trees aged 13 years, the decline in

pasture yield was 13% of that in open pasture at 50 sph, while at 200 sph the diminution was 82% (Hawke, 1991). Trials conducted in the South Island with trees of the same age estimated smaller reductions of 19%, 27% and 49% at 100, 200 and 400 sph, respectively (Cossens & Crossan, 1995). For trees aged 15 years, other work reported significant differences between tree-pasture systems and open pasture at 400 sph, but not at 100-200 sph (Cossens & Crossan, 1991).

Tree planting pattern is another important factor affecting pasture yield. Thus, *P. radiata* stands at 100 sph but in two spatial patterns (even; rowed planting) resulted in different pasture yields (Hawke, 1991). However the same trend of a slow decline in yield up until tree age 13 years, followed by a rapid decline, occurred in both cases. The percentage of pasture production compared with open plots was 61% at Year 13 and 56% at Year 14 for row plantings, whereas for even-spaced trees the percentages were 50% and 35%, respectively. These results agree with the assumption that homogeneous distributions minimize tree competition but maximize tree-pasture interaction, in comparison with border distributions (fencing, riparian, shelterbelt) (Mosquera-Losada et al., 2005).

With mature trees, the reduction in pasture yield increases dramatically. For instance, beneath *Populus* aged 16 and 19 years, pasture accumulation was 12.5% and 23% less than for adjacent open pasture during summer (Gilchrist et al., 1993), and annual production was 23% less beneath 15 year-old *Populus* (Douglas et al., 2001). A reduction in annual production of 40% was recorded under mature trees (29-40 years old) at 37 sph (Guevara-Escobar et al., 1997; 2007). For *P. radiata* trees, together with the lack of light, the smothering of pasture by needles becomes relevant (Percival & Hawke, 1985; Percival & Knowles, 1988; Hawke, 1991). Pasture production in a stand aged 16 years was 59% of that in open pasture with stocking rates of 80-105 sph (Cossens & Crossan, 1991). By Year 18-20, pasture production beneath *P. radiata* at 100-200 sph may decrease up to 75-93%, and with densities of 400 sph, production may cease (Percival & Knowles, 1988; Cossens & Hawke, 2000). Results from trials conducted in Northwest Spain and in Australia also showed a decline in pasture productivity under *P. radiata* stands. However these reduction effects seemed to be delayed because tree growth was slower because of lower soil fertility, and a

drier climate, respectively (Bird et al., 1994; Kellas et al., 1995; Mosquera-Losada et al., 2006).

Pruning and thinning debris can decrease pasture production because it shades/covers the available pasture area (Kellas et al., 1995). Tree debris of deciduous trees may influence the potential pasture area, contributing to reduced pasture accumulation (Hurst et al., 2000). However, fast-growing evergreen species produce greater quantities of litter during the year (Montard et al., 1999) and it decomposes more slowly than material from deciduous trees, for example *Populus* spp. (Guevara-Escobar et al., 1997). It was estimated in a *P. radiata* stand at 200 sph and aged 18 years that pasture production was reduced by 93% compared to open pasture and 35% of the pasture was affected by smothering by needles from the trees (Percival & Knowles, 1988).

Seasonal and location effects

Seasonal effects and the relative location of trees vary significantly according to the type of tree species. In evergreen stands the importance of seasonal changes or location effects on pasture production are small compared to deciduous trees, because the former do not lose all needles in autumn as the latter do with their leaves. Therefore, few studies have considered these factors with evergreen trees. During tree establishment, differences in pasture production can vary with position around the tree and season. Pollock et al. (1994) reported that early summer pasture production was lower on the shaded side of rows of 2 and 3 year-old *P. radiata*, 10-15% less than in the centre (just in the row), and 15-35% less than on the sunny side. Meanwhile, productivity of the shaded side seemed to be more similar to that of other positions around a tree during times of soil water deficits, such as frequently occur in late summer or autumn (Gautam et al., 2002). It is recommended that trees be planted in a north-south direction because it maximises direct sunlight penetration to the understorey, in order to optimise pasture/tree biomass (Garrity, 1996).

In contrast, numerous studies conducted beneath deciduous trees have shown seasonal variation in pasture yield because of leaf fall. Across three years, Douglas et al. (2006a) estimated that the average biomass accumulation of swards beneath a stand of *Populus* spp. at 25-100 sph and aged 8-11 years was 23% less than open pasture. However, this figure varied seasonally with

differences being greater in spring, summer and early autumn and more similar during the leafless period in late autumn and winter. Differences were also detected around trees, with annual pasture growth decreasing 7% and 14% on the north (sunny) and south (shaded) sides compared to open pasture, respectively (Douglas et al., 2001).

Similar to trends with young stands, seasonal variations in production beneath mature stands align with the presence or absence of leaves. During winter, negligible differences in pasture accumulation occur under trees compared with open pasture (Crowe & McAdam, 1992b; Gilchrist et al., 1993; Guevara-Escobar, 1999; Douglas et al., 2006a; Guevara-Escobar et al., 2007), which coincides with the period of least pasture growth. Spring is a critical season for pasture growth because the potential for growth is usually highest (Gilchrist et al., 1993). However the largest differences in pasture growth beneath trees and in the open occur in summer, and last until mid-autumn when herbage productivity decreases in both situations and reaches similar levels (Guevara-Escobar, 1999; Douglas et al., 2001; Guevara-Escobar et al., 2007). However, pasture production in autumn is highly dependent on current weather, with substantial differences in productivity beneath and beyond trees possible in moist autumns, whereas differences are negligible when autumns are dry (Miller et al., 1996) because of limited pasture growth.

The relative location of trees also affects pasture growth and changes with variation in foliation. There is a marked effect of tree spacing and distance to the trunks on pasture production. Thus, pasture production in summer at 1 m from the trunks of *Populus* trees with a crown canopy diameter of 5 m was 20% lower than at 4 m and beyond (Gilchrist et al., 1993). Devkota et al. (1997b) found a reduction of 65% in pasture yield beneath *Populus* aged > 30 years, but pasture accumulation increased with increasing size of the gaps between trees. Wall (2006) analysed the variation in pasture production below *Populus* aged 25-30 years, and in the gaps between them, according to canopy closure as a stand density estimate. The relationship between pasture productivity and canopy closure showed a rapid decline in annual herbage accumulation when transitioning from open pasture to beneath the *Populus* crowns. Directly underneath the *Populus* trees, annual net accumulation had a negative and concave relationship with canopy closure. Above 20% canopy closure, annual net

accumulation was approximately 50% of that in open pasture. The shape of this relationship (negative and concave curvature) was similar to that between light transmission and canopy closure with leaves (CCL) and without leaves (CCNL). Measurements taken in the vertical projection of canopy gaps showed that crowns had a linear and weaker influence in these partially shaded places than beneath the crowns. In this case, annual herbage accumulation was about 62% of that in open pasture at 50% CCL. Seasonal variations were also detected in this research. Thus, in summer, herbage accumulation was higher in the gaps, reaching 50% of that in open pasture, whereas beneath the trees accumulation was 30% of that in open pasture. In autumn, pasture accumulation under trees was 35% of that in open pasture, which was similar to that in the entire inter-tree space with 70% CCL (higher stocking rates). In contrast, pasture accumulation in the gaps of less stocked stands (50% CCL) was very similar to open pasture values.

Effects on pasture composition

Lack of light, cool temperatures and low SWC reduce the growth rate of pasture species, and consequently delay their life cycle (Balocchi & Phillips, 1997; Peri et al., 2001). Hence the shade tolerance of a species will determine its capacity to survive and complete its life cycle beneath trees. The most shade-tolerant species are those that under low PAR maintain a comparatively high absolute and relative shoot yield. The main pasture species in New Zealand have been screened for their responses to shade with *Holcus lanatus* L. and *Dactylis glomerata* L. being the most shade-tolerant grasses (Devkota et al., 1997a, 1998; Peri et al., 2007), and *Lotus uliginosus* Schk. cv. 'Grasslands Maku' being the most shade-tolerant legume (West et al., 1991; Devkota et al., 1997a). *Lolium perenne* L., *Festuca arundinacea* Schreb. and *Poa trivialis* L. exhibited poor shade tolerance (Vartha, 1973; Devkota et al., 1997a, 1998). *Medicago sativa* and *Phalaris aquatica* L. have also yielded more than *L. perenne* and *Trifolium repens* L. pastures in silvopastoral systems (Pollock et al., 1997). *Agrostis capillaris* L. and *Poa annua* L. were shade-tolerant but only under light or moderate shade (Devkota et al., 1997).

Botanical composition

Modifications to botanical composition are caused by changes in the microclimate and soil properties, which vary with crown size, position relative to the tree, extent of foliation, and tree spacing. Livestock grazing, including grazing behaviour in the presence of trees, may also modify sward composition. The changes beneath widely spaced evergreen trees have been more pronounced than those under deciduous trees.

The botanical composition of pasture beneath trees (both *Populus* and *P. radiata*) generally deteriorates over time because there is a decline in legume (Percival & Hawke, 1985; Hawke, 1991; Miller et al., 1996; Cossens & Hawke, 2000; Douglas et al., 2006a) and *L. perenne* contents (Percival & Hawke, 1985; Hawke, 1991; Crowe & McAdam, 1992b; Miller et al., 1996; Cossens & Hawke, 2000; Douglas et al., 2006a; Guevara-Escobar et al., 2007), and an increase in the contents of litter and dead matter (Gillingham, 1984; Percival et al., 1984a; Percival & Hawke, 1985; Hawke, 1991; Guevara-Escobar et al., 2007). The overall content of annual grasses increases under trees (Hawke, 1991; Kellas et al., 1995; Douglas et al., 2006a). Trials have shown that the content of *H. lanatus* (Crowe & McAdam, 1992b; Kellas et al., 1995; Guevara-Escobar, 1999; Wall, 2006), *D. glomerata* (Miller et al., 1996; Douglas et al., 2001), *Agrostis stolonifera* L. (Crowe & McAdam, 1992a, 1992b) and *P. annua* (Crowe & McAdam, 1992a; Guevara-Escobar, 1999; Wall, 2006) increases beneath trees, likely related to their shade tolerance, tillering ability, phenological development and growth in winter.

These effects are more marked at higher stocking rates and beneath older trees, as some trials conducted with *P. radiata* have shown. Hawke (1991) found that the content of both *L. perenne* and *T. repens* at 100 and 200 sph was very similar to that in open pasture when the stand was aged 9 years (around 50% of total understorey biomass). However by the fifteenth growing season after planting, the total content of both pasture species had decreased significantly, particularly at 200 sph, to less than 5%. Cossens and Hawke (2000) also found beneath a 100-sph stand of *P. radiata* that the content of *L. perenne* decreased in Year 6, and similarly for *T. repens* in Year 9. In contrast, the content of *Trifolium* spp. in pastures beneath older *P. radiata* trees with large canopies increased with increasing tree density at 7 years when soil water deficits existed, such as in Western Australia (Anderson & Moore, 1987).

Botanical composition varies under *Populus* spp. with distance from the trunk, aspect and season. The gaps among mature trees are influenced by the size and foliage density of the tree crowns (canopy) and by the type of litter and its influence on soil properties, which is not restricted to within the crown domain. Thus, the contents of grass species located in gaps were intermediate between those in open plots and directly below the trees (Wall, 2006). The grass content of swards on the sunny side of young and intermediate-aged *Populus* spp. was higher than on the shaded side (Douglas et al., 2001, 2006a). Seasonal differences in botanical composition between sites with and without trees are smaller during summer (Wall, 2006), mainly because the grass content declines, particularly in open pasture and during dry summers (Suckling, 1960; Douglas et al., 2006a; Wall, 2006). Meanwhile the senescence of grasses is delayed with wet summers and under trees (Crowe & McAdam, 1992b; Wall, 2006).

Nutritional value

Changes in sward botanical composition and species phenology affect the nutritional value of pasture under trees. Most relevant data have been collected for swards beneath widely spaced *Populus*, and these swards generally have a similar chemistry to adjacent open pastures. However some pastures under *Populus* have slightly poorer nutritional value than those beyond trees, with lower content (% DM) of soluble carbohydrate and higher contents of neutral and acid detergent fibre. Higher crude protein content (% DM) has been found in swards under *Populus* (Guevara-Escobar, 1999; Wall, 2006) and *P. radiata* (Balocchi & Phillips, 1997; Peri et al., 2001, 2007), which can be attributed to a decrease in the rate of tree photosynthesis or to an increase in soil organic matter content, with a consequent rise in N concentration (Wilson & Ludlow, 1991; Balocchi & Phillips, 1997; Peri et al., 2001). Season also plays an important role in nutritional value of the understorey pasture. Spring pasture usually has acceptable nutritional characteristics beneath and beyond *Populus* trees whereas the lowest nutritional values occur in summer (Guevara et. al., 1997), for example, increased fibre content. Furthermore, the content of fibre (% DM) in open pasture usually reaches similar levels to that in pasture beneath the trees. Organic matter digestibility decreases from spring to summer, and this is more pronounced in open pasture. It is an increasing practice to use the foliage of

Populus and *Salix* spp. as supplementary forage because fresh leaves in summer have a forage value similar to open pasture (Wall, 2006), and their crude protein content and digestibility are similar to those of *M. sativa* hay (Hewson, 1993; New Zealand Poplar Commission, 1995).

Tree management

Tree management, including silvicultural operations, has an important influence on tree-pasture relationships. The main effects of trees on pasture are largely governed by tree type, age, and density. For trees of similar age and density, the effects on pasture yield are related to tree size (Percival & Hawke, 1985).

For stands of *P. radiata*, management is focused on producing good quality timber for sawlogs, that is long, straight and knot-free stems. Thus, earlier thinning and pruning are frequently recommended, although they should not be conducted following a rigid prescription. In many situations, trees of *P. radiata* are pruned annually from age 3 or 4 years by removing whorls of branches up to 6 m height, and thinned to final stocking densities of 50-250 sph. Despite the increasing light transmission to the understorey after these operations, pasture growth may be limited by the pruning and thinning debris, because of the loss of area available for pasture production (Percival & Hawke, 1985; Hawke, 1991; Kellas et al., 1995). Therefore, subsequent collection of debris, and its placement or use should be planned.

With deciduous trees, *Populus* and *Salix* spp., an optimum density is also sought, but because they are normally planted at wider spacings, the management of size becomes of particular importance. Due to its good nutritive value (McCabe & Barry, 1988; Kemp et al., 2001; Oponng et al., 2001), foliage of these trees is increasingly used for supplementary fodder in summer and autumn droughts (Douglas, 1996; Oponng et al., 1997). By regular pruning/pollarding these trees are kept at a manageable size, thereby preventing potential problems of large trees such as injury to farmers and livestock, and damage to infrastructure (tracks, buildings, fences), and costly and dangerous removal is avoided (Olsen & Charlton, 2003). Fodder of *Populus* and *Salix* spp. can be supplied to livestock by establishing special-purpose blocks (Charlton et al., 2003; Douglas et al., 2003; Olsen & Charlton, 2003; National Poplar and Willow Users

Group, 2007) planted in unproductive parts of the farm (*Salix* spp. are more suitable in very wet areas such as swamps) that can be coppiced to < 300 mm above-ground or browsed directly. Another option for providing tree fodder is pruning some or all foliage of existing widely spaced or row planted trees (fenceline and shelter planting) every 2-5 years, or pollarding them at a similar frequency at 2.0-2.5 m above ground (Olsen & Charlton, 2003; Evans, 1973). This operation enables the farmer to harvest the fodder safely above cattle height, and tree regrowth is above livestock grazing height. Pruning or pollarding also reduces the size of the tree canopy and facilitates pasture growth.

Trees of *Populus* spp. can be managed for timber, whilst providing erosion control, shade/shelter, and fodder during drought in the early years. The National Poplar and Willow Users Group (2007) recommends regular pruning of side branches beginning at the fourth or fifth year, continuing with pruning of the lower two whorls of branches at two years after the first pruning, and then annual pruning of a whorl of branches up to 6 m height. However, limited research has been undertaken to evaluate *Populus* spp. for timber and the potential value of *Salix* spp. to the wood industry (Wilkinson, 1995, 1999). A limited market for these species is being developed in New Zealand (Percival & Hawke, 1985; New Zealand Poplar Commission, 1995).

Developing silvopastoral systems: Considerations

Silvopastoral systems supply benefits additional to those of one-objective systems. Apart from the evident environmental externalities, such as beauty to farm landscapes, increasing structural and biological biodiversity, stabilising erosion-prone hill country, and shade/shelter and consequent welfare for livestock, the economic impact of these diversified systems is arguably the most important reason for their adoption by farmers and land owners.

Different studies overseas have developed computer programs and models to simulate agroforestry performance and quantify the biophysical interactions, which may help to appraise their economic impact e.g. a model of water, nitrogen and light capture interaction in agroforestry systems (WaNuLCAS) (Van Noordwijk & Lusiana, 1999). There is a plot-based model simulating the temporal biophysical behaviour of a silvopastoral system, called ALWAYS (Alternative Land-Use With AgroforestrY Systems) (Bergez et al., 1999). Methodologies are

available to assess factors relating to silvopastoral adoption decisions (environmental, economic and social), like the approach described by Shrestha et al. (2004), which is a combination of a strengths-weaknesses-opportunities-threats approach with an analytic hierarchy process (SWOT-HP), and the Resource Dynamics Model (RDM) developed by Etienne and Herlant (1999).

Economic studies have inferred financial benefits only with appropriate tree species and managements compared to monocultures, such as those carried out in the southern United States by Grado et al. (2001) and Husak et al. (2002), where the monetary benefits are due to the diversity and productivity of the systems and to a minor extent on the market and price fluctuations for livestock and timber. These trends have been supported in New Zealand studies. Thorrold et al. (1997) compared four land use alternatives in the North Island: grazing in open pasture with sheep and beef, and three silvopastoral treatments comprising *P. radiata*, *Eucalyptus fastigata* and *Acacia melanoxylon*. The results showed that all three silvopastoral options produced higher long-term returns than the traditional sheep and beef farm, and the *P. radiata*–pasture system produced a higher return than the two other systems. Parminter et al. (2001) evaluated the economic incentives for farmers to plant *Populus* spp. to control erosion on steep hill country. In this case, any monetary benefits required the trees to be harvested and sold because reliance on the soil conservation and fodder benefits alone was uneconomic. Any benefit from planting and harvesting poplars on erodible sites is partly counterbalanced by the loss in pasture production because of the trees (Hicks, 1992; Miller et al., 1996). The study by Parminter et al. (2001) is valuable because it indicates some of the circumstances under which the decision to plant poplars is potentially worthwhile for farmers, such as high risk of erosion (as an insurance against disasters), animal welfare and reduction of lamb losses, and whether subsidies are available.

Bearing these in mind, the choice of tree species and knowledge of their establishment and management (densities, canopy size/closure) are crucial. The selection of tree species is related primarily to the characteristics of the site, including limitations such as susceptibility to summer drought, and soil properties (e.g. stoniness, shallowness, seasonal wetness). Knowledge of these and the potential to ameliorate one or more of them are important e.g. the use of deciduous trees in acid soil to increase the pH as Wall (2006) proposed, or

establishing a plantation of fast-growing species on erodible sites or in swampy soils (Wilkinson, 1999). The other main factor affecting tree selection is the target farm output(s). *Pinus radiata* plantations are primarily for large scale erosion control and/or timber production. Thorrold et al. (1997) estimated that the economic return from *P. radiata* production on farm land is maximised when the trees are grown for quality timber production. Meanwhile, *Populus* and *Salix* timber has high potential for a range of purposes, but it has a very limited market and there is currently no clear marketing infrastructure for farmers. However when livestock enterprises are the primary aim and other tree functionalities are required, such as minimising the suppression of pasture growth, soil protection and stabilisation, shade/shelter, and supplementary fodder for grazing animals, deciduous trees like *Populus* and *Salix* spp. are often more appropriate.

Finally, management of the tree canopy has an important influence on pasture productivity. Trees of an appropriate species/clone (with suitable architecture and tolerance to specific site limitations), at low stocking rate and pruned or pollarded regularly, will likely increase pasture production and enhance sward botanical composition. Within the first five years of establishing a stand, there are negligible effects of the trees on pasture, regardless of the tree species, apart from the results of terrain pre-treatments such as spot-spraying of herbicides. During the first part of the rotation, the effects of deciduous and evergreen trees on pasture dynamics are often negligible, particularly at low stocking rates. Even improved pasture yields have been attained in silvopastoral systems under water stress conditions or extreme temperatures. The effects of deciduous trees on pasture seem slightly less than those of evergreen species because of partial recovery during the leafless period (deciduous) and higher pasture smothering by needles (evergreen). Several authors found for young *Populus*-pasture systems that pasture yield beneath trees at 100 sph was 10-20% less than that beyond trees, and beneath young *P. radiata* stands, reductions were 13% at 50 sph and 20-40% at 100 sph. With increasing tree density and/or in the second part of the rotation (> 15 years), the reduction in pasture yield by tree shade increases dramatically, especially with *P. radiata*. For example, reductions determined for trees of this species aged 18-20 years were 75% at 100 sph, 83% at 200 sph and 100% at 400 sph. Furthermore, a decline in pasture quality occurs with increasing shade, with decreasing proportions of legumes (e.g. *Trifolium*

spp.) and grasses (e.g. *Lolium* spp.), and increasing proportions of dead matter and other grasses with lower nutritive value such as *H. lanatus*.

Knowledge of a number of the interactions between trees and pasture is comprehensive, but in a farming context, they must be appraised in conjunction with an adequate knowledge of livestock performance and management. This applies whether the silvopastoral system involves evergreen or deciduous tree species, and both the effects of trees on animals and the effects of animals on trees should be determined for a complete assessment.

Future directions

Silvopastoral systems will continue to be an integral part of New Zealand's pastoral farming landscape, particularly in hill country, where the spaced trees frequently have two or more functions such as erosion control, shade and shelter for livestock, supplementary fodder, vista enhancement, and nutrient recycling. Recent severe storms caused significant damage in some parts of the country (Dymond et al., 2006) and severe summer droughts have been experienced in a number of regions. With climate change, the frequency and severity of such storms and droughts are predicted to increase (Salinger, 2000; Kenny, 2001), and spaced trees (and also exotic and indigenous forests) can have an important role in mitigating the effects of such extreme weather events.

Spaced trees of *Populus x euramericana*, aged 14-17 years and planted at approximately 20 x 20 m spacing on erodible slopes near Gisborne in the East Cape of the North Island, reduced pasture production losses due to landslides during a cyclonic storm by 13.8%. On average, each tree saved 8.4 m² of ground from failure (Hawley & Dymond, 1988). It was estimated that, had the trees been planted in a 10 m x 10 m grid, and assuming 100% survival, storm damage would have been reduced by at least 70%. Mature trees of *Populus* and *Salix* spp. and other broadleaved species at spacings of 12 m (70 sph) or less can reduce mass movement in pasture by 50-80% (Hicks, 1995). It has also been shown that mass movement can be reduced by 10-20% with just partial tree planting on erosion-prone slopes or in areas where older tree stands have not been maintained (Hicks, 1995). During summer/autumn drought, some tree species such as *Populus* and *Salix* spp. can provide valuable supplementary feed (McWilliam et al., 2005)

through options such as pollarding spaced trees and leaving material on-site, or carrying it off-site (Charlton et al., 2003; Olsen & Charlton, 2003).

Future research on silvopastoral systems in New Zealand is anticipated to address the following aspects.

1) Effectiveness of spaced trees for controlling erosion. There is very little quantitative information on how effectively spaced trees reduce the prevalence and severity of mass movement (e.g. landslides, earthflow and gully erosion) on erodible pastoral hill country. Furthermore, surveys conducted (e.g. Hicks, 1991; Thompson & Luckman, 2003; Hicks & Crippen, 2004) have rarely described the dimensions of the spaced trees. Knowledge of both the size of individual trees (height, diameter at breast height (dbh), canopy dimensions) and spacing between trees is required to enable more objective appraisal of silvopastoral systems that have either successfully stabilised slopes, or failed to provide adequate protection.

2) Root distribution of trees. Development of a root network on a slope over time and space (both laterally and vertically) is critical for maintaining soil intactness in the face of storm events and saturated soil conditions. Limited studies of roots of spaced trees on slopes have been conducted such as those on *Populus* spp. (McIvor et al., 2005, 2008). Knowledge and understanding of root growth and development and how they change with factors such as position on slope, aspect, and soil type will enable improved recommendations on tree spacings to achieve satisfactory soil stability and adequate pasture production and quality on various terrains.

3) Managing tree size. There are many examples of spaced trees of several genera, particularly *Populus* and *Salix*, that have received negligible or no management since planting around 30 years ago. They are now very large and may topple or lose branches as they age or are subjected to strong winds. Consequently these trees are a potential liability to livestock, farm infrastructure (tracks, fences, buildings), and landowners. Practical methods have been developed to kill large trees involving strategic use of herbicides injected into holes drilled in the trunk or removing sections of the bark and cambium layers through ring-barking or girdling (National Poplar and Willow Users Group, 2007).

Newly planted spaced trees should be managed over their lifetime but the most appropriate ways of conducting this are not well defined as yet. Limited

farmer experience indicates that pollarding trees above animal grazing height at, for example 2.0-2.5 m above ground every 2 or 3 years is a potential long-term option (Charlton et al., 2003). There is, however, negligible information on the effect of this technique on tree regrowth above- and below-ground or on how root development, with the associated implications for slope stability, may change.

4) Modelling silvopastoral systems. Our ability to model the impacts of spaced-tree systems on erosion processes are weak, in comparison to our ability to model the effect of trees on pasture growth and composition. Progressing (1), (2) and (3) will contribute directly to the inclusion of a vegetation component into existing soil erosion models. This would increase our capacity to explore and advance our understanding of the role of vegetation in the management of landscapes susceptible to erosion under changing climatic conditions.

5) Tree canopy shape. The effects of *P. radiata* and *Populus* spp. on understorey pasture dynamics are well known, as shown in this review. In New Zealand, *P. radiata* is predominantly used in forestry and its role in silvopastoralism is diminishing with few remaining examples of extensive systems on commercial farms, with the notable exception of shelterbelts. In contrast, *Populus* spp. will continue to be used widely on hill country. There is current debate about the best shape of a tree for use on pastoral land with some landowners and land consultants regarding the fastigate *Populus nigra* 'Italica' planted extensively in the 1960s and early 1970s, as ideal because of its minimal shading of pasture and tolerance of strong winds. Excellent examples of this clone remain today. Canopies of *Populus* clones released over the last decade are tending towards a fastigate form. All studies on *Populus*-pasture interactions in New Zealand have involved non-fastigate tree forms, and there is a need to determine how tree shape affects the pasture understorey and the relationship between tree shape and root distribution, and water use.

6) Tree species. The use of longer-lived species other than *P. radiata* and *Populus* spp. offer potential advantages in silvopastoral systems including soil stability over a longer timeframe, and reduced disruption to farm management and reduced cost because of the less frequent need for establishing replacement trees. A range of exotic and indigenous species are potential candidates, however research is needed on appropriate establishment and management techniques, optimum growth form, root architecture, tree spacing, and tree-pasture

interactions. On erodible hillslopes, a succession from spaced trees of *Populus* and *Salix* spp., planted for initial stabilisation, to slower-establishing indigenous species, has been achieved by partial defoliation of the exotic tree canopy (Douglas et al., 2004).

7) Carbon sequestration. Plantings of spaced trees may provide supplementary income for landowners through their potential ability to sequester significant amounts of C in above-ground biomass and soil. New Zealand is a party to the Kyoto protocol and in the short- to medium-term plans to meet about half of its target reductions in greenhouse gas emissions through various afforestation/forestation schemes involving establishing exotic and indigenous species on sites such as steep, erosion-prone, pastorally farmed hill country (Trotter et al., 2005; Funk & Kerr, 2007). On these and other sites, for example, *P. radiata* accumulates at about 8 t C ha⁻¹ yr⁻¹ over a typical rotation cycle (Arneth et al., 1998; MacLaren, 2000), while indigenous shrubland comprising *Kunzea ericoides* and *Leptospermum scoparium* has the potential to accumulate C in the range 1.9-2.5 t C ha⁻¹ yr⁻¹ over a period of 40 years (Trotter et al., 2005). *Populus* spp. have received international interest owing to their potential for C sequestration when grown in plantations (Zabek & Prescott, 2006), but very little research on this subject has been conducted either in New Zealand or overseas for silvopastoral systems involving widely spaced trees (Guevara-Escobar et al., 2002). Guevara-Escobar et al. (2002) found that the soil-plant C pool in a poplar-pasture system could be as much as 30% higher than open pasture. This requires more detailed study.

8) Shade and shelter. The combined influences of the need to create kinder environments for animals for maximum performance (e.g multiple bearing ewes) and demonstrate high standards of care, will require the greater use of vegetation on our landscapes. Our understanding of the interaction between plantings designed for erosion control and the protection needs of animals has not been explored.

9) Economics of silvopastoral systems. Analyses have been conducted for systems in New Zealand involving *P. radiata* (Arthur-Worsop, 1985; MacLaren & Knowles, 1999) and *Populus* spp. (Parminter et al., 2001), and at least one analysis has been conducted on the benefits of using *Populus* and *Salix* spp. as supplementary fodder for livestock during drought (Orsborn et al., 2003). The

need to manage trees in silvopastoral systems, potential new applications of the systems such as C sequestration, and expanded thinking of species options in the systems, together with updated costings, warrants economic analysis of site- and regionally-specific systems. To date, however, analysis of the benefits and costs of shade and shelter provided by spaced trees to both livestock and the farm enterprise, has received scant attention.

Description of the current socioeconomic and agrarian scenario

Description of the inner-Western county of Asturias

The studied county² is located in the inner Western area of the Autonomous Community of Asturias (Northwestern Spain), henceforth referred to as the county. It comprises a surface area of 2,109 km² (20% of the surface area of Asturias) and embraces eleven councils or towns: Allande, Cangas del Narcea, Degaña, Grandas de Salime, Ibias, Illano, Pesoz, San Martín de Oscos, Santa Eulalia de Oscos, Taramundi and Villanueva de Oscos (Figure 6.1). The geographical coordinates which mark the limits of the county are: North latitude 43°25' - 43°08'; and West longitude (referred to Greenwich Meridian): 6°21' - 7°07'.

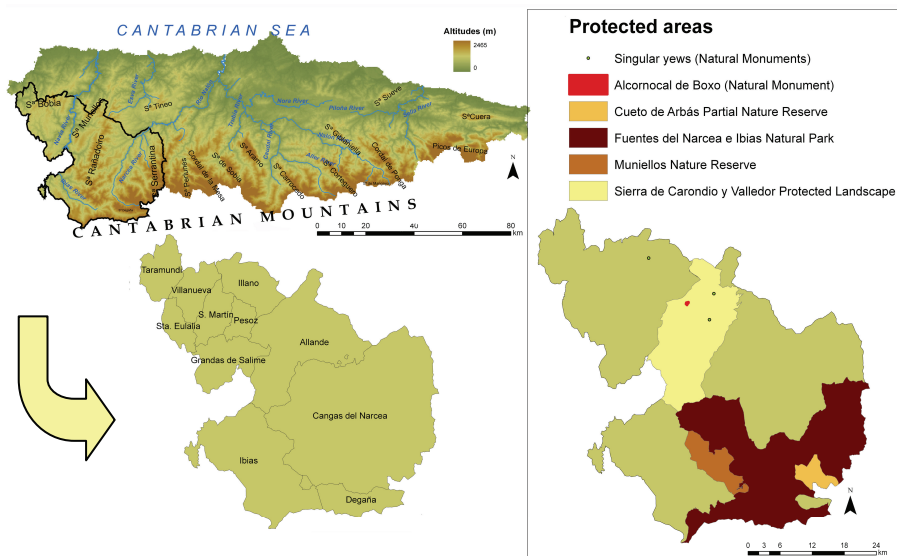


Figure 6.1. Location of the inner-Western County with its towns and protected areas.

This region is characterised by steep topography, with altitudes ranging from 70 to 2,002 m. 78% of the territory is between 400 and 1200 m, and 89% of it

² The Rural Development and Fishing Department of the Local Government proposed different agropastoral counties, in order to analyse the statistics derived from the Sanitary Campaigns for Livestock and milk production quotas.

has slopes greater than 20%, with 45.2% exceeding 50%. Sierras and valleys cross the region from south to north (almost at right angles to the coast). The wildest countryside can be found in the southernmost part of the county where the highest peaks of the Cantabrian Mountains reach 2000 m above sea level. Apart from the Cantabrian range, there are several other mountain ranges within the county: the Sierra de Rañadoiro in the centre, Sierra Serrantina at the eastern limit of the county and Sierra de la Bobia and Sierra de Muriellos in the north.

The main river in the region is the Navia, which rises in the Sierra de los Ancares (Lugo), crosses the county from Ibias to Illano, and finally flows into the Cantabrian Sea in Navia. Tributaries of the Navia also cross the county through steep sided valleys. The most important of these tributaries is the Ibias, the upper basin of which falls within the Natural Park of Fuentes del Narcea y del Ibias. The others are the Carbonel, Llouredo, Oro and Agüeira rivers. Besides the Navia, the other significant river system is that of the Narcea headwater basin in Cangas del Narcea, which has short tributaries characterised by rapids and clear water. These include the Gillón, Muniellos, Coto, Luiña, Onón and Argancinas rivers.

Much of the surface area of the county (68.4%) is dedicated to forestry (Consejería de Medio Rural y Pesca, 2002). This proportion is higher than that for the region of Asturias as a whole (54.3%). This category of land use includes woodlands and shrublands as well as uncultivated and non-grazed grasslands. Forests and woodlands comprise a large proportion of this land although the percentage is lower than that for the province as a whole (38% and 54% respectively), with shrubland accounting for 31% in the study area as opposed to 23% for the whole province. Land dedicated to permanent meadows and pastures also covers a significant proportion of the total area; nearly 20% of the whole county, although this is inferior to the regional figure (29.3%). Finally, the surface which corresponds to cultivated land is negligible in the county (1.4%), since the characteristics of its complex orography make the area more suited to pastoral land use.

The significance of the county in terms of natural resources should also be mentioned. The Asturian laws (Decree 38/1994, 19 May, following the local Law 5/91 Protection of Natural Habitats, based on national Law 4/89 Conservation of

Natural Landscapes and Wild Plants and Animals) make provision for the protection of the natural environment by facilitating the designation of areas of special interest as: National Parks, Natural Parks, Nature Reserves, Protected Landscapes and Natural Monuments. In the county, it can be enumerated (Figure 6.1.) the following protected areas:

- Las Sierras de Carondio y Valledor as Protected Landscapes.
- The Natural Park of las Fuentes del Narcea, Degaña e Ibias.
- Cueto Arbás Partial Nature Reserve and Muniellos Nature Reserve (Reserve of Biosphere by UNESCO).
- Three thousand-year-old yews: Tejos de Lago, de Santa Coloma and de Pastur, and the Alcornocal (corkland) de Boxo, are included in The Natural Monuments list.

Finally, the Natura 2000 Network includes a list of Sites within the county which are considered of Community Importance (declared in 2004 according to the Habitats Directive 92/43/EEC) including most of the aforementioned Protected Habitats as well as the river system features: Fuentes del Narcea and del Ibias, Muniellos, Cuenca del alto Narcea, Alcornocales de Navia, Río Ibias, Sierra de Lagos, Río del Oro, El alto Navia and Cuenca del Agüeira. The designated protected areas for birds in the county (according to Bird Conservation Directive 79/409/CE) are the protected area of Fuentes del Narcea, Degaña e Ibias, excluding the Nature Reserve of Muniellos which constitutes another protected area for birds.

Demographic analysis

Demographic structure

Population is one of the main variables considered in socio-economic analysis since it reflects the changing needs of the society over time. In 2007, the Asturian population represented 2.4% of the national total (INE, 2007). The trend during the XX century was of continuous increase up until 1981, when the population of Asturias began to decrease slightly. This decreasing trend in population has continued up to the present. Today, Asturias is considered one of the least dynamic areas of Spain in terms of demographic behaviour (Ministerio de Hacienda, 2000).

Furthermore, over the last few decades, the population has tended to concentrate in the central part of Asturias, to the detriment of the western and eastern regions. More than 77% of the Asturian population lives in the central part (20% of the total surface area). Consequently, the population of the county, which also constitutes 20% of the total surface area of Asturian, represents only 2.3% of the total Asturian population (24,406 people). This implies a population density of 9 people km⁻², compared to the regional figure of 101.3 people km⁻². Hence, it is a very sparsely populated area, having suffered a great population drop in the 60s (Figure 6.2) which has continued, albeit at a slower rate, to the present. During the XX century, the population drop was estimated around 65-75% in every town, except for Cangas del Narcea and Degaña, where it only decreased by 32 and 26%, respectively.

It can be seen from the demographic pyramid for 2004 that 50.7% of the Asturian population were men and 49.3% were women (INE, 2007) (Figure 6.3.). In general, the male population is higher than female population for adults between 15-64 years old, with differences of as much as 5 points. However, for older people (over 65) the trend reverses due to the higher frequency of late-age mortality in females. The fact that the proportion of adult women (particularly aged between 20 and 49) is relative small, partially explains the low number of births and, consequently, the drop in the number of young people. This is particularly noticeable in Ibias and Illano, where the percentage of women is nearly 18 points below that of men.

The Asturian population, and especially that of the county, displays a marked ageing trend, as shown in the pyramid. The ageing index for each was around 222.1 in the case of Asturias and 450.5 for the study county, which in statistical terms means that there are 2 and 4.5 people respectively aged over 65 per child under 15. The figure in both cases is much higher than the figure for Spain of 117.4 (INE, 2006d). This fact is evident from the information provided in Table 6.1, which shows that the population of the county comprises a smaller proportion of young people and higher proportion of elderly people in comparison to Asturias and Spain as a whole.

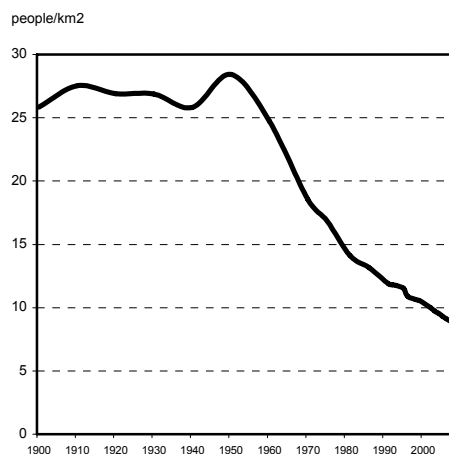


Figure 6.2. Mean population density evolution in the county. 1900-2007

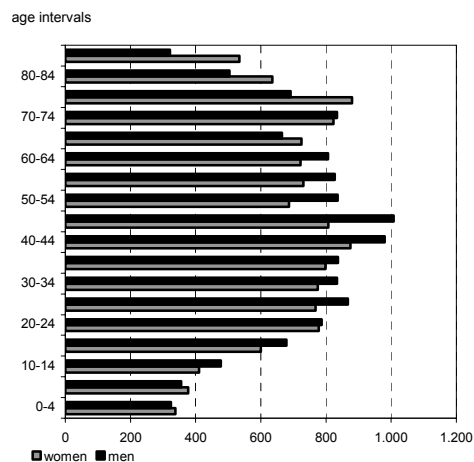


Figure 6.3. Population pyramid of the county. 2006

(Source: Local Town Population Census. Several years. INE)

Table 6.1. Population distribution (%) according to age. 2006

	<15 years	15-64 years	>=65 years
County	9.2	64.3	26.6
Asturias	9.9	68.2	22.0
Spain	14.3	69.1	16.7

(Source: Local Town Population Census 2006. INE)

Natural Population Movement

'Natural Movement' refers basically to the number of births, marriages and deaths occurring in a population over a given period of time. In Spain, the birth rate underwent an important change after the baby boom in the 70s, and since 1994, Spain, together with Germany, Italy and Greece, has had one of the lowest birth rates in the European Union (EUROSTAT, 2006). This trend is also found in Asturias and in the county. Between 1990 and 2006, the number of births in Asturias fell by 2.9%, whereas in the county the fall was around 53%. The number of children per woman (fertility rate) has also dropped both at national and at regional level. In Asturias, the average number of children per woman fell from 2.4 in 1975 to 0.8 in 1998 (the minimum value), and the average age of maternity has increased from 27.6 in 1975 to 31.5 in 2006. Since the beginning of this

century, there has been a slight increase in the average number of children per woman, although this increase is insufficient to guarantee 'replacement-level fertility' (the number of births per woman required to maintain the population in the long term, approximately 2.1 births per woman).

The small population of the county can result on significant deviations when analysing the birth and mortality rates. Hence, very different ranges can be obtained for different years. In 2006 (SADEI, 2007f), the birth rate for the county was 4.4‰ and the mortality rate reached 14.2‰ (Table 6.2). Since 1990, the latter has grown by 25%, due to the ageing population. The number of marriages has also dropped over the same period, both in Asturias and in the county, with a shrinking rate of 33.1% in the county and 8.3% in Asturias. This higher rate in the county is associated with the depopulation, the fact that the population is ageing and the unbalanced proportion of men and women.

Table 6.2. Main characteristics of the Population's Natural Movement. 2006

	Birth rate (‰)	Mortality rate (‰)	Natural balance (‰)
County	4.4	14.2	-9.8
Asturias	7.2	11.4	-4.3

(Source: Natural Movement of Population. INE. SADEI, 2007f).

Migratory Flow

Together with 'natural movements' the migratory flow is one of the basic components of population growth. It indicates whether the socioeconomic situation motivates people to immigrate from other places, or to emigrate.

Internal Migration

This is the migratory flow that takes place between the county and the other councils of Asturias, as well as between the county and other Spanish provinces. The result is a negative balance in both cases, because more people emigrated to the central part of Asturias (Oviedo, Gijón, Avilés and Siero) and to other places in Spain (Madrid, Castilla y León, Canarias, Cataluña, Galicia) than immigrated to the county (SADEI, 2007e). Data from 1998 to 2005 showed a steady negative net migration in the county. Likewise, Asturias also registered more people leaving than entering from other provinces during this period.

External Migration

During the last few decades, foreign immigration has led to a change in the structure of the Spanish society, not only in its demographic profiles, but also in its socioeconomic characterization.

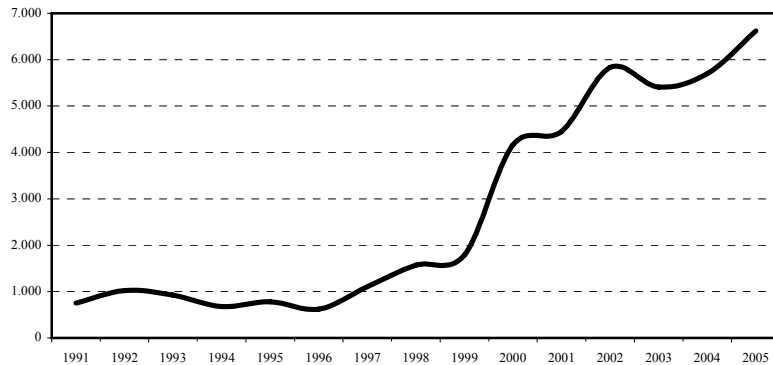


Figure 6.4. Evolution of foreign immigrants in Asturias. 1991-2005

(Source: Residence Variation. Local Town Population Census, INE. SADEI, 2007e).

There has been a notable increase in foreign immigration in Asturias since the late 90s (Figure 6.4.) (SADEI, 2007e). In 2005, the 14.9% of these immigrants were Spanish people returning to their homes, and the remaining 85.1% were foreigners, particularly from South America (Brazil, Colombia, Ecuador, Argentina and Venezuela). However, Asturias together with La Rioja, Cantabria and Extremadura, has one of the lowest immigration rates in Spain. Moreover, the foreign immigrants arriving at Asturias rarely choose to settle in the studied county (only 1.6% in 2005). On the other hand, few Asturian people and few people from the county usually choose to move abroad, so this phenomenon usually results in a positive balance.

In short, if we only consider national flows, emigration in Asturias exceeds immigration (Table 6.3). However, a positive balance exists thanks to the arrival of foreign people, especially those coming from South America. At local level, much movement has occurred from rural areas to more industrialised areas. These areas include the central part of Asturias and other Spanish provinces such as Madrid, Castilla y León and Canarias. Therefore, the net migration in the county remains negative, despite the abovementioned foreign immigration.

Table 6.3. Summary of net migration. 2005

	External Migration			Internal Migration						Total balance
				Interior Migration			Interregional Migration			
	E	I	B	E	I	B	E	I	B	
County	3	107	104	524	172	-352	209	139	-70	-318
Asturias	680	6620	5940			0	10049	9353	-696	5244

E: emigrants, I: immigrants, B: balance.

(Source: Residence Variation, Local Census, INE. SADEI, 2007e).

Education

Education provides the basis for different employment opportunities, social mobility and development of a region. In the school year 2004-2005 (SADEI, 2007b), the number of registered students at schools belonging to the general education system in Asturias comprised 2.1% of the total number of students in Spain. 18.0% of these corresponded to Nurseries, 36.4% to Primary Schools, and 45.1% to Secondary Schools. Differences are found between towns in the county, according to their population size and number of education centres. Some councils lack any educational institution (Pesoz, Villanueva, San Martín), or only cater for a specific level (Illano only has one Primary Education School), so the students in these places have to move to other towns to go to schools. Around 70% of the students in the county study in Cangas del Narcea, where the majority of educational institutions are to be found.

Another aspect worthy of mention is that in some towns, there are fewer students in secondary schools than in primary schools. This is the reverse of the situation in the rest of Asturias or Spain as a whole. Despite increasing the age for compulsory schooling (from 14 to 16) and the higher proportion of children aged over rather than under 12, there are less students registered in the secondary education. This may be a sign of early school abandonment.

Research into the level of education of working people (over 16) in 2001 (SADEI, 2005a), revealed high levels of illiteracy, people considered as having no education, and others who had only an elementary level of education. The proportion of illiterate people in the county (1.5%) exceeded the Asturian average (0.8%). The figures for Illano, Ibias, Pesoz and San Martín de Oscos were especially alarming, with figures over 2.6%, the highest rates in Asturias. Furthermore, the figures for those considered as 'uneducated' (schooling less than

5 years) and those with only primary education exceeded the regional average (18.8% and 33.5% in the county *vs.* 11.0% and 26.0% in Asturias), whereas in the case of secondary and higher education the figures were 41.7% and 4.6% respectively in the county *vs.* 49.0% and 13.3% in Asturias as a whole.

Level of Income

To study the level of income in the county, the household income per capita is used. This is considered as the total income that people perceived from work (earned income), plus the capital gains, social security benefits, etc., minus taxes and the payments related to Social Security affiliation, during a year.

Table 6.4. Annual household income per capita and per council (€). 1998-2004

	1998	2000	2002	2004	Index (2004)
Allande	7,064	8,270	9,446	10,968	81.3
C. Narcea	8,102	9,251	11,072	12,979	97.4
Degaña	9,520	10,772	11,572	13,004	97.6
G. Salime	6,988	8,188	9,596	11,725	88.0
Ibias	8,338	9,472	11,017	12,145	91.1
Illano	6,611	7,571	9,322	10,392	78.0
Pesoz	6,592	7,464	9,846	11,477	86.1
San Martín	6,708	7,761	9,365	11,118	83.4
Santa Eulalia	6,715	7,685	9,504	11,621	87.2
Taramundi	6,883	8,019	8,481	10,329	77.5
Villanueva	6,759	7,812	9,204	10,220	76.7
County average	7,298	8,388	9,857	11,453	85.9
Asturian average	8,900	10,517	11,779	13,326	100.0

(Source: Asturian councils' incomes. Several years. SADEI 2007g).

In 2004, the average household income per capita reached 11,453 € in the county, which is 14% less than the average for Asturias (13,326 €). In fact, the studied area comprised some of the poorest councils in Asturias (Table 6.4.). In last years, some of the lowest incomes in Asturias have been recorded in Taramundi, Pesoz, Illano, San Martín, Santa Eulalia and Villanueva (SADEI 2007g).

In Cangas del Narcea, Ibias and Degaña, average incomes are somewhat higher, at around 90% of the provincial average. The higher income in Degaña reflects the importance of its mining activities. Ibias, on the other hand, has a

slightly higher average income as a result of investment gains derived from a National Lottery award that benefited many of their inhabitants in 1993 (SADEI, 2003). As regards Cangas del Narcea, the income level is related to its industrial activity along with a significant development of the service sector.

The difference in average incomes between the richest and the poorest towns in Asturias grew between 1980 and 2000, and the local growth rate was lower than the mean regional rate. However, in 2002 and 2004 this tendency was reversed and the growth rate in the county was higher than that for Asturias (17.5% compared to 12% in 2002, and 16.2% compared to 13.2% in 2004). This was due on the one hand to the high sensitivity of small (depopulated) rural towns to any slight increase in population and on the other hand, to the fact that a large proportion of their inhabitants are over 60 and receive incomes from the Government, such as old age pensions or early retirement from mining.

Labour Statistics

The Labour Market is a fundamental element in the social fabric of society since it determines to a great extent the level of income and consequently, the standard of living of the inhabitants. To analyse the Labour Market, data were taken from the 'Economically Active Population Survey' (EAPS), undertaken by the National Statistics Institute (INE, 2006c), along with data provided by the Spanish Employment Agency (INEM, 2006). Analysis at local level was carried out using data taken from the 2001 Population and Housing Census (SADEI, 2005).

Economically Active Population

According to the EAPS, the activity rate in 2006, defined as the ratio (expressed as a percentage) of economically active people (working or looking for a job) aged 16 or over to the total population in this age bracket, was slightly lower in Asturias (49.8%) than in Spain as a whole (58.3%). This is probably due to a combination of factors such as the continual readjustments in industry (particularly in mining, and the iron and steel industry) that have taken place in recent decades, the high percentage of people aged over 65 and the lack of new entrepreneurial initiatives to replace the previous economic model in Asturias (Ministerio de Hacienda, 2000).

An analysis of the evolution of the active population and the activity rate between 1996 and 2006 reveals a trend of steady growth although in Asturias, this growth rate was slightly lower than that for Spain as a whole (0.7% and 1.2%, respectively). In 2006, 57% of the active population were men and 43% were women. Although the proportion of women in the active population is smaller, the rate of increase in the number of women consistently exceeded that for men throughout the whole period (1996-2006). Therefore, it is probable that the active rate increase over the last decade is partly due to the growing participation of women in the labour market.

At local level, the economically active population in the county according to figures for 2001 represented 2.2% of the total for Asturias. The proportion of the population in employment was greater than that for Asturias (87.3% *vs.* 84.4% of the total number of active people); hence, the rate of unemployment was below the regional level (12.7% *vs.* 15.6%). In part, this may be a consequence of emigration from the county to more industrialised parts of Asturias and the rest of Spain. In spite of having a higher working population rate and lower unemployment rate, the activity rate for the county is lower than that for the region as a whole (43% and 48.3% respectively). This means that there are a large number of inactive people (those aged 16 or over who are neither working nor seeking employment), such as pensioners or women who work at home or on family run farms but are neither registered with the Employment Agency nor pay the National Insurance contributions.

Employment

In 2006, the employment data for Asturias (SADEI, 2007c) showed that only 1.9% of the jobs were located in the county. There were also notable differences within the county itself, with Cangas del Narcea providing more than half of the total employment in the county (60.6%), compared to only 0.6% in Pesoz. Such differences in employment figures reflect the differences in population sizes.

After a significant drop in the early 90s, reaching a minimum in 1996 (Figure 6.5.), the employment situation in Asturias has recovered and the current figures are higher than those for 1990. However, although the situation appears to have recovered at regional level, there is much variability within the region according to the sectorial specialization of the towns. In the case of the study

county, there has been a steady fall in the number of employed people over the last decade or so (Figure 6.6.), with the percentage hovering around 36.7% during this period.

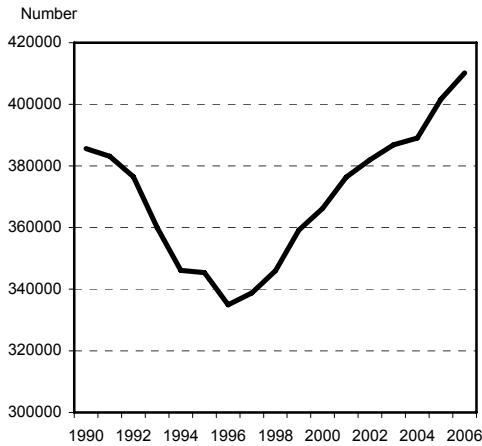


Figure 6.5. Employment evolution in Asturias. 1990-2006

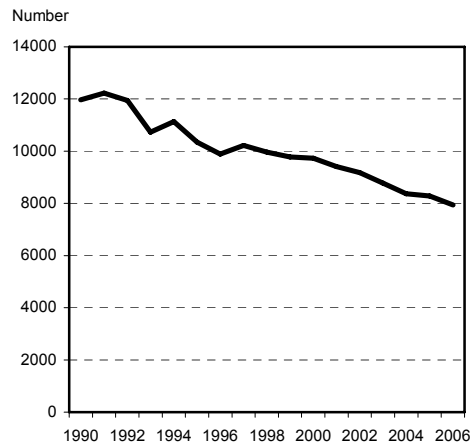


Figure 6.6. Employment evolution in the county. 1990-2006

(Source: SADEI. Labour statistics. SADEI 2007c)

If the employment is categorised into sectors (SADEI, 2007c) we find that 68.0% of the employment in Asturias belongs to the tertiary (service) sector, followed by industry (14.5%), construction (10.7%), and finally, the primary sector -agriculture, livestock breeding and fishing- (5.0%). This structure is similar to that found at national level. However, the sectorial distribution of the employment in the county is very different (Figure 6.7.). Although the most important sector is also the tertiary sector, the proportion is lower (48.0% of the total employment). The proportion of employment within the Primary sector is relatively high, 26.8%, as opposed to the provincial figure of 5.0%, although the proportion varies from one town to another. In Cangas del Narcea, where the service sector is most developed, more than the 50% of employment corresponds to this sector. In some districts (Pesoz, San Martín and Villanueva de Oscos) the contribution of the primary sector to the employment market is around 55%, whereas in other more industrialised districts there is less employment in the primary sector and more in the industry sector. The latter situation exists in Degaña where only 4.8% of the jobs are in the primary sector, whilst employment

in industry accounts for 69.8%, which exceeds the provincial rate. The building industry provides employment in every town, although this rarely exceeds 13% of the total (with the exception of Ibias at 22.8%) and the local average is around 7.8%.

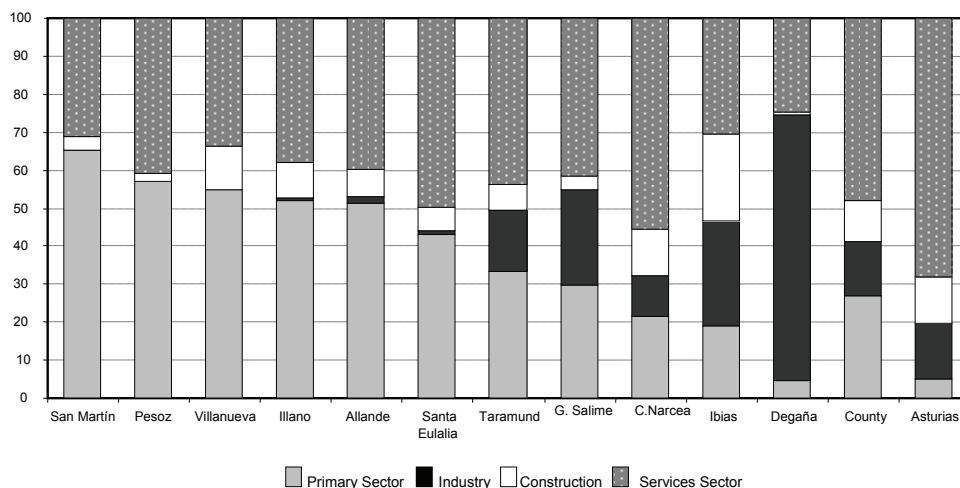


Figure 6.7. Sectorial distribution of the employment per town, 2006

(Source: Labour statistics 2006, SADEI 2007c).

Over the last decade, employment in the tertiary sector has grown steadily, both in Asturias and in the county, whereas employment in the primary sector as well as in industry has fallen gradually. Employment in the building sector remained constant for 8 years, although the number of jobs has increased in the last couple of years.

Unemployment

In accordance with EAPS (INE, 2006c), in 2006, the Asturian average unemployment was 9.3%, figure slightly greater to the Spanish value (8.5%), supporting a good evolution after the late 90s, when Asturias had one of the highest unemployment rates of every region. In 2006, the unemployment in the County represented 1.9% of the Asturian total, according to The Spanish Employment Agency in 2006 (INEM, 2006), and it consisted of 58.6% men and 41.4% women. The evolution from 1991 to 2006 has shown that the unemployment has decreased not only in Asturias (Table 6.8.), but it also in the

County (Table 6.9). Female unemployment has been superior to male one in Asturias during the whole period. Conversely, female unemployment in the County has been traditionally inferior, probably due to its rural nature and agrarian tradition, where women normally work in their houses and in the family land without registering on the Employment Agency. However, since 1997 there was a notable fall in men unemployment that resulted in a higher female unemployment proportion.

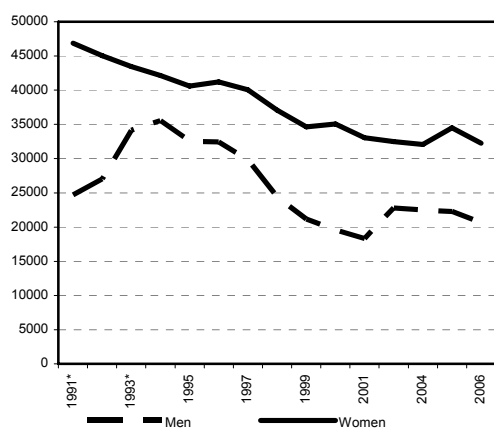


Figure 6.8. Unemployment evolution in Asturias. 1991-2006

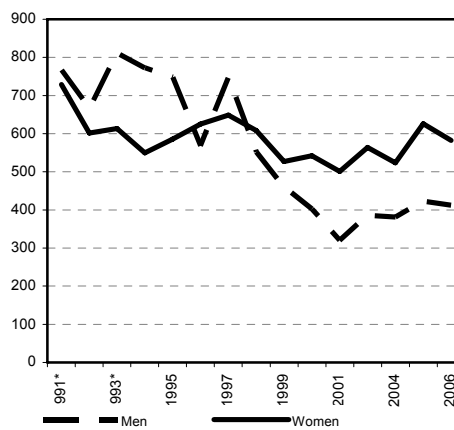


Figure 6.9. Unemployment evolution in the county. 1991-2006

* No incluye los parados sin adscripción municipal

(Source: Provincial Office of Employment. Several years. INEM, 2006).

Table 6.5. Unemployment distribution (%) according to the economic activity. 2006

	Total	Primary sector	Industry	Construction	Services	Without previous job
Allande	44	0.0	6.8	22.7	61.4	9.1
C. Narcea	754	2.3	17.4	9.0	54.2	17.1
Degaña	68	0.0	17.7	2.9	58.8	20.6
G. Salime	34	0.0	23.5	17.7	50.0	8.8
Ibias	52	0.0	19.2	9.6	53.9	17.3
Illano	16	6.3	6.3	6.3	68.8	12.5
Pesoz	11	0.0	0.0	27.3	63.6	9.1
San Martín	14	0.0	0.0	7.1	85.7	7.1
St Eulalia	16	0.0	12.5	6.3	81.3	0.0
Taramundi	18	0.0	11.1	33.3	50.0	5.6
Villanueva	22	4.6	0.0	13.6	72.7	9.1
County	1049	1.8	16.1	10.1	56.2	15.8
Asturias	56753	1.2	10.0	10.6	64.8	13.4

(Source: Provincial Office of Employment, 2006. INEM, 2006)

In 2006, the pattern of unemployment for the county was similar to the regional pattern (Table 6.5.). Most of the unemployed people belonged to the service sector (64.8% in Asturias and 56.2% in the county), and the primary sector registered the lowest levels of unemployment (1.2% and 1.8%, respectively). In the industry sector, unemployment was greater in the studied county than in Asturias as a whole (16.1% and 10%, respectively), whilst in the building industry, the level of unemployment was similar for both areas (around 10%). There were a high proportion of people looking for their first job in the county (15.8%), particularly in those towns with a high proportion of young people, such as Degaña, where unemployment was around 20.6%.

Economic Sectors

The relative weight of the different economic sectors can be analysed through three variables: workers, companies and production.

In 2006, the sectorial distribution of the workforce follows the same pattern as the aforementioned employment distribution³. It was characterised by a high proportion of the workforce employed in the service sector (64.5% in Asturias) and a relatively small proportion in the primary sector (5.6%) (INE, 2006c). The most recent data available at town level, from 2001 (SADEI, 2005a) revealed that the majority of the workforce in the county was employed in service and agrarian activities, with a total of 43.5% and 27.6% respectively. A high proportion of the workforce in each town in the county was employed in the agrarian sector (over 20%), with the exception of Degaña, where this sector accounted for just 4.3% of total employment whereas 56.6% was provided by the industry sector (exceeding the regional average).

Since 1990 the number of workers employed in the tertiary sector in Asturias has increased from 50% in 1990 to 64.5% in 2006. There has also been a slight increase in the number of workers employed in the building industry, reaching 11.6% of the total. Conversely, the primary and industry sectors have lost workers, declining in the case of the former from 15.8% in 1990 to 11.5% in 2006 and from 24.4 to 18.5% in the case of the latter.

³ The number of occupied people -workforce- does not consider the possibility of people having more than one job. Furthermore, whilst the employment of a particular area is considered as the number of people working in this area, the figure for 'occupied people' relates to the the number of working people who live in the area.

In order to analyse the second variable, i.e. the number of companies, the census of licenses registered for Trading Taxes was used (Cámara de Comercio de Oviedo, 2006). This information presents certain limitations when used to analyse the economic importance of the sectors since important data are lacking such as the size of the company, the production or other important variables can not be extracted. Nevertheless, it is useful when combined with the other indicators. In 2006, the licenses in the county revealed a high number of enterprises included in the service sector, totalling 75.6%, slightly inferior to the provincial figure of 77.9% (Table 6.6). In the county, most of these licenses were associated with businesses in Cangas del Narcea, where the service sector is most developed. The proportion of licenses registered for industry, construction (building industry) and the primary sectors is higher in the county than in Asturias as a whole.

As regards the tertiary sector, the most common enterprises were those related to either commerce/repair shops or hotels/restaurants which accounted for 34.5% and 17% respectively of all the licenses granted in the county. In the case of industrial enterprises, the greatest number of licenses corresponded to manufacturing companies which accounted for 5.9% of the total.

Table 6.6. Number of licences and their distribution (%) according to the different economic activities. 2006

	Total	Agriculture CNAE A	Industry CNAE C-D-E	Construction CNAE F	Services CNAE G-H-I-J-K-M-N-O
County	3578	1.8	7.3	15.3	75.6
Asturias	107045	0.9	7.2	14.1	77.9

(Source: Company census. Cámara de Comercio, Industria y Navegación of Oviedo, Gijón y Avilés 2006)

Finally, the most appropriate indicator of the economic importance of a sector is the Gross Added Value at base prices (bp) which it generates. This index is defined as the difference between the production value and the amount which that the producer receives from the consumers for each product or service, taking into account any product subsidies and excluding the taxes associated with the products.

In 2006, the sectorial distribution of the GAV bp presented a similar structure at regional and national levels (INE, 2006a). The primary sector contribution was very small in both cases (2.4% vs. 2.9%, respectively). However,

at regional level, the contribution of the tertiary sector was lower than at national level (61.2% *vs.* 66.7%) whereas the reverse was the case for industry (22.2% *vs.* 18.2%) and construction (14.3% *vs.* 12.2%). Since the mid 90s, the service sector and building industry have increased in Asturias, whilst the opposite has occurred in the primary sector and industry.

At town level (Table 6.7.), the data revealed (SADEI, 2007g) that more than the half the GAV bp for the county is generated by Cangas del Narcea (62.2%), whilst the combined GAV bp for Villanueva, San Martín, Santa Eulalia, Pesoz, Illano and Taramundi totalled 8.2%. In terms of sectorial distribution, the industrial and primary sectors contribute more to the local economy than is the case at provincial level. The total contribution of industry contribution at county level (29.2%) is greatly influenced by the amount of money from industry which enters the economies of Degaña (with a local contribution of 78%) and Grandas de Salime (with 53.8%). The primary sector contribution (10.4% of the local economy) exceeded 20% of the local GAV in many of the towns. Conversely, the tertiary sector and building industry contribute less to the GAV in the county than in Asturias as a whole (51.6% and 8.9%, respectively).

Table 6.7. Sectorial distribution of the GAV b.p. per town. 2004

	Total Thousand €	Agriculture		Industry		Construction		Services	
		%	Thousand €	%	Thousand €	%	Thousand €	%	Thousand €
Allande	19,263	34.6	6,659	2.2	421	9.7	1,862	53.6	10,321
C. Narcea	175,713	7.5	13,235	23.9	41,972	9.9	17,365	58.7	103,141
Degaña	32,233	1.0	308	78.0	25,148	4.4	1,432	16.6	5,345
G. Salime	19,611	9.4	1,849	53.8	10,552	3.5	680	33.3	6,530
Ibias	12,464	11.3	1,413	19.8	2,463	13.5	1,683	55.4	6,905
Illano	3,741	27.6	1,032	0.0	0	18.2	680	54.2	2,029
Pesoz	1,179	40.9	482	0.0	0	3.1	36	56.1	661
San Martín	3,236	41.0	1,328	0.0	0	5.5	179	53.4	1,729
St Eulalia	5,095	24.7	1,256	1.3	64	5.6	286	68.5	3,489
Taramundi	7,123	15.8	1,126	25.9	1,842	5.5	394	52.8	3,761
Villanueva	2,706	28.2	763	0.0	0	19.8	537	52.0	1,406
County	282,364	10.4	29,451	29.2	82,462	8.9	25,134	51.5	145,317
Asturias	16,040,851	2.2	346,825	24.8	3,975,756	9.8	1,563,590	63.3	10,154,680

(Source: Asturian councils' incomes, 2004. SADEI, 2007g)

Primary sector

The primary sector in Asturias, which is defined to a great extent by the orography and climatic conditions of the region, embraces two fundamental

activities, namely, livestock breeding (85.7% of the production at base prices) and agriculture, which only accounts for 14.3% of the production in this economic sector (Table 6.8.) (Consejería de Medio Rural y Pesca, 2005). Certain factors associated with this sector compromise its competitiveness such as small farm size, excessive land division (fragmentation), poor education, ageing workforce and lack of new technology. There is still a high dependence on cattle farming and dairy products due to the lack of alternatives suited to the environment and resources, and despite the limitations imposed by European Union policies (Ministerio de Hacienda, 2000).

Apart from these two main subsectors, the agrofood subsector should also be mentioned. This is basically concerned with the production of dairy items and, in this region, some of the leading companies coexist with small and medium sized industries which have been affected more seriously by the reorganization of the dairy sector. Meat production is the second most important activity in this agrofood subsector although there are other activities which should be mentioned such as cider making or vegetables handling and packing. There are also a growing number of traditional industries based on quality craftworks. As regards the fishing industry in Asturias, the sector is characterised by low productivity and has no importance in the agropastoral inner-Western county.

Table 6.8. Summary of Asturian Agriculture Accounts 2005.

	Millions €	Contribution to total production (%)
Total Agricultural Production (a)	53,639	14.3
Total Livestock Production (b)	321,779	85.7
Meat and Livestock	117,588	(31.3)
Milk	194,726	(51.9)
Others	9,465	(2.5)
Total Production (1)=(a+b)	375,418	100.0

(Source: Production of Asturian Agriculture. Consejería de Medio Rural y Pesca de Asturias, 2005)

Agriculture and Livestock Subsectors

It is of interest to analyse the characteristics of the farms and the land ownership given their relevance in the county. Data were extracted from 1999 Agricultural Census (SADEI, 2004), information from the most recent livestock census carried out as part of Livestock Sanitary management (2006) and from

SIMOGAN 2006 -National System of Cattle Identification and Registry- (SADEI, 2007d).

- General distribution of Agrarian Surface Area (ASA)

Land can be sorted according to its use: cultivated land (herbaceous crops, woody crops, fallows and family gardens), land under permanent meadows or pastures and other land (uncultivated lands, shrublands, forest and woodlands). In 1999, the ASA made up 75.5% of the total area of Asturias, a decrease of 3.7% since 1962 (Table 6.9.). Land under permanent meadows or pastures increased more than 150% during this period, but this increase did not offset the 300,000-hectare loss of cultivated land and other land. The useful agrarian surface⁴ (UAS), however, doubled in size over the same period (Table 6.9.).

Table 6.9. Evolution of landholdings area according to land use in Asturias

	Surface area (%)				
	1962	1972	1982	1989	1999
ASA	100.0	100.0	100.0	100.0	100.0
Cultivated land	6.3	4.9	3.6	3.5	3.5
Meadows and pastures	21.3	22.9	39.7	45.1	55.9
Other land	72.4	72.2	56.7	52.4	40.7

(Source: 1999 Agriculture Census, INE. Results in Asturias. SADEI, 2004)

In 1999, cultivated land accounted for 2.3% of the ASA in the county (Table 6.10.), slightly below the provincial figure (3.5%). This land includes herbaceous crops (cereals, leguminous plants, potatoes, cotton plantations, fodder beet, forage crops, vegetables, etc), fruit trees, vineyards and others. More than 80% of crops in Asturias as well as in the county were herbaceous crops, except in Ibias, which had a lot of fruit trees. 36% of the surface area of the county was land under permanent pastures, covering a surface of at least 20% in all the districts. This type of land consists of permanent meadows and pasture (which accounts for 60.9% of this surface), along with other pastures such as uncultivated lands and scrubland where the latter are used for livestock grazing. The remaining 61.7% of the surface was defined as 'other lands' (40.7% in Asturias as a whole). Three quarters (76.8%) of this was uncultivated land and scrubland, above the provincial percentage of 55.6%, whereas the surface area dedicated to woodland

⁴ UAS consists of cultivated lands and lands under permanent meadows and pastures

was inferior to the regional average (22.3% *vs.* 41.3%). This is a direct consequence of the traditional pastoral culture of the county and of the high recurrence of forest fires in this area.

Table 6.10. Distribution of total agrarian area (%) according to land use. 1999

	ASA	Useful agrarian surface (%)		Other land (%)
		Cultivated land	Permanent meadows/pastures	
County	100.0	2.3	36.0	61.7

(Source: 1999 Agriculture Census, INE. Results in Asturias. SADEI, 2004)

- General characteristics of lands

With regard to the size of the fields, there were a greater number of small farms in Asturias as a whole than in the county. 16% of the farms in Asturias were 1 ha or less in size, and 55% of them ranged from 1 to 10 ha. In the county (Table 6.11.) most of the farms were between 1 and 10 ha in size (33.4 %), although this was well below the provincial figure of 55%. There were a notable number of larger farms in Ibias (12.4% were bigger than 100 ha).

Table 6.11. Distribution of the holdings according to the size per council. 1999

	No. holdings	UAS (ha)	UAS per farm (ha)	Holding size (%)					
				<1ha	1-10ha	10-20ha	20-50ha	50-100ha	>100ha
Allande	499	6871	13.8	1.4	31.9	28.5	25.5	7.0	5.8
C. Narcea	1751	45495	26.0	0.9	26.6	30.0	30.1	7.3	5.1
Degaña	82	3340	40.7	1.2	82.9	2.4	3.7	4.9	4.9
G. Salime	223	2400	10.8	4.9	48.9	20.2	21.1	2.7	2.2
Ibias	412	2696	6.5	3.6	48.8	21.6	9.0	4.6	12.4
Illano	208	2724	13.1	3.9	39.9	27.9	18.3	2.4	7.7
Pesoz	54	559	10.3	7.4	33.3	38.9	14.8	3.7	1.9
San Martín	136	1917	14.4	3.7	27.9	26.5	37.5	2.9	1.5
Sta. Eulalia	111	1558	14.0	4.5	29.7	29.7	26.1	8.1	1.8
Taramundi	196	1674	8.5	0.5	34.7	24.5	33.7	5.1	1.5
Villanueva	103	2306	22.4	1.0	17.5	21.4	29.1	21.4	9.7
County	3775	71537	19.0	2.0	33.4	27.1	25.5	6.4	5.6
Asturias	43510	473109	10.9	16.0	55.0	16.8	8.3	1.2	1.2

(Source: 1999 Agriculture Census, INE. Results in Asturias., SADEI, 2004)

The towns in the study county registered an average UAS per farm of 19 ha compared with the provincial average of 10.9 ha, and some towns doubled or even quadrupled this value, such as Villanueva (22.4 ha) or Degaña (40.7 ha).

Furthermore, there was a high level of fragmentation in the area, with an average number of plots per farm of 27.5 (provincial average of 12.5 plots). Pesoz, Villanueva and Illano had the highest fragmentation of all the towns in Asturias, with figures reaching 41.7, 36.4 and 30.9 plots per farm, respectively.

- *Land ownership and legal personality of owners.*

The predominant type of land tenure in the county was the private ownership (about 77.7%), and another 15.5% was classified as 'other tenures', which included communal lands (Table 6.12.). The remaining 6.9% corresponded to leasehold, and sharecropping was almost negligible. At provincial level, the dominant form of tenure was also private ownership (82.9%), although there was a higher number of leasehold properties (10.5%) and less communal land than in the county. The most frequent legal personality of the owners is the natural person (93.4% of the farms in the county and 96% in Asturias as a whole).

With regard to land tenure of UAS (cultivated lands and permanent pastures), the proportions of communal land and leaseholds properties was greater (22.8% and 10.7% respectively) in the county. The number of properties in private ownership was smaller; 66.0% in the county and 77.6 % in Asturias as a whole. There was a notably high proportion of communal land in Illano, 47.6%, whereas property in private ownership only accounted for 41.2 % of the area.

Table 6.12. Distribution of lands according to ownership. 1999

		Private		Leasehold		Sharecropping		Other tenures	
		ha	%	ha	%	ha	%	ha	%
SAS	County	144,943	77.6	12,509	6.7	354	0.2	28,916	15.5
	Asturias	661,055	82.9	83,922	10.5	1,806	0.2	50,838	6.4
UAS	County	47,246	66.0	7,616	10.7	329	0.5	16,312	22.8
	Asturias	367,120	77.6	75,159	15.9	1,536	0.3	29,294	6.2

(Source: 1999 Agriculture Census, INE. Results in Asturias., SADEI, 2004)

Family labour in Asturian farms was very significant. It was estimated at 38,203 Annual Labour Units (ALU, equivalent to the full time work of a person during a year), which accounted for 94.9% of the total (40,259 ALU) and was the highest figure for all the Spanish regions, except for Galicia. This proportion was even higher in the studied county, reaching 97.2% of the total ALUs. The labour

undertaken by the owner represented 63% of the total family labour in the county, followed by that of their partners (20%), and the remainder corresponded to labour input by other relatives. A similar structure was identified at provincial level. With respect to non-family labour, 85% of the total Annual Labour Units corresponded to permanent employees in Asturias as a whole and 78% in the county, whereas the national figures indicated that temporary workers accounted for 61.1% of the total non-family work.

- *Livestock composition*

Asturias is one of the Spanish regions with the highest contribution of cattle to the state livestock industry. The cattle in the province accounts for 7.3% of the total heads only exceeded by Galicia, Castilla y León, Cataluña, Andalucía and Extremadura. On the other hand, only 0.4% of sheep and 1.5% of goats are bred in Asturias. The province is characterised by the low number of heads per farm, one of the lowest in Spain, together with Galicia. The average number in Asturias is 17.5 animals per farm in the case of cattle, 11.9 for sheep and 20.9 for goats in 2006 (Table 6.13.). This suggests that stockbreeding in Asturias tends to be a family business based on traditional, non-intensive systems.

According to the last census of livestock (SADEI, 2007d), cattle are the main species in farms throughout Asturias, including the studied county (Table 6.13.) where they make up 80% of the total livestock, except in Villanueva and Pesoz where the number of sheep and goats far exceeds the regional average. The concentration of animals in farms (heads per farm) in the county is slightly higher on average than in Asturias as a whole. In this respect we might mention the high ratios as regards stocking rates of sheep and goats in Illano (due to an experimental farm belonging to SERIDA), cattle in San Martín and Santa Eulalia de Oscos, and goats in Allande.

Since cattle are the main livestock species, their composition is analysed. As far as breeds are concerned, the most important one in the county is the local breed '*Asturiana de los Valles*', the proportion of which almost doubled the provincial rate (77% *vs.* 42.8%). This was followed by Holstein cows, which account for 20% of the total cattle in some towns such as Grandas de Salime and Pesoz. However, this figure was below the regional average, which was around 34%. The very small numbers of cows of the other local breed '*Asturiana de las*

Montañas' should also be mentioned (0.4% in the county and 4.5% in Asturias as a whole).

Table 6.13. Distribution of livestock according to species and per town. 2006

	Total number	Cattle			Sheep			Goats		
		No	%	A/F	No	%	A/F	No	%	A/F
Allande	10288	8721	84.8	29.3	252	2.5	19.4	1315	12.8	164.4
C. Narcea	28275	23492	83.1	20.6	3106	11.0	24.9	1677	5.9	23.3
Degaña	419	329	78.5	10.0	90	21.5	11.3	0	0.0	-
G. Salime	3194	3153	98.7	27.7	24	0.8	3.4	17	0.5	5.7
Ibias	2153	1776	82.5	8.7	369	17.1	12.3	8	0.4	4.0
Illano	2861	2007	70.2	19.5	543	19.0	543.0	311	10.9	155.5
Pesoz	2868	432	15.1	17.3	1667	58.1	10.9	769	26.8	18.3
S.Martín	3031	2972	98.1	40.2	14	0.5	3.5	45	1.5	7.5
Sta. Eulalia	3127	3096	99.0	41.3	31	1.0	5.2	0	0.0	-
Taramundi	2210	1196	54.1	12.9	438	19.8	9.5	576	26.1	41.1
Villanueva	2226	1593	71.6	27.5	109	4.9	27.3	524	23.5	131.0
County	60652	48767	80.4	23.2	6643	11.0	61.0	5242	8.6	61.2
Asturias	492405	405520	82.4	17.5	58823	12.0	11.9	28062	5.7	20.9

A/F: Mean number of animal per farm.

(Source: SIMOGAN (2006), Agricultura Asturiana. SADEI, 2007d).

- *Classification of farms according to the main productive objective*

The so-called economic-technical orientation of the farm (European classification of agrarian lands based on relative composition of gross margin, according to different activities) further highlighted the great importance of the livestock breeding, particularly cattle, within the whole primary sector in Asturias and in the county (Table 6.14.). 29.5% of the farms in Asturias breed cattle for meat production, 10 points below the county rate. In order of importance, dairy cattle farms came next, with 19.6% of the farms, although in the county dairy farming only represented 4.4% of the total. A mixed cattle or mixed livestock (with sheep or goats or other herbivores) is present on 79.5% of the farms in Asturias and 79.0% in the county. On the other hand, farms orientated towards agriculture, horticulture, policrops and woody crops constituted only 11.6% of the farms in Asturias, and just 10% of the farms in the county.

Table 6.14. Farms classification (%) according to economic-technical orientation. 1999

County	Agriculture & Horticulture	Woody crops	Cattle			Sheep, goats & others	Granivores	Policrops	Mixed livestock	Crops & livestock
			Dairy	Meat	Mixed					
County	3.4	1.2	4.4	39.3	3.3	11.0	0.8	5.3	20.9	10.4
Asturias	2.7	5.5	19.6	29.5	2.9	19.1	1.6	3.3	8.5	7.3

(Source: 1999 Agriculture Census, INE. Results in Asturias. SADEI, 2004).

Forestry subsector

In spite of the small contribution of this subsector to the regional economy, it is important as the basis of the timber and paper industries (included in the industry sector), and for its key role in land use planning.

According to the III National Forestry Inventory (Ministry of Environment, 2003), forestry land covers 72.1% of the total surface area of Asturias and accounts for 42.5% of the tree-covered area (451.117 ha). The percentage corresponding to this land use in the studied county is even higher at 48%, with some towns exceeding this figure such as Pesoz, Taramundi, Illano, Degaña and Cangas (>50%). These figures reveal the high potential of this activity, which is still underutilised (low contribution to the local GAV) despite the subsidies granted by the European Union (SADEI, 2004).

It should be remembered that Forestry (silviculture and forest exploitation) was extremely dependant on the public administration until ten years ago, although today, the existence of new enterprises has given momentum to the sector (Casero, 2002). Another hindrance to the growth of the forestry subsector is that most of the forestry land is in private hands and forest exploitation has always been regarded by many as a poor business proposition given the long-term nature of the profits and the scarce subsidies to private landowners. In 2000, the contribution of the forestry subsector to the total agrarian GAV bp was only 8.4%.

The amount of employment generated by Forestry in Asturias is also very small. In 2005 it provided only 0.2% of the total employment (SADEI, 2007d), although it acquires a special importance in rural areas where employment is scarce, helping to establish settlement in rural areas. In the studied county, forestry generates 1.7% of the total employment and 5.4% of the total in the primary sector (Table 6.15.).

Table 6.15. Agrarian employment. 2005

	Total	Agriculture and Livestock		Forestry	
		No	%	No	%
County	2598	2457	94.6	141	5.4
Asturias	22711	21837	96.2	874	3.0

(Source: The Asturian agricultute. SADEI, 2007d)

Industry Sector

The crisis which has been affecting the industry sector in Asturias, for more than a decade, has resulted in changes to the regional composition of Gross Added Value (GAV). Today, Asturias has become a blatant example of a region with an industrial tradition in decline. The industrialisation process in Asturias, which was based on the traditional sectors of mining, iron and steel and shipbuilding, gained strength in the 50s, but then started to enter a crisis in the early 70s (Ministerio de Hacienda, 2000). As a result of the crisis, the contribution of industry to the regional GAV bp has declined. Between 1995 and 2006 it fell more than five points (27.8% *vs.* 22.2%) (INE, 2006a). Nevertheless, the contribution of the sector to the Asturian economy is still significant in comparison the Spanish average.

According to the 2006 DIRCE (Central Directory of Enterprises) (INE, 2006b) there were 4,322 active companies included in this sector in Asturias, comprising 1.8% of Spanish total and employing 2.4% of the total industrial workforce in Spain.

The Asturian industry sector is characterised by its specialization and the lack of diversification. In 2006, the areas of industry which employed the most workers were the metallurgy and manufacturing of metal products with nearly one third of the total industrial workforce (SADEI, 2007a), followed by mining, quarrying and companies related to energy and water supply (14.7% of the industrial workers). Food, beverages and tobacco manufacturing accounted for a further 14.3%.

If the situation is assessed in terms of the number of employees and the number of companies, we find that there were a large number of small companies, with no employees at all or less than 10 employees (95.2% of the industrial companies). Only 0.3% of companies employed more than 100 workers (mining, steel and iron industry, chemical industry, electricity, gas and water supply

industry). However, the latter companies employed 52.5% of the total occupied population in this sector.

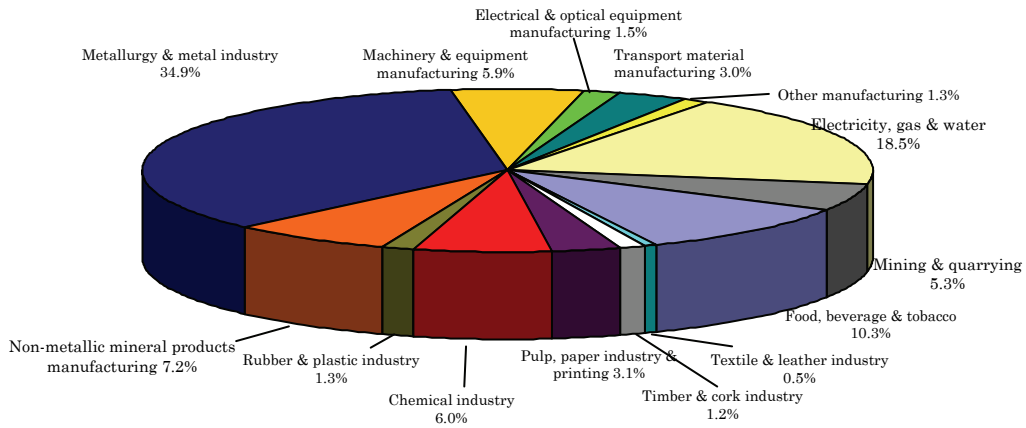


Figure 6.10. Sectorial distribution of the industrial GAV in Asturias. 2006 (Source: Industrial Companies Survey, INE. SADEI, 2007a).

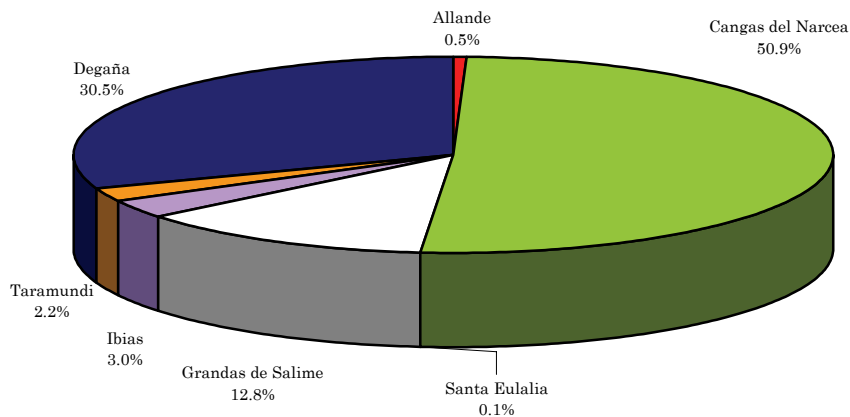


Figure 6.11. Contribution of the different councils to the industrial local GAV.2004

Note: Illano, Pesoz, Villanueva and San Martín de Oscos do not appear because their contribution is zero.

(Source: Asturian councils' incomes, 2004 (SADEI, 2007g).

The greatest contribution to the Asturian industrial Gross Added Value (34.9%) comes from metallurgy and the manufacturing of metal products (Figure 6.10.). The next highest contributors are those companies associated with electricity, gas and water supply, food products, beverages and tobacco as well as

the manufacture of other non-metallic mineral products, mining and quarrying which together contributed with 47.3% of the regional GAV within industrial sector.

A Company Census in 2006 (Cámara de Comercio de Oviedo, 2006) revealed that 7.3% of the companies located in the county belonged to the industrial sector. 59.3% of these are situated in Cangas del Narcea, and 12% are located in Taramundi (associated with the traditional iron manufacturing industry). Most of the companies are related to food and beverages production (26.4%) or the manufacturing of wood and metal products (19.5% and 14.9% respectively). The majority of these companies are small establishments, with less than 10 employees, except for the mining and quarrying industries (12.6% of the enterprises) located in Degaña, Cangas del Narcea and Ibias which employ more than 100 workers.

In 2004, the contribution of the industry to the local GAV reached 29.2% thanks to the high input from some towns (SADEI, 2007g). These towns were Degaña and Ibias (mining industry), Taramundi (traditional manufacturing of knives and pocket knives), and Grandas de Salime (food related, especially dairy sector). The high contribution from these towns offset the lack of industry in other towns such as Illano, Pesoz and the Oscos region (Figure 6.11).

Construction Sector

The socioeconomic importance of the construction industry lies, not only in its contribution to the regional GAV bp (14.3% in 2006), but also in the multiplier effect which it provides for other economic activities. Through the creation and improvement of infrastructures such as road networks, telecommunications, hydraulic and energy-production works, a knock-on effect is produced in other areas of industry, enabling Asturias to be more competitive and, thus, increase the possibilities of industry and services sectors. Construction is therefore a key sector to boost economic growth in Asturias (Ministry of Hacienda, 2000).

According to the DIRCE (INE, 2006b), in 2006, the companies related to this sector accounted for 14.1% of all the companies in Asturias and the annual average number of workers was estimated at 11.5% of the total occupied population in Asturias.

In 2006, 15.3% of the companies appearing on the census of district councils in the county (Cámara de Comercio de Oviedo, 2006) fell into the construction sector. In some towns, there were no construction businesses (Pesoz and San Martín de Oscos). However, 66.3% of the total were located in Cangas del Narcea. As regards to employment, 11.1% of the workforce resident in the county worked in this sector.

The GAV bp generated by construction in Asturias increased more than 200% between 1995 and 2006. However, in this respect, the construction sector continued to trail behind the service and industry sectors although its growth rate was higher. In the studied county, data from 2004 (SADEI, 2007g) shows a smaller contribution (8.9%) than that for Asturias as a whole in that year (9.8%).

Service Sector

The situation in the service sector is the opposite of that in the industrial sector. A steady *terciarization* of the regional economy has taken place, although not to the same extent as has occurred nationally (INE, 2006a). In Asturias, this sector accounts for 61.2% of the regional GAV bp, 64.5% of workers (INE, 2006c), and 79.8% of the total companies censused (INE, 2006b). Commerce and the hospitality industry are the mainstays of this growth. It should be mentioned that tourism has gained considerable importance during recent years, providing further business opportunities.

The most recent data at local level reveals that the service sector contributes more money to the local GAV than any other economic activity (51.5% in 2004) (SADEI, 2007g). This sector also has the most companies (80% of those censused by the Cámara de Comercio de Oviedo, 2006) and employs the most workers (43.5% of the occupied population) (SADEI, 2005a). However, there are notable differences between districts. Thus, Santa Eulalia de Oscos, Cangas, Ibias and Illano showed a relative high degree of *terciarization*, with a local contribution to the GAV over 60%, whilst the contribution of Degaña and Grandas did not exceed 35%.

Commerce comprises 47% of the businesses included in the tertiary sector in the county (nearly 14 points above the provincial rate of 33.4%, Figure 6.12.), and the hospitality industry accounts for 29% of the companies (more than double the provincial figure of 15.8%). The fact that other types of services are lacking in the

majority of districts in the studied area, means that the inhabitants of the county have to go to bigger towns for certain types of goods or services.

As regards the commerce, 73.5% of the shops were retail shops, surpassing 60% in every council, except for Ibias, where wholesale trade is important. Within the retail trade, large number of establishments trade with food, beverages and tobacco and there are a surprisingly high number of non-specialized stores with a mix of products ranging from food and household goods to hardware and textiles, etc. The existence of this kind of outlet is understandable given the small size of these towns since the greatest demand from the limited population will be for basic essentials and daily consumption products (grocer's, tobacconist's, butcher's, baker's...).

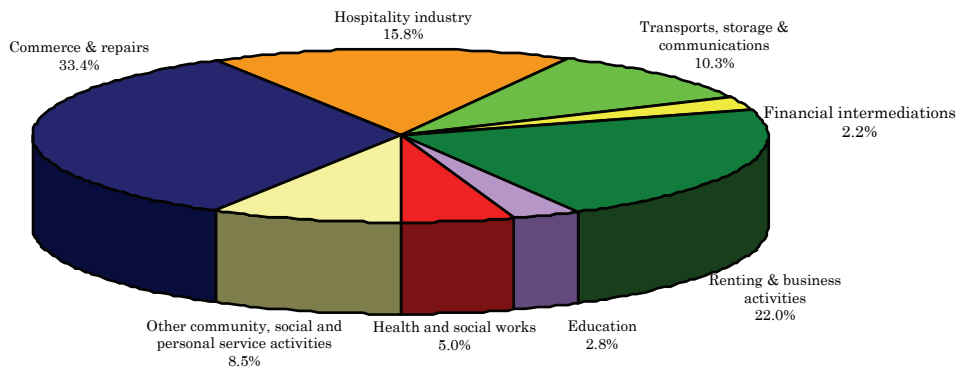


Figure 6.12. Distribution of the companies related to the tertiary sector in Asturias according to the different areas of activity. 2006.

(Source: DIRCE. INE, 2006b).

Tourism is considered the other key activity within the service sector, and it is currently a growing sector both in Asturias as a whole as well as in the county. Tourism also has a multiplier effect on the economy because it not only brings direct profits, but also results in indirect benefits, for example, from the investment in infrastructures required for this tourism. In Asturias, tourism is enjoying a period of continuous growth which has led to an increase in the supply of accommodation, especially rural housing. The hotel industry is also experiencing this expansion with the creation of 'first-class'. The advance Annual Report 2006 *Tourism in Asturias*, issued by the 'System of Tourist Information in

Asturias' (SITA, 2007), reports a steady increment in the number of tourists in over the last few years (e. g. the number of tourist in 2006 was 6% higher than in 2005).

As a consequence of this trend, the amount of accommodation in the county is also increasing. 32.8% of this accommodation is situated in Cangas del Narcea, and another 35.2% in Taramudi and Santa Eulalia. The preferred option (40% of the business) is rural housing (above the mean provincial rate of 37.3%). Hotels provide another 28% of the accommodation in the area (Sociedad Regional de Turismo, 2004).

Summary and final thoughts

The Demographic Analysis shows that the inner-Western county of Asturias is one of the many rural areas in Spain that suffered considerable depopulation during the last century, losing more than the half its population. With a mean density of 9 people km⁻², it lost most of its population in the 60s, and this fall has continued up to the present although the rate of shrinkage has decreased.

The main reason for this depopulation seems to be the unfavourable balance of migration. Over the last few decades, the population of these towns has tended to move to the central part of Asturias, economically the most dynamic and industrialised area in the region. This migratory flow continues to occur, with population migrating not only to the central part of the province but also to other parts of Spain. Since the late 90s, foreign immigration has grown considerably in Asturias, but the county has not been the preferred choice for the immigrants. Thus, although the balance of migration with other countries is positive, it has not offset the loss of population.

In addition, the remaining population of this region is ageing, more than the rest of Asturias and Spain (the ageing index in this region doubles the index for Asturias and quadruples that for Spain). There are also more men than women within the adult population.

This situation, together with the changing scenario of the current society, which is characterised by increased participation of women in the labour market, lack of job security, and housing problems, has led to a lower proportion of marriages and births, an increase in the average age of maternity and a decrease

in the number of births per woman. Furthermore, the ageing of the population has led to an increase in the mortality rate, compounding the already negative balance of this society.

Another important aspect of the population in this area is the low level of education. The county has the highest percentages of illiterate people in the whole of Asturias, reaching almost 4% in some towns (Illano and Ibias). There are also a high number of people classed as 'uneducated' or who only have a primary level. Education is key to the progress of the society since the level of education can limit access to the job market, impede social mobility and consequently, hinder the development of an area.

The question which remains is; why people are leaving the studied region?

In terms of wealth, the studied area is also one of the poorest in Asturias. Some of the towns have been listed amongst the poorest towns for many years, and in 2004 the average household income was 14% below the regional mean. In this county, there are only three towns with an acceptable family income per capita rate: Cangas del Narcea, Ibias and Degaña. The average income is higher in these towns thanks to a greater presence of industry and services.

The analysis of the labour market shows a drop in employment creation over the last few years as a result of the rural to urban migration of economically active population to more dynamic regions. On the one hand, one consequence of this emigration is a low unemployment rate, but on the other hand, the county has a very low activity rate (the ratio of people over 16 years old either working or looking for work to all the people of working age), which indicates a high number of inactive people, such as pensioners or women who work at home or on family run farms but are neither registered with the Employment Agency nor pay National Insurance contributions. The lack of economic dynamism in the area means that job opportunities are few and far between. Consequently, many of the unemployed are people looking for their first job.

The main activities in the region fall into the primary and the tertiary sectors. Although the latter contributes more to the zonal Gross Added Value (51.5%), with more workers (43.5%) and more companies (75.6%), the county is a rural area and as such is very dependant on the primary sector. This sector contributes 10.4% to the GAV and employs 27.6% of the resident workers.

Within the primary sector, the main activity is the livestock farming which accounts for 85% of the sectorial GAV. This is partly a consequence of the complex topography, more suited to livestock than to agriculture farming. Hence, only 2.3% of the total agrarian surface of the county is devoted to cultivated land, while 83% comprises permanent pastures and shrublands.

Both for historical reasons and as a consequence of the topography, Asturias has a higher than average percentage of smallholdings in comparison with the rest of Spain (93.2% of the holdings are smaller than 20 ha). The farms in the studied county are characterised by a high proportion of useful agrarian surface (this can be considered as a sign of greater land utilisation) as well as a high atomisation of it, with many plots per holding (exceeding 30 plots in some towns). Private ownership of property is the predominant form of land tenure (about 77.7%), but communal lands are also important (15.5% of the land, and 22.8% of the useful agrarian land). Most of the private properties are family run, with family labour accounting for more than 97% of the Annual Labour registered. The county and Asturias in general, are characterised by a low number of heads per farm. This reflects the fact that livestock farming in Asturias tends to be a family business based on traditional, non-intensive systems.

The main livestock in the county is beef cattle, and especially the local breed '*Asturiana de los Valles*' (77% of the total cattle), although dairy cattle (Holstein cows) are frequent in some districts. On the other hand, small ruminants are very scarce and are present in only a few towns.

The tertiary sector in the county is mainly made up of retail commerce. There are a large number of establishments that trade with food, beverages and tobacco and a surprisingly high number of non-specialized stores with a mix of products ranging from food and household goods to hardware and textiles etc. Thus, since the towns are small, there are not many businesses in the area and those which do exist tend to provide basic essentials and products for daily consumption (grocer's, tobacconist's, butcher's, baker's...), together with a number of bars and cafes.

The other important subsector within the tertiary sector is the hospitality industry, which is currently experiencing a period of expansion. In the County,

the supply of tourist accommodation, particularly rural housing, continues to increase in Cangas del Narcea, Taramundi and Santa Eulalia de Oscos.

In summary, the tertiary sector contains the greatest number of businesses, creates the most employment, contributes most to the GAV, and of the three sectors it is that which offers the greatest opportunities for future growth, particularly in the field of tourism. However, the importance of the tertiary sector in the study area, which is characterised by low diversification and lack of services, is far below the national or regional level.

Finally, with regard to the secondary sector, the county is a mainly a rural area with very little industrialization compared to other regions of Asturias, and the existing industry (basically production of handicrafts, food and beverage products and mining) is concentrated in 5 districts: Degaña, Ibias, Taramundi, Cangas del Narcea and Grandas de Salime, raising the local industrial contribution to the local economy and offsetting the total lack of industry in other towns. On the other hand, growth in the construction industry within the county was confirmed by data from 2006 which revealed a contribution of 14.3% to the local GAV, although again, this figure is well below that for the whole country. Construction in the area is a key element which is more concerned with improvements to the local infrastructures than with speculative building.

Considering all the aspects discussed above, it becomes clear that studied county is an example of a rural area in state of abandonment. Young people leave the area in order to find better job opportunities than those offered by agriculture as well as to improve their standard of living. The remaining people are ageing, and consequently there is less business initiative. The likelihood of modernizing farms by introducing new knowledge and technology also decreases with the loss of the younger generations. This rural to urban exodus not only endangers the continuity of old traditions, values and ways of living, but also jeopardized the landscape. The studied region, with a tradition of livestock farming, has lost many forested areas over the centuries. Today, with the abandonment of the agrarian activities, shrublands have become more abundant and have an increased amount of phytomass. This increases the risk of fire and in recent years, fires have become more frequent, leading to increased erosion.

New plans and policies should be devised in order to create better conditions for people living in these less-favoured areas. Support should be

provided to the local population by land use managers and other experts in order to reorganize farms as sustainable systems.

7. Pastoral management of heath and gorse communities.

7.1. Grazing behaviour of ruminants according to flock type and subsequent vegetation dynamics on improved heathlands

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Abstract

The management of different livestock species may promote different vegetation dynamics that will affect subsequent animal performance and the sustainability of extensive grazing systems for meat production. The complementary use of goats in partially improved heathlands grazed by cattle or sheep may enhance the effective utilisation of these heterogeneous resources. The grazing behaviour of two livestock species (cattle and sheep) under two different managements (monospecific or mixed with goats), and the subsequent vegetation dynamics were studied on mechanically cleared heathlands (*Ulex gallii* Planchon, *Erica* spp.), with one third improved with perennial ryegrass-white clover pasture (*Lolium perenne* L.-*Trifolium repens* L.). The experiment was carried out from 2002 to 2006. Results showed that animals in mixed herds spent more time grazing than in monospecific groups. Goats spent more proportional time grazing on shrubland

(0.68) compared to sheep (0.35) and cattle (0.19), which spent most of the time on the improved pasture. The analyses of diet composition also confirmed that these two animal species basically selected herbaceous species (0.89-0.95) whilst gorse was an important element of goats' diets (0.28). Vegetation dynamics showed an increment of gorse cover, height and phytomass during the experiment, especially remarkable under single grazing management, whereas dead matter and herbaceous covers decreased more under single than under mixed grazing. Besides, a higher increase in heather percentage and gorse height were found under cattle than under sheep grazing. On the improved areas the sward height was significantly higher with cattle treatments, and the gorse sprouting was more controlled under sheep grazing treatments. It is concluded that the complementary grazing of goats can enhance the utilisation of these heterogeneous plant resources, providing a more efficient way for both productive and environmental goals than single cattle or sheep grazing, in order to achieve the sustainability of grazing systems.

Key words: Cattle; Sheep; Goat; Diet selection; Heathland; Succession

Introduction

Heathlands are shrubby vegetation communities covering large areas of the Atlantic regions of Western Europe with acidic and poor soils (Webb, 1998). With some exceptions, these communities are serial stages that evolve through succession into forest climax communities (Díaz González & Fernández Prieto, 1994). In most of its natural distribution area, i.e. from Brittany (France) to Scandinavia and eastwards, heathland areas have decreased drastically during the last century, mainly due to the replacement of traditional livestock farming by intensive systems (overgrazing, agricultural transformation) and eutrophication (Diemont et al., 1996; Webb, 1998), being actually reduced to small and fragmented areas whose conservation is seriously endangered (EC Habitats Directive 92/43/ECC). In contrast, heathlands are actually widespread in the Northern Spain and Portugal as consequence of the abandonment of agricultural and livestock managements since 1950s, particularly in the most infertile and erodible lands where the succession to forests is restricted by soil thickness and fertility, and by frequent fires.

In Asturias, heathlands cover 21% of the total area (Álvarez et al., 2004)

and are usually extensively managed with domestic livestock, mainly feral cattle and horses, at very low stocking rates. In the last decades, the increasing frequency of wildfires associated to these shrublands (Marquínez et al., 2003), characterised by its high combustibility and flammability (Núñez-Regueira et al., 1996), is becoming a problem as recurrent fires are causing a great soil erosion in many areas, with high environmental and economical losses (MMA, 2007). Hence, it means a high risk for the conservation of the natural resources and the rural development of these marginal and less-favoured areas (Hadjigeorgiou et al., 2005).

The productivity of heathlands is quite low, mainly due to the low nutritive value of the dominant woody species for grazing livestock (Hodgson & Eadie, 1986; Osoro et al., 2007). Currently, partial transformation of heathlands is being studied, establishing adjacent areas of improved pasture, usually of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*), to meet the nutritional requirements of livestock (Osoro et al., 1999). Also some heathland areas are mechanically cleared to reduce the encroachment of woody plants such as heather species (*Erica* spp, *Calluna vulgaris*) and gorse (*Ulex* spp), increasing consequently the presence of herbaceous species and preventing fires. However, the benefit of such investment procedures will depend on the following grazing management (livestock species and breed, single or mixed grazing, stocking rate, etc.).

Animal species display different foraging behaviour due to their different eco-physiological adaptations (mouth and dental anatomy, digestive capacity, etc.), and therefore they have different ability to exploit the available plant resources (Hofmann, 1989; Illius & Gordon, 1993). Cattle are primary grazers that hardly consume woody plants like heather and gorse (Aldezabal, 2001; Celaya et al., 2007b). In contrast, small ruminants like sheep or goats are able to select more efficiently the green shoots of these shrubs, complementing their diet when the availability of green herbaceous pasture is reduced (Grant et al., 1984; 1987). Nevertheless, sheep are able to graze on very short swards without reducing the level of intake below their maintenance needs (Osoro et al., 2000c). On the other hand, goat is a more browser species that uses woody species at a higher degree than the former (Lu, 1988; Narjisse, 1991). Therefore, the utilisation of different animal species may promote different vegetation dynamics

that will affect subsequent animal performance and the sustainability of extensive grazing systems for meat production. The complementary use of goats in partially improved heathlands grazed by cattle or sheep may increase the effective utilisation of these heterogeneous resources (Allan & Holst, 1996), i.e. reducing the encroachment of shrubs and controlling the re-growth of invasive plants like gorse (Radcliffe, 1985; Celaya et al., 2007a), as well as diversifying the production.

The objective of this work was to study different grazing managements (type of flock) on mechanically cleared heathland areas with one third of improved perennial ryegrass-white clover pasture, regarding aspects on grazing behaviour and subsequent plant succession in the heathland areas. For this purpose, single grazing of cattle and sheep and mixed grazing of the former species with goats were assessed.

Material and Methods

Study site

The experimental site was located in the North-west of Spain, San Isidro mountain range, Illano, Asturias (43° 21' N, 6° 53' W), at an altitude of 950-1000 m a.s.l. The climate is oceanic, humid temperate of medium mountain, with annual mean temperatures of 10.2°C (averaged 4.7°C in January and 16.1°C in August) and annual rainfalls of 1550 mm occurring mainly from October to January (data recorded in the experimental site from 2002 to 2007). The soils are shallow acidic (pH around 4) and with deficiency in most of nutrients, particularly phosphorus, calcium and magnesium (2, 6 and 25 mg kg⁻¹, respectively).

The natural vegetation is composed of shrublands dominated by heather species such as *Erica umbellata*, *E. cinerea* and *Calluna vulgaris*, together with gorse (*Ulex gallii*), a thorny and woody legume. Herbaceous species, mainly tough grasses such as *Pseudarrhenatherum longifolium* and *Agrostis curtisii*, cover the gaps remaining among the shrubs. This community is classified as *Halimio alyssoidis-Ulicetum gallii* association (Díaz González & Fernández Prieto, 1994).

Experimental design and animals

The trial was conducted in eight plots (0.9-2.7 ha), grouped in two blocks

(Table 7.1.1.). The plots were established in a west-facing slope, originally covered with heather-gorse shrublands. In 2001 all surface was mechanically cleared using a brush cutter, and one third of the area was improved by ploughing, dressing and sowing perennial ryegrass and white clover. Heathland area was in the upper part of the plots and the improved pasture area was in the lower one. Although each plot had an outer fence, no fences were used between the different vegetation areas, so animals had access to every type of vegetation within the plot.

Table 7.1.1. Total surface area of the experimental plots and number of animals managed in each year and treatment: CA: cattle alone; C+G: cattle with goats; SA: sheep alone; S+G: sheep with goats.

Livestock Management Treatment	Block 1				Block 2			
	Cattle		Sheep		Cattle		Sheep	
	Alone CA	Mixed C+G	Alone SA	Mixed S+G	Alone CA	Mixed C+G	Alone SA	Mixed S+G
Plot area (ha)	1.8	2.7	0.9	1.8	2.7	2.7	0.9	1.8
Animals ⁽¹⁾								
2002	4 b	4 b + 12 g	12 s	12 s + 12 g	7 b	4 b + 12 g	12 s	12 s + 12 g
2003	2 c	3 c + 20 g	10 s	10 s + 10 g	3 c	3 c + 20 g	10 s	10 s + 10 g
2004	2 c	4 b + 12 g	9 s	9 s + 9 g	3 c	4 b + 12 g	9 s	9 s + 9 g
2005	2 c	4 b + 16 g	10 s	10 s + 10 g	3 c	4 b + 16 g	10 s	10 s + 10 g
2006	2 c	3 c + 18 g	10 g	12 s + 12 g	3 c	3 c + 18 g	10 s	12 s + 12 g
2007	2 c	3 c + 22 g	12 g	18 s + 18 g	3 c	3 c + 22 g	12 s	18 s + 18 g

⁽¹⁾ b: yearling bulls; c: cows with calves; s: ewes with lambs; g: goats with kids.

Each block comprised two plots with cattle and two plots with sheep, both under two management options (monospecific or mixed herds with goats). Therefore, four treatments replicated twice were studied: cattle alone (CA), cattle with goats (C+G), sheep alone (SA) and sheep with goats (S+G). Asturiana de los Valles beef cows with their winter-born calves or yearly bulls grazed at a stocking rate of approximately 1.1 lactating cows per hectare or 1.5-1.7 yearly bulls per hectare, and in mixed herds (C+G) a ratio of 1 cow to 7 goats was established (Table 7.1.1). Sheep of Gallega breed and Cashmere goats, with their lambs and kids, grazed at a stocking rate of 10 adult breeding females per hectare, and in mixed flocks (S+G) they grazed at a ratio of 1:1. These treatments were maintained during four grazing seasons (from April-May to October-November), from 2002 to 2005. In the following growing seasons (2006 and 2007), the plot with sheep grazing alone of one block was replaced by goats to compare their

grazing behaviour at single grazing.

In addition to the grazing treatment plots, at the beginning of the experiment (2002) small enclosures of approximately 20 x 4 m in the heathland areas were fenced and excluded from grazing as control treatment (no grazing). There were six ungrazed enclosures (three per block) allocated in between the large grazed plots.

Every year animals were balanced for body weight and randomly assigned to each plot according to the treatment. Lambs and kids were born in March-April and weaned in July. Calves were born in February-March and weaned in September. Ewes were sheared in July. All animals were drenched with ivermectin (Oramec®, Merial Lyon, France) against gastrointestinal nematodes two weeks before turning them out.

Grazing behaviour and diet selection

The time spent grazing by each animal species on each vegetation type (improved ryegrass-clover pasture or cleared heathland) was determined by recording the grazing activity of adult animals every 15 minutes from dawn to dusk during two consecutive days in 2003 (14-15 May), 2005 (17-18 July), 2006 (18-19 July) and 2007 (30-31 July).

The composition of the diet selected by grazing animals was estimated in May of 2003 and 2004 using *n*-alkane markers (Dove & Mayes, 1991). Faecal grab samples were collected from individual animals in each plot. Samples of the main plant components, gorse, heather, natural grasses (*Pseudarrhenatherum longifolium* and *Agrostis capillaris*), perennial ryegrass and white clover, were also collected. All samples were stored at -20°C and then freeze-dried and milled prior to analytical procedures. The alkanes (from C₂₁ to C₃₆) were extracted using the method of Mayes et al. (1986) modified by Oliván and Osoro (1999), and quantified by gas chromatography. The proportions of the plant components in the diet were estimated using an iterative least-squares procedure (ILS; Dove & Moore, 1995) which minimises the discrepancies between the observed concentrations of each *n*-alkane in the faeces and the estimated proportions of plant components in the diet. Alkanes from C₂₅ to C₃₃ were used in the ILS due to the very low concentrations of shorter- and longer-chain alkanes in both faeces and herbage. Faecal alkane concentrations were previously adjusted for

incomplete faecal recovery using recovery data obtained in validation studies carried out with cattle (Ferreira et al., 2007a), sheep (Ferreira et al., 2007b) and goats (Ferreira et al., 2005). The inclusion of clover in the ILS gave non-sensical results, probably because of its much lower alkane concentrations than the other plant components, so it was removed from such procedure. Even more, the grass species had similar alkane profiles and thus could not be discriminated from each other, so their averaged alkane concentrations were used in the ILS, coming to three final diet components: gorse, heather and herbaceous plants.

Vegetation measurements

Chemical composition of plant samples harvested in May of 2003, including gorse, heather, natural grasses (*P. longifolium* and *A. capillaris*), perennial ryegrass and white clover, was analysed following the procedures of the Association of Official Analytical Chemists (AOAC, 2006) for ash and nitrogen (N). Crude protein (CP) was calculated as $N \times 6.25$. Neutral-detergent fibre (NDF), acid-detergent fibre (ADF) and acid-detergent lignin (ADL) were analysed by the methods of Van Soest et al. (1991).

In order to evaluate the herbage availability in the improved pasture and assess the grazing pressure over it, the sward surface height was measured several times throughout the grazing seasons since 2002 to 2005, recording randomly 100 measurements per plot using the HFRO swardstick (Barthram, 1986). The number of samplings was not homogenous among years and thus, the mean heights of pasture of each plot were averaged for two periods, i.e. from April-May to the end of July and from August to October-November, henceforth referred as P1 and P2, respectively.

At the beginning of each grazing season, plant cover and height in the cleared heathland areas were assessed using the point-quadrat technique (Grant, 1981) along five 13 m-long permanent transects in each plot. Transects were randomly allocated the first time and marked. In every transect, 100 vertical hits at 4 cm intervals were recorded, grouped in 5 segments separated 2.2 m each other (500 hits per plot). In May 2006 the ungrazed enclosures were also controlled using the same technique and recording 100 hits per enclosure (300 per block).

Phytomass samples were collected in the shrubland areas every year,

harvesting the vegetation contained in 0.2 x 1 m quadrats at ten random sites on each plot at the beginning of every grazing season. The samples were fresh weighed, and four of those with middle weights were selected for subsequent separation into three main components: gorse, heather and herbaceous plants. These botanical components together with the non-sorted samples were dried in a forced-air oven at 80°C for 24 h and weighed for dry matter (DM) determination. The composition from the sorted samples was applied to the total phytomass accounted for the ten samples from each plot. In 2006, phytomass from ungrazed enclosures was also sampled taking off six quadrats per block (two per enclosure) and sorting all of them.

The control of gorse sprouting in the improved areas by the different types of flock was estimated in May 2006. A quadrat of 1 m x 1 m was randomly thrown 100 times per plot and the presence or absence of gorse sprouts was recorded, and when present they were clipped and pooled per plot. Then the samples were dried in a forced-air oven at 80°C for 24 h and weighed for DM determination.

Statistical analyses

All analyses were performed using SAS System software (SAS, 2001). Plant chemical composition (CP, NDF, ADF, ADL) was analysed by one-way analysis of variance (ANOVA) to examine the differences between the main plant components.

Sward height in the improved pasture areas was analysed using a mixed model procedure (Proc Mixed), including in the model the fixed effects of livestock (cattle *vs.* sheep), management (single *vs.* mixed grazing), year (2002-2005), and period (P1 *vs.* P2) as the repeated measure, and all the possible interactions among them, considering plots as the experimental units.

Grazing behaviour data were subjected to a General Linear Model procedure (Proc GLM), examining the fixed effects of animal species (A: cattle, sheep, goat), management (M: single *vs.* mixed) and year (Y: 2003, 2005, 2006, 2007), and the interactions A x M, A x Y, M x Y and A x M x Y. In the case of goats, mixed grazing was either with cattle or sheep, so it was previously checked and verified that no significant differences in the goats' behaviour occurred according to the companion species. Diet composition data were analysed using Proc GLM for the effects of animal species, management, year (2003, 2004) and

their interactions, with plots as a random source of variation and individual animals as replicates.

Botanical data (cover, height and phytomass in the shrubland areas) from 2002 to 2006 were analysed using the Proc Mixed for repeated measures (Littell et al., 1998), examining the fixed effects of livestock (L), management (M) and year (Y: 2002-2006) as the repeated measure factor (with plots as the experimental units or subjects), and the interactions L x M, L x Y, M x Y and L x M x Y. Final botanical data at the end of the experimental treatments (May 2006) were subjected to one-way ANOVA to check the differences between the four grazing treatments and the ungrazed control treatment, using Tukey's test to examine the pair-wise differences. Data from the three ungrazed enclosures in each block were pooled, coming to two replicates, to equalise the sampling effort and accuracy between the ungrazed and grazed treatments. All percentage data were angular transformed prior to analyses.

Data on gorse sprouting in the improved pasture areas (% presence and plant weight) did not meet the homogeneity of variances assumption because of zero values. Thus, the non-parametric Mann-Whitney *U* test was employed to examine the effects of livestock species (cattle *vs.* sheep) and management (single *vs.* mixed) independently.

Results

Nutritive quality of vegetation

Nutritive quality of the vegetation showed significant differences between the main plant components ($P < 0.001$). Clover presented the highest mean CP concentration, 359 g kg⁻¹DM, and heather (108 g kg⁻¹DM) and *P. longifolium* (148 g kg⁻¹DM) the lowest one, even lower than that obtained with gorse (204 g kg⁻¹DM). Cell wall components (NDF) were particularly high in *P. longifolium* (731 g kg⁻¹DM), followed by *A. capillaris* and woody species, gorse and heather (568-576 g kg⁻¹DM). Large differences in the lignin content (ADL) were found. The woody species registered ADL contents around 330 and 132 g kg⁻¹DM in heather and gorse, respectively, being significantly higher than those observed in ryegrass and clover (11 and 17 g kg⁻¹DM, respectively).

Sward height in the improved pasture area

Sward height in the improved pasture area decreased significantly as the season advanced (Figure 7.1.1), averaging 8.7 cm in P1 (from April-May to July) and 5.4 cm in P2 (from August to October-November) across 2002-2005 (s.e.m. 0.27; $P < 0.001$), although the mean values and the decrease rate were also significantly different among years ($P < 0.001$).

The type of livestock (cattle *vs.* sheep) significantly affected the sward height ($P < 0.01$), with higher mean values in cattle grazed plots than in sheep ones (7.7 *vs.* 6.4 cm; s.e.m. 0.29). The interactions between livestock species and year ($P < 0.001$) and between livestock and period ($P < 0.05$) were also significant (with higher differences found in P1 than in P2).

On the other hand, no significant differences were found between both managements (7.09 cm under single grazing *vs.* 7.0 cm under mixed grazing with goats; s.e.m. 0.29), though the interaction with year was significant ($P < 0.001$).

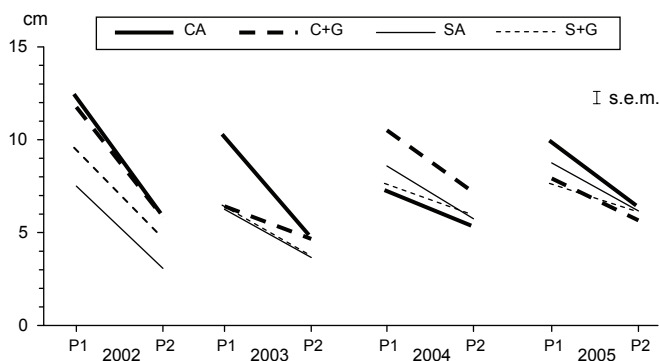


Figure 7.1.1. Mean sward height in the improved pasture area grazed by cattle alone (CA), cattle with goats (C+G), sheep alone (SA) or sheep with goats (S+G) across four grazing seasons (P1: from April-May to July; P2: from Aug. to Oct.-Nov.)

Foraging behaviour

Grazing time

In general, goats spent more time grazing than cattle and sheep (595, 550 and 512 min day⁻¹, respectively; $P < 0.05$), though there was a strong interaction with year ($P < 0.001$). In 2003, sheep grazed more time than cattle, while in 2007 the grazing times of both sheep and goats were much lower than those observed in cattle (Figure 7.1.2).

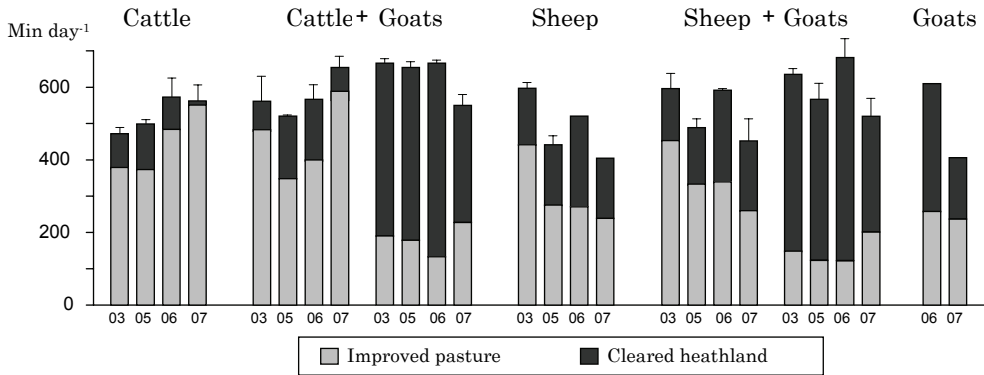


Figure 7.1.2. Distribution of the daily grazing time of cattle, sheep and goats on improved pasture areas and mechanically cleared heathland areas according to the type of flock (single or mixed grazing). Vertical bars show standard deviations of total grazing time.

The grazing management (type of flock) also affected significantly the grazing time ($P < 0.001$); all three species grazed for longer when they were managed in mixed herds compared to single grazing (576 *vs.* 524 min day⁻¹ in cattle; 534 *vs.* 491 in sheep; 605 *vs.* 505 in goats in 2006-2007).

Significant differences in the proportional grazing time spent on improved pasture and on shrubland were also registered between animal species (Figure 7.1.2). Goats spent more grazing time on shrubland (0.68) than sheep (0.35) and cattle (0.19; $P < 0.001$). Furthermore, these values varied according to the type of flock ($P < 0.05$). The time spent by cattle and sheep on improved pasture was slightly higher in monospecific groups compared to mixed herds (0.84 *vs.* 0.78 in cattle, 0.67 *vs.* 0.64 in sheep), while the difference was especially noted in goats (0.50 *vs.* 0.30 in 2006-2007), although no significant interaction was found between animal species and management. Year had a significant effect on the proportional times grazing on improved pasture or shrubland ($P < 0.01$), but no significant interaction of year with animal species or management was observed.

Diet selection

The proportions of the main vegetation components selected by each animal species in different types of flock are shown in Table 7.1.2. Significant differences between animal species were observed in the selection of gorse and

herbaceous species ($P < 0.001$). The mean proportion of gorse accounted for 0.28 in the diet of goats while it accounted for 0.07 in sheep and 0.02 in cattle diets. Herbaceous species represented higher proportions in cattle and sheep diets (0.95 and 0.89 respectively) than in goat diets (0.68). Heather was consumed at similar low proportions by goats (0.04), sheep (0.04) and cattle (0.03). For cattle and sheep, a significant management effect ($P < 0.05$) was observed in the selection of gorse, with higher proportions found in the diets of animals grazing in single flocks (0.05) compared to those grazing with goats (0.03). In general, gorse proportion increased from 2003 to 2004 whilst that of herbaceous plants decreased ($P < 0.05$).

Table 7.1.2. Diet composition of cattle, sheep and goats on partially improved gorse-heather shrublands, according to the flock type (single or mixed grazing). CA: cattle alone; C+G: cattle with goats; SA: sheep alone; S+G: sheep with goats.

Treatment Species (A)	CA		C + G		SA		S + G		Significances			
	Cattle	Cattle	Goats	Sheep	Sheep	Goats	s.e.m.	A	M	Y	A x M	
May 2003												
Gorse	0.013	0.010	0.296	0.072	0.017	0.233	0.044					
Heather	0.038	0.030	0.043	0.025	0.053	0.041	0.009					
Herbaceous	0.949	0.960	0.661	0.903	0.930	0.726	0.043					
May 2004												
Gorse	0.033	0.016	0.172	0.101	0.077	0.343	0.079					
Heather	0.030	0.028	0.034	0.031	0.045	0.037	0.016					
Herbaceous	0.937	0.956	0.794	0.868	0.878	0.620	0.078					
Average												
Gorse	0.023	0.013	0.234	0.087	0.047	0.288	0.040	***	*	*	ns	
Heather	0.034	0.029	0.038	0.028	0.049	0.039	0.008	ns	ns	ns	***	
Herbaceous	0.943	0.958	0.728	0.885	0.904	0.673	0.040	***	ns	*	ns	

A: animal species effect (cattle *vs.* sheep *vs.* goats). M: management effect (single *vs.* mixed), Y: year effect (2003 *vs.* 2004), and A x M only for cattle and sheep. * $P < 0.05$; *** $P < 0.001$; ns not significant ($P > 0.05$). Y x A, Y x M, and Y x A x M interaction effects were non-significant for all variables.

Vegetation dynamics in mechanically cleared heathlands

Cover

In April 2002, data taken at the beginning of the trial reported an initial mean cover of $33.7 \pm 7.12\%$ of live gorse, $4.6 \pm 3.81\%$ of live heather, $29.0 \pm 8.93\%$ of live herbaceous plants and $1.3 \pm 0.94\%$ of bare ground. There was a high cover of dead matter, $31.3 \pm 7.23\%$, mostly due to the debris coming from the mechanical clearing performed the year before.

The cover changes during the trial (2002-2006) are shown in Figure 7.1.3

for each treatment. From 2002 to 2006 the mean cover percentage of gorse increased significantly ($P < 0.001$), while that of herbaceous plants and dead matter decreased ($P < 0.001$). The mean percentages of heather and bare ground showed no significant changes throughout the years (Table 7.1.3.).

There was a significant interaction between type of management and year for all the examined components, due to the different trends found between monospecific and mixed groups. From 2002 to 2006, gorse cover increased more ($P < 0.01$) under single grazing (from 36.6 to 63.1% in CA; from 31.7 to 64.3% in SA) than under mixed grazing (from 38.3 to 48.5% in C+G; from 28.3 to 43.3% in S+G). Heather cover increased under single grazing from 4.4 to 6.0%, whereas it decreased under mixed grazing from 4.9 to 2.9% ($P < 0.05$). The cover of herbaceous plants increased the first year, and then decreased in both managements until the end of the trial, with a higher reduction rate ($P < 0.05$) under single grazing (from 21.5% in 2002 to 7.8% in 2006 in CA; from 32.4 to 17.4% in SA) than under mixed grazing (from 27.0 to 17.4% in C+G; from 35.1 to 31.0% in S+G).

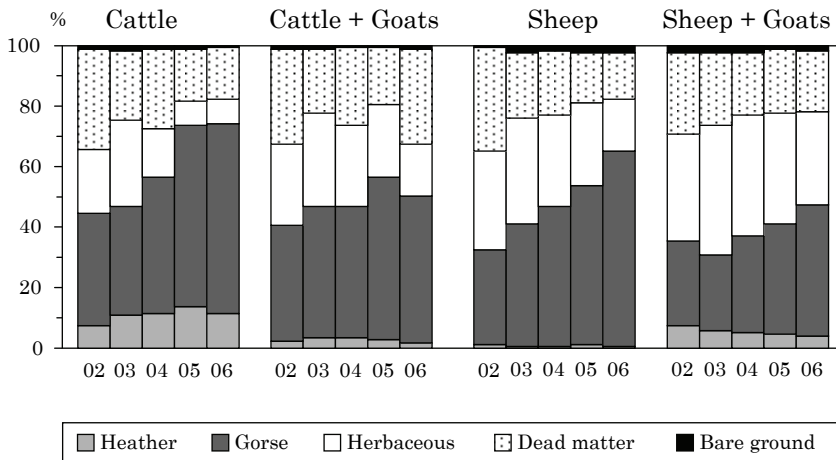


Figure 7.1.3. Mean cover percentages in mechanically cleared heathlands grazed during four grazing seasons by cattle or sheep at single or mixed grazing with goats.

The percentage of dead matter decreased more ($P < 0.05$) under single grazing (from 33.7 to 16.3%) than under mixed grazing (from 29.0 to 25.7%) over the years. The percentage of bare ground increased from 0.9 to 1.5% under single grazing, whereas it decreased from 1.8 to 1.3% under mixed grazing ($P < 0.05$).

Nevertheless, it never exceeded maximum values of 2.3% in any treatment and year.

The interaction between livestock species (cattle or sheep) and year was not significant for any of the studied components, except for heather ($P < 0.05$). Its cover percentage increased under cattle grazing from 5.0% in 2002 to 6.5% in 2006, whereas it decreased from 4.3 to 2.3% under sheep grazing (Table 7.1.3.).

Table 7.1.3. Effects of main livestock species (L: cattle *vs.* sheep), management (M: single grazing *vs.* mixed with goats) and year (Y) on plant cover, gorse height, and phytomass of mechanically cleared gorse-heather shrublands (least square means from 2002 to 2006).

Treatments designated as: CA: cattle alone; C+G: cattle with goats; SA: sheep alone; S+G: sheep with goats.

Livestock Treatment	Cattle		Sheep		s.e.m.	Significances					
	CA	C+G	SA	S+G		L	M	L x M	Y	Y x L	Y x M
Cover (%)											
Gorse	48.2	45.6	47.1	33.0	6.79	ns	ns	ns	***	ns	**
Heather	10.9	2.7	0.8	5.4	2.75	ns	ns	*	ns	*	*
Herbaceous	16.5	25.2	28.3	37.2	4.65	+	ns	ns	***	ns	*
Dead matter	23.3	25.6	22.0	22.6	2.70	ns	ns	ns	***	ns	*
Bare ground	1.1	0.9	1.8	1.9	0.65	ns	ns	ns	ns	ns	*
Gorse height (cm)	14.2	10.6	11.0	8.6	1.14	*	*	ns	***	**	***
Phytomass (kg DM ha ⁻¹)											
Gorse	11914	8242	12980	7559	2279	ns	+	ns	***	ns	*
Heather	2045	735	294	891	609	ns	ns	ns	ns	+	+
Herbaceous	4221	4629	3132	4695	748	ns	ns	ns	ns	ns	ns
Total	18180	13605	16406	13145	1631	ns	+	ns	***	ns	*
Phytomass (%)											
Gorse	62.6	59.9	76.2	57.2	6.81	ns	ns	ns	***	ns	ns
Heather	12.1	5.4	1.8	7.0	3.69	ns	ns	ns	*	**	+
Herbaceous	25.3	34.7	21.9	35.9	6.48	ns	+	ns	**	ns	ns

+ $P < 0.1$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns not significant ($P > 0.1$). Y x L x M interaction was non-significant for all variables.

At the end of the experiment (May 2006), significant differences among treatments were observed in the cover percentage of every component, except for bare ground (Table 7.1.4.). Gorse cover was significantly higher in the ungrazed enclosures (94.3%) compared to mixed grazing treatments (45.9%; $P < 0.05$). Heather cover was higher in CA (11.2%) than in SA (0.7%; $P < 0.05$), although no significant differences were found between the ungrazed treatment and any grazed treatment. The percentage of herbaceous plants was lower in the ungrazed treatment (2.7%) compared to C+G and SA (17.4% in both cases; $P < 0.05$), and to S+G treatment (31.0%; $P < 0.01$). The percentage of dead matter was lower ($P < 0.01$) in the ungrazed enclosures (1.4%) than in the grazing treatments (21.0%).

Height

Mean heights of all examined plant components showed similar trends and similar treatment effects as they were highly correlated among themselves, so only the results concerning the dominant species, i.e. gorse, will be reported (Figure 7.1.4).

Gorse height increased significantly across years ($P < 0.001$). Such increase was significantly ($P < 0.001$) higher under single grazing (from 4.9 cm in 2002 to 18.9 cm in 2006) than under mixed grazing (from 5.2 to 13.3 cm), and it was also higher ($P < 0.01$) under cattle (from 4.9 to 18.4 cm) than under sheep grazing (from 5.2 to 13.7 cm). The mean gorse height resulted significantly different between both managements (12.6 cm under single grazing *vs.* 9.6 cm under mixed grazing; $P < 0.05$), and also between both livestock species (12.4 cm under cattle grazing *vs.* 9.8 cm under sheep grazing; $P < 0.05$; Table 7.1.3.), through the experiment.

At the end of the trial, gorse height was significantly higher in the ungrazed enclosures (53.7 cm) compared to the grazed plots (16.1 cm; $P < 0.001$). The difference was also significant ($P < 0.05$) between CA and S+G treatments (21.9 and 11.5 cm, respectively; Table 7.1.4.).

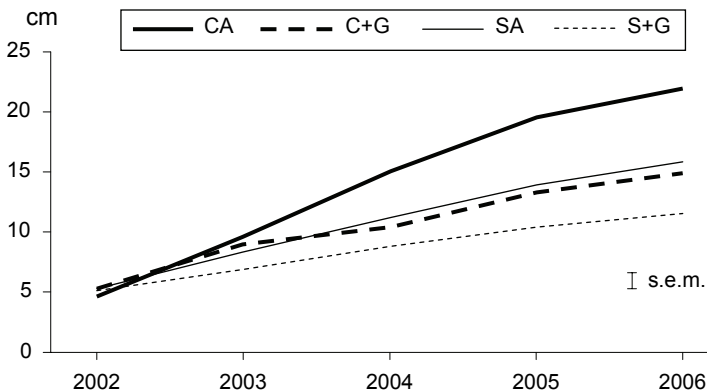


Figure 7.1.4. Mean height of gorse in mechanically cleared heathlands grazed during four grazing seasons by cattle alone (CA), cattle with goats (C+G), sheep alone (SA) or sheep with goats (S+G).

Phytomass

The total amount of aerial phytomass increased significantly ($P < 0.001$) during the experiment from 12.0 t DM ha⁻¹ in 2002 to 20.3 t DM ha⁻¹ in 2006 (Table 7.1.3.), being higher ($P < 0.05$) under single grazing (from 12.2 to 24.4 t DM ha⁻¹) than under mixed grazing (from 11.8 to 16.2 t DM ha⁻¹; Figure 7.1.5.). Gorse

was the main component of the phytomass, so its amount was affected by the same year and management effects. Although its percentage was not affected by the grazing treatment, a significant increase across years (from 58.9 to 72.3%; $P < 0.001$) was observed. Heather percentage increased from 6.8% in 2002 to 7.1% in 2006 under single grazing, whereas it decreased from 9.9 to 4.8% under mixed grazing ($P < 0.01$). The decrease was somewhat greater ($P = 0.052$) under sheep grazing (from 7.2 to 3.3%) compared to cattle grazing (from 9.4 to 8.6%). Herbaceous percentage was reduced across years, from 32.7% in 2002 to 21.8% in 2006 ($P < 0.01$), without significant differences between treatments.

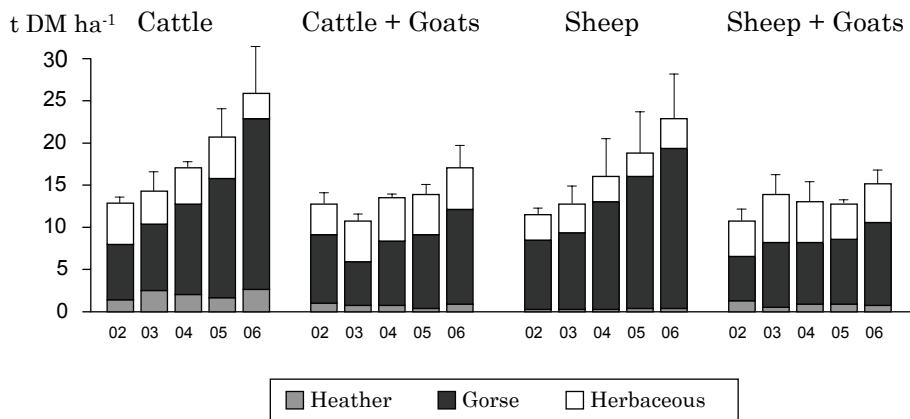


Figure 7.1.5. Phytomass amount and composition in mechanically cleared heathlands grazed during four grazing seasons by cattle or sheep at single or mixed grazing with goats. Vertical bars show standard deviations of total phytomass.

At the end of the trial (2006), gorse amounts (and so total phytomass) were significantly higher under no grazing (36.4 t DM ha⁻¹) than under mixed grazing with goats (10.6 t DM ha⁻¹; $P < 0.05$; Table 7.1.4). Gorse percentage was also greater in the ungrazed enclosures (91.9%) compared to mixed grazing treatments (65.3%; $P < 0.05$). Conversely, herbaceous percentage was lower in the ungrazed treatment (7.1%) than in the mixed grazing treatments (29.9%; $P < 0.05$). CA and SA treatments were not significantly different from the other treatments for any phytomass component.

Table 7.1.4. Treatment effects on the final (2006) cover percentages, gorse height and phytomass of mechanically cleared gorse-heather shrublands. Treatments from 2002 were: CA: cattle alone; C+G: cattle with goats; SA: sheep alone; S+G: sheep with goats; NO: no grazing.

Treatment	CA	C+G	SA	S+G	NO	s.e.m.	sign
Cover (%)							
Gorse	63.1 ^{ab}	48.5 ^b	64.3 ^{ab}	43.3 ^b	94.3 ^a	7.14	*
Heather	11.2 ^a	1.8 ^{ab}	0.7 ^b	3.9 ^{ab}	1.6 ^{ab}	2.20	*
Herbaceous	7.8 ^{bc}	17.4 ^{ab}	17.4 ^{ab}	31.0 ^a	2.7 ^c	2.89	**
Dead matter	17.2 ^a	31.3 ^a	15.5 ^a	20.1 ^a	1.4 ^b	3.40	**
Bare ground	0.7	0.9	2.3	1.7	0.0	0.59	ns
Gorse height (cm)	21.9 ^b	15.0 ^{bc}	15.9 ^{bc}	11.5 ^c	53.7 ^a	1.58	***
Phytomass (kgDM ha ⁻¹)							
Gorse	20272 ^{ab}	11311 ^b	18969 ^{ab}	9840 ^b	36403 ^a	3665	*
Heather	2622	902	417	760	402	870	ns
Herbaceous	3004	4885	3463	4630	2809	814	ns
Total	25899 ^{ab}	17098 ^b	22849 ^{ab}	15230 ^b	39614 ^a	3384	*
Phytomass (%)							
Gorse	76.8 ^{ab}	65.8 ^b	81.8 ^{ab}	64.7 ^b	91.9 ^a	4.45	*
Heather	12.3	4.9	1.9	4.8	1.0	4.71	ns
Herbaceous	10.9 ^{ab}	29.3 ^a	16.3 ^{ab}	30.5 ^a	7.1 ^b	4.40	*

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns not significant ($P > 0.05$). Means with different superscripts are significantly different using Tukey's test ($P < 0.05$).

Gorse sprouting in the improved areas

Gorse sprouts in the improved pasture areas were more efficiently controlled under sheep grazing (0% presence) than under cattle grazing (3.8% presence, 1.0 g DM m⁻²; $P < 0.05$). The management, single or mixed grazing, did not significantly affect the gorse sprouting, although in the case of cattle treatments, both the presence percentage and plant weight were lower in C+G (0.5%, 0.01 g DM m⁻²) than in CA (7.0%, 1.9 g DM m⁻²; $P = 0.121$).

Discussion

Nutritive quality of vegetation

In general, the chemical composition of the main components showed the low nutritive quality of the natural vegetation, particularly of heather. For the sampling date (May), gorse presented high CP concentrations, around 200 g kg⁻¹DM, which seems reasonable for a leguminous plant. Conversely, *P. longifolium* revealed a low nutritive quality, as it is a tough grass, with lower CP concentrations than gorse, and remarkably high NDF concentrations. Similar values were observed in other studies conducted in the same site (Celaya et al.,

2007b; Osoro et al., 2007), even though higher lignin concentrations were found in gorse (200-300 g kg⁻¹DM) in the aforementioned works than in the present one (120-150 g kg⁻¹DM).

As expected the improved pasture (ryegrass and clover) showed a higher nutritive quality compared to the natural vegetation, as described previously in other works (Hodgson & Eadie, 1986; Celaya et al., 2007b), pointing out the convenience of establishing improved pasture areas adjacent to this heathland vegetation, in order to meet the livestock's requirements throughout the grazing season (Maxwell et al., 1986; Osoro et al., 1999).

Pasture availability and grazing pressure

The results showed a general trend for lower sward height in the improved pasture under sheep (SA and S+G) than under cattle grazing (CA and C+G). This is in accordance with other studies where it was observed a higher ability of sheep to graze shorter swards due to their lower intake limitation than cattle (Forbes & Beattie, 1987; Hodgson et al., 1991). In contrast, the effect of grazing management (single or mixed) on sward height was non-significant, indicating that differences in vegetation dynamics in the cleared heathland areas were a consequence of the presence or absence of goats in the flock, and not of a different grazing pressure exerted by single or mixed flocks.

Foraging behaviour

The results showed a rather distinct foraging behaviour among the different ruminant species. Cattle are widely considered as grazers, as they normally select herbaceous species and reject the woody ones (Aldezabal, 2001; Celaya et al., 2007b). This seems to be related to their muzzle anatomy that gives them a lesser ability to feed selectively on the green shoots, despite their higher capacity to digest fibrous components efficiently, i.e. maintaining them for longer time in the digestive tract (Illius & Gordon, 1993). Conversely, small ruminants are able to use woody species when the availability of the improved pasture decreases. However, a distinct foraging behaviour of sheep and goats is acknowledged (Lu, 1988; Narjisse, 1991; Allan & Holst, 1996). Sheep are able to maintain their live weight at a lower sward height (Osoro et al., 2000c) and graze more intensively on improved ryegrass-clover pastures than goats (Grant et al.,

1984). It has been observed that goats select gorse species more intensively than sheep, both *Ulex europaeus* (Clark et al., 1982; Radcliffe, 1986) and *U. gallii* (Celaya et al., 2007b). Differences in heather selection between both animal species are not so obvious, as it partly depends on the species (Bartolomé et al., 1998) and season (Celaya et al., 2007b) considered. In addition, in the current study there was a low proportion of heather available in all plots.

Some differences in the grazing behaviour were noticed in cattle and sheep, and more clearly in goats, according to the type of flock (single or mixed). Another trial conducted in the same farm showed also behavioural differences in goats when they were managed together with sheep, grazing more time on shrubland than on improved pasture relative to single flocks of goats (Osoro et al., 2000c). In the same work, sheep behaviour hardly changed when they were stocked alone or with goats. The higher gorse proportions found in the diets of animals under single than under mixed grazing (mainly in the case of sheep, especially in May 2003) may reflect the differences in gorse availability between both managements. Likewise, the increase in dietary gorse from 2003 to 2004 would reflect a parallel increase in gorse cover percentage in shrublands.

Vegetation dynamics

Gorse (*Ulex gallii*) was the dominant species in the shrubland since the experiment started (one year after the mechanical clearing). It might be due to its ability to sprouting from basal buds, in addition to the seed bank in the soil (Stokes et al., 2003) and its competitive and stress-tolerant strategy (Clément & Touffet, 1990). Likewise to mechanical clearing, a high re-growth ability of gorse has been observed after superficial fire (Jáuregui et al., 2007). Consequently, after disturbances like clearing or burning, gorse can compete more efficiently than heather species, at least during the early successional stages, though in the longer term heather species usually reach dominance in the absence of disturbances (Celaya et al., 2007a).

Generally, no great differences were noticed in the re-growth of the shrubland after clearing between cattle or sheep grazing. Although the shrub encroachment was higher in CA than in SA, limiting the presence of herbaceous plants, the differences found in most of the studied variables were non-significant. A higher increase in the mean height of gorse was found throughout the cattle

treatments than in sheep ones, and heather percentage (both in terms of cover and phytomass) also increased significantly more in the former ones. It has been pointed out the lower ability of cattle to consume the green shoots of shrubs, especially noticed with heather species such as *Calluna vulgaris* (Grant et al., 1987; Oliván & Osoro, 1998). In spite of this selective inability of cattle, previous studies found a higher reduction in heather cover and phytomass under cattle than under sheep grazing, due to the fact that cattle can pull up more shoots or even the whole plants (although they will not ingest them), in addition to a higher treading damage compared to sheep (Hodgson & Grant, 1981; Osoro et al., 2000b). The higher increase of heather under cattle than under sheep grazing found in the current study could be the consequence of a limited accessibility to the shrubland by a barrier effect caused by the thorny gorse plants, as also observed in the hills of Galicia, Northwest Spain (Sineiro et al., 1984), and so heather plants were able to thrive protected by gorse.

With regard to the grazing management (single *vs.* mixed), the effects on the temporal trends of the shrubland vegetation were more evident. Mixed grazing treatments slowed down more the shrub encroachment, particularly in the case of gorse, which in turn let a higher growth of herbaceous plants in these treatments compared to single grazing. This was due to the more browser behaviour of goats as stated above. In a previous study carried out in the same experimental farm, on partially improved plots comprising cleared heathland areas as well, it was observed that gorse cover increased greatly after three years under sheep grazing from 21 to 41%, whereas it was maintained around 16-17% under mixed grazing or even decreased from 24 to 19% under goat grazing (Celaya et al., 2007a). A greater control of the re-growth of gorse in previously burnt stands was also noticed under goat grazing compared to sheep grazing (Jáuregui et al., 2007).

In the absence of grazing, the accumulation of phytomass, mostly accounted for gorse, was remarkable, almost reaching 40 t DM ha⁻¹ after five years since clearing, with 92% gorse. In the study of Celaya et al (2007a), amounts of 18.5 t DM ha⁻¹ with 46% gorse were obtained after five years with no grazing since a mechanical clearing. These differences could be due to different levels of soil fertility between both trials.

A greater control of gorse sprouting in the improved areas was achieved

under sheep grazing than under cattle grazing. No gorse was found in the samplings on sheep-grazed plots (neither SA nor S+G), and thus the effect of goats' presence was only noted in the case of cattle grazing, even though previous works had reported a better control of gorse with goats than with sheep (Sineiro, 1982; Celaya et al., 2007a).

Conclusions

The domestic ruminant species, cattle, sheep and goats, showed a distinct foraging behaviour when stocked on partially improved gorse-heather shrublands. Cattle and sheep preferentially grazed on the improved area, selecting herbaceous species with higher nutritive quality than those present in the shrubland, whereas goats utilized more the woody vegetation. Thus the presence of goats together with cattle or sheep led to a higher control of gorse encroachment (which became the dominant species after heathland clearing), accompanied by a higher presence of herbaceous plants in the canopy, compared to monospecific flocks of cattle and sheep. Such vegetation dynamics found under mixed grazing with goats could have beneficial effects on the future management of these marginal areas, with improved nutritive quality of available vegetation for other livestock species, and reducing the fire risk through a lower accumulation of combustible woody phytomass.

7. Pastoral management of heath and gorse

communities.

7.2. Grazing behaviour and performance of lactating suckler cows, ewes and goats on partially improved heathlands

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Abstract

The foraging behaviour (grazing time and diet composition), live-weight changes and parasitic infection (faecal egg counts of gastrointestinal nematodes) of 12 beef cows, 84 ewes and 84 goats suckling their offspring, managed in mixed grazing on heathlands with 24% of improved pasture of perennial ryegrass-white clover, were studied during the years 2003 and 2006. The results showed that goats tended to graze for a longer time, and utilised significantly more heathland vegetation than cattle and sheep, including in their diet an average of 0.39 herbaceous plants, 0.11 gorse and 0.51 heather over the grazing season, comparing with respective mean values of 0.85, 0.02 and 0.13 in cattle and sheep. Dietary overlap was higher between cattle and sheep (0.76) than between sheep and goats (0.53) or between cattle and goats (0.47). Despite the high performance

of autumn-calving cows in spring, sheep had the best live-weight changes per livestock unit (LU) during the whole grazing season. Goats' performance per LU was much lower than sheep but similar to that achieved by spring-calving cows. Mean nematode eggs/g fresh faeces (epg) during the grazing season were higher in goats (91 epg) compared to sheep (34 epg) and cattle (14 epg), particularly from September to December. In conclusion, sheep performed best on these heathlands with improved pasture areas if the entire grazing season was considered, despite the good level of production in spring from autumn-calving cows. The results suggested the complementary use of goats in order to increase the effective utilisation of the available vegetation, achieving production levels similar to those from spring-calving cows. Therefore, mixed flocks of sheep and goats would be the most appropriate sustainable systems from the animal production and vegetation use points of view.

Keywords: Domestic ruminants; Marginal land; Grazing; Live weight; Gastrointestinal nematode.

Introduction

The establishment of sustainable grazing management systems under any vegetation condition requires the understanding of animals' grazing behaviour and their responses in animal performance (live-weight changes, welfare) as well as their effects on vegetation dynamics. Significant differences in the grazing behaviour have been observed between animal species (Rook et al., 2004) and breeds (Osoro et al., 1999). Small ruminants, especially goats, are able to include high proportions of browse species such as heather (*Erica* spp) and gorse (*Ulex* spp) in their diets. Goats select gorse in different proportions during the year (Clark et al., 1982). In contrast, sheep graze mainly the new green shoots of gorse in spring, while cattle hardly select this shrub and only consume small proportions of heather species (Celaya et al., 2007b). In spite of considerable differences between animals of the same species (Prache et al., 1998), differences in body size affect dietary choice and absolute intake capacity, and obviously it would affect the nutrient requirements (Illius & Gordon, 1993). These requirements and thus the responses in performance also vary depending on the physiological status of the animal (lactating, dry, pregnant).

Many mountain areas of temperate regions are grazed by multispecies flocks of sheep, goats, cattle and even horses. In this respect, knowledge of the performance of these species when grazing under the same conditions is required, although these conditions (pasture availability and quality) change over the season as a consequence of the continuous management, in addition to the changes in climatic conditions. Variables related to grazing behaviour (e.g. diet selection, intake, grazing times) can be controlled, even though it would be very difficult to quantify the impact of each species on vegetation dynamics. For that purpose, another experimental work compared single and mixed grazing and studied their impact on vegetation dynamics (Benavides et al., submitted). This information would be important from the biodiversity and conservation point of view and, therefore, to analyse the sustainability of these different managements for environmental concerns.

High dietary overlap between animal species means a high interspecific competition for the same plant resources (Wright & Connolly, 1995). Hence, the levels of complementarity in grazing behaviour between domestic ruminant species will affect the productivity and sustainability of the systems. Previous studies have set out the complementary levels between herbivores (Lechner-Doll et al., 1995; Aldezabal, 2001), showing low complementarity between cattle and horses, being high between cattle and goats, and intermediate between cattle and sheep. Nevertheless, these complementarity levels may change depending on the available vegetation (quantity and quality). The degree of dietary overlap between sheep and goats grazing together also vary seasonally and according to the relative stocking rates of each species (Bullock, 1985).

It is widely accepted that the sward height that maximizes pasture intake differs between animal species. In perennial ryegrass (*Lolium perenne*)-white clover (*Trifolium repens*) pastures established in lowlands, ewes were able to maximize live-weight gains on pastures with 5-6 cm mean sward height (Osoro et al., 2002), while cattle needed at least 8 cm for similar vegetation conditions (Wright & Whyte, 1989; Osoro et al., 2000d), reducing the level of intake below their maintenance needs on shorter pastures. Goats also responded linearly to the reduction of sward height between 4 and 11 cm (Merchant & Riach, 1994). Previous studies (Maxwell et al., 1986; Osoro et al., 2007a) have already shown the limitation of heather-gorse communities located in marginal lands with poor

soils to develop sustainable production systems with ruminants, supporting the necessity to establish improved areas, as they would increase the digestible dry matter intake and consequently improve the animal performance and welfare.

On the other hand, animal welfare should also be considered as significant differences in parasite infection between animal species, e.g. between sheep and goats, have been observed (Hoste et al., 2008), affecting differently according to the grazing management and available vegetation components (Osoro et al., 2007b).

Grazing behaviour, live-weight changes and gastrointestinal nematode infection of suckler beef cows, ewes and does grazing with their calves, lambs and kids were recorded during the spring-summer grazing season, as well as grazing alone in the autumn, after weaning at the end of summer, in a heathland vegetation area with 24% of the total available area converted to perennial ryegrass-white clover pasture. The aim of this study was to analyse the interactions between grazing behaviour, animal performance and gastrointestinal nematode infection of different animal species grazing together in a heathland incorporating an area of improved pasture.

Material and methods

Experimental site

The experiment was conducted in years 2003 and 2006 on one plot of 22.3 ha located at 900-1000 m a.s.l. at the Carbayal Research Station, Sierra de San Isidro, Illano, western Asturias, NW Spain (43° 21' N, 6° 53' W). Annual rainfalls recorded at Carbayal (2002 to 2006) averaged 1557 mm, being more abundant from October to January. Mean temperature was 10.2 °C with a maximum of 16.4 °C in August and a minimum of 4.0 °C in February.

The natural vegetation covered 17 ha (76.2%) and it mostly consisted (67.8%) of short (less than 50 cm high) heather-gorse shrubland, dominated by heather species (*Erica umbellata*, *E. cinerea*, *Calluna vulgaris*) and gorse (*Ulex gallii*), a thorny and woody legume. Tall scrublands (up to 2 m high) dominated by *Erica australis* subsp. *aragonensis* and *E. arborea* were more sparsely present (7.8% of total plot area), as well as a small pinewood (0.5%) of Scots pine (*Pinus sylvestris*). The rest of the plot area (5.3 ha) was improved during 1999 by soil

breakingup, dressing, and sowing of perennial ryegrass (*Lolium perenne* cv 'Phoenix'), hybrid ryegrass (*L. x hybridum* cv 'Dalita') and white clover (*Trifolium repens* cv 'Huia'), and reseeded again in 2002 with the same mixture. Previous experiences indicated that 33% of improved area allow satisfactory animal performances with small ruminants (Osoro et al., 2002) and cattle (Osoro et al., 1999).

Animals and management

The grazing season extended from May to December of both 2003 and 2006. Adult animals were lactating females, with sheep and goats lambing and kidding at the beginning of the spring. Cows calving took place in autumn in year 2002 and spring in year 2006. During each grazing season, six Asturiana de los Valles beef cows (532 ± 31.4 kg live weight (LW)), 42 Gallega and Lacha crossed ewes (43 ± 1.0 kg LW) and 42 Cashmere does (38 ± 1.1 kg LW) were managed together in a mixed herd under continuous grazing to have the same opportunities for diet selection, shelter, etc. The equivalence established by EU between cattle and small ruminants in our conditions is 1:7, and therefore such a ratio was chosen to maintain a theoretical equilibrium between these animal species. Offspring were weaned according to the normal practice and market weights. The lambs and kids were weaned in July-August, when ageing around 4 months old, and calves with 6-8 months, in August-September. Wintering period for mating began depending on the weight losses and body condition.

All animals were drenched with ivermectin (Oramec®, Merial Lyon, France) against gastrointestinal nematodes two weeks before turning out.

Vegetation measurements

The botanical composition (percentage cover) of the short heathlands was estimated in June 2003 and 2006 by recording 300 random hits with the HFRO swardstick (Barthram, 1986). The composition of the pasture in the improved area was assessed at the beginning of June 2003 and 2006 by recording randomly 250 vertical hits with a point-quadrat (Grant, 1981). Availability of green pasture was measured weekly recording the sward surface height at 100 random points on the improved pasture area using the HFRO swardstick.

Samples of the main vegetation components (heather, gorse, herbaceous plants growing in the heathland area, and improved pasture composed of perennial ryegrass and white clover) were harvested monthly during 2003 for chemical analysis. In the compound (multi-species) samples, the individual species were collected in similar proportions to those present in the sward. Samples were analysed following the procedures of the Association of Official Analytical Chemists (AOAC, 2006) for ash and nitrogen (N). Crude protein (CP) was calculated as $N \times 6.25$. Neutral-detergent fibre (NDF), acid-detergent fibre (ADF) and acid-detergent lignin (ADL) were analysed by the methods of Van Soest et al. (1991).

Grazing behaviour and diet selection

The time spent grazing by each animal species on each vegetation type (short heathland, tall heathland, pinewood, ryegrass-clover pasture) was determined by recording the grazing activity of adult animals every 15 minutes from dawn to dusk during two consecutive days in six occasions over 2003 (19-20 June, 1-2 July, 5-6 August, 15-16 September, 20-21 October, and 2-3 December).

The composition of the diet selected by each livestock species was estimated using the n-alkane markers (Dove & Mayes, 1991). Faecal grab samples were collected during the grazing season of 2003 in five occasions: 25 June, 30 July, 27 August, 12 November and 10 December. Since faeces from individual ewes and goats were seldom enough quantity for alkane analysis, samples from 4-6 animals were pooled to obtain 6-10 samples for each species. At the same time, samples of the main plant components were collected, i.e. leaves and/or green shoots of short heather (including *E. umbellata*, *E. cinerea* and *C. vulgaris*), tall heather (*E. australis* and *E. arborea*), gorse, heath grasses (mostly *Pseudarrhenatherum longifolium* and *Agrostis curtisii*), and improved pasture (including ryegrass and clover). All samples were stored at -20°C and then freeze-dried and milled prior to analytical procedures. The alkanes (from C21 to C36) were extracted using the method of Mayes et al. (1986) modified by Oliván and Osoro (1999), and their contents determined by gas chromatography. The proportions of the plant components in the diet were estimated using a least-squares procedure which minimises the discrepancies between the observed concentrations of each n-alkane (C25 to C33) in the faeces and the estimated proportions of plant components in

the diet (Dove & Moore, 1995). For diet composition calculations, the alkanes C21, C23, C35 and C36 were not used due to their low concentrations in all plant species. The faecal concentrations were previously corrected using faecal recoveries calculated in previous validation studies with cows (Ferreira et al., 2007a), ewes (Ferreira et al., 2007b) and goats (Ferreira et al., 2005).

The degree of selection-rejection for a determined vegetation type or plant component in the diet was assessed by calculating the Jacobs' modification of Ivlev's electivity index as $S_i = (c_i - a_i) / (c_i + a_i - 2c_i a_i)$, where c_i is the proportion of i vegetation type in the grazing time or plant component in the diet, and a_i is the proportion of i vegetation type or plant component available in the field. The index ranges from -1 (not used) to +1 (exclusively used), with 0 indicating proportional use to its availability.

The overlap in vegetation use (grazing time) and diet composition between animal species was estimated by the Kulczyński similarity index as $KSI = \sum c_i / \sum (a_i + b_i)$, where c_i is the least proportion of i vegetation type (grazing time) or i plant component (diet composition) in the two animal species, and $(a_i + b_i)$ is the sum of the proportions of each vegetation type or plant component in both animal species. This index ranges from 0 (no overlap) to 1 (total match).

Animal performance and welfare

LW and body condition

Monthly every animal was weighed and the body condition of mothers scored (cows: Lowman et al., 1976; sheep: Russel et al., 1969; goats: Russel, 1990), starting one week after the turn-out and until the end of the grazing season. To explore and analyse these data, the grazing season was divided into three seasons: spring (from May to June), summer (from July to mid-September), and autumn (from mid-September to mid-December).

Nematode parasites

During 2006 faecal samples were taken monthly from all species and faecal egg counts (FEC) were carried out using a modified McMaster technique (MAFF, 1978), with one egg representing 15 eggs g⁻¹ fresh faeces (epg). Gastrointestinal

nematode genera present in faeces were identified monthly in basis of infective third-stage larvae obtained by coprocultures (Van Wyk et al., 2004).

Statistical analyses

Chemical composition data from each plant component were pooled for each season (spring: May-June; summer: July-September; autumn: October-December) and differences between plant components (heather, gorse, heath grasses and improved pasture), seasons and their interaction were analysed by two-way analysis of variance (ANOVA). Tukey HSD test was used to examine pair-wise comparisons between plant components.

Sward height on the improved pasture area was analysed by repeated measures ANOVA, examining the effects of year (2003, 2006), season (spring, summer, autumn) and the interaction year x season, with the sampling time nested within year as the repeated measure.

Overall diet composition data set over the grazing season could not be normalized nor the variances equalized by transformation due to many zero values found at several sampling dates. Thus, differences between cows, ewes and goats' diets were analysed for each date, using the non-parametric Kruskal-Wallis test. Comparisons between pairs of livestock species were examined applying the Mann-Whitney U test. This approach was also used to analyse the selectivity values (Jacobs' index) of each plant component in the diet, as well as FEC data.

Individual daily LW changes and per livestock unit (LU, according to the equivalences established by the Common Agricultural Policy between cattle, sheep and goats: 1 cow = 7 ewes = 7 goats), and body condition score changes during the different periods of the grazing season were subjected to a General Linear Model ANOVA. The model was $y = \mu + Sp + Y + Sp*Y + \varepsilon$, where y is the measured LW or body condition score change, μ is the overall mean, Sp is the main effect of animal species (cattle, sheep, goat), Y is the main effect of year (2003, 2006), $Sp*Y$ is the interaction effect between animal species and year, and ε is the residual error term. Post-hoc differences between animal species were examined using Tukey test.

All analyses were performed using the program STATISTICA 6.0 (StatSoft Inc., 2001, Tulsa, OK, USA).

Results

Available vegetation

Natural vegetation

The short heathland was dominated by heather species, with cover percentages of 68% and 56% in 2003 and 2006, respectively. In particular, *Erica umbellata* was the dominant species accounting for 58% in 2003 and 47% in 2006. Gorse percentage varied between 14% in 2003 and 19% in 2006, whilst other shrubs only represented 3% and 2% in 2003 and 2006, respectively. Herbaceous plants consisted mainly of tough grasses such as *P. longifolium* and *A. curtisii*, accounting for 8% in 2003 and 13% in 2006, and the percentage of dead matter varied between 7% (2003) and 10% (2006).

Improved area

The improved pasture was dominated by perennial ryegrass in both years, although with higher figure in 2003 (66%) than in 2006 (51%). Conversely, the percentage of white clover increased from 19% (2003) to 23% (2006). The same trend was observed for the indigenous grass species, mainly *Agrostis capillaris* (13% in 2003 and 21% in 2006). Other unsown species only accounted for 2% and 5% in 2003 and 2006, respectively.

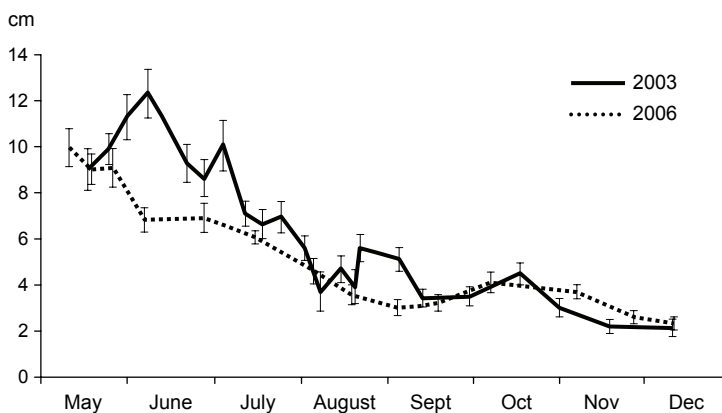


Figure 7.2.1. Sward height in the improved pasture area during the grazing season of the two study years (2003 and 2006). Vertical bars show \pm standard errors of the means.

Available sward height of the improved pasture area decreased significantly ($P < 0.001$) during the grazing season in both years (Figure 7.2.1), from a mean of 9.0 cm in spring (May-June) to 5.2 cm in summer (July-September) and to 3.2 cm in autumn (September-December). Significant ($P < 0.05$) differences between years were observed, but these occurred mainly in spring (10.3 and 7.7 cm in 2003 and 2006, respectively), so the interaction year x season was also significant ($P < 0.05$). In summer, mean sward heights were 5.9 and 4.5 cm in the first and the second year, respectively, whilst in autumn the means were equally low in both years, 3.2 and 3.4 cm, respectively.

Chemical composition of vegetation

All the chemical parameters differed significantly ($P < 0.001$) between vegetation components (Table 7.2.1). The improved pasture had higher CP contents and lower fibre (NDF, ADF) contents than the natural plant components. Lignin content (ADL) was higher in shrubs (heather and gorse) than in the herbaceous plants. In general, the nutritive value of all plant components decreased as grazing season passed. Average CP content decreased from 133 g kg⁻¹ DM in spring to 119 and 94 g kg⁻¹ DM in summer and autumn respectively ($P < 0.001$), while NDF and ADF contents increased from 574 to 642 g kg⁻¹ DM ($P < 0.05$), and from 387 to 432 g kg⁻¹ DM ($P < 0.1$), respectively.

Foraging behaviour

Grazing time

On average, goats spent more daily time grazing than the other species throughout the grazing season (633 min day⁻¹ compared to 537 and 527 min day⁻¹ spent by cows and ewes, respectively). This difference was particularly marked during summer, when the averaged grazing activity of goats exceeded 720 min day⁻¹, compared to the figures of cattle and sheep that remained nearly steady. On the contrary, autumn controls showed shorter grazing periods for goats (mean values of 609, 593 and 512 min day⁻¹ for cows, ewes and goats, respectively).

Differences in the proportion of grazing time spent on each vegetation type were also registered among animal species (Figure 7.2.2). The proportional time that goats spent grazing on shrubland (including short and tall heathlands) was

greater than for the other two species, and it was frequently higher than 0.50 of the grazing time, whereas cows and ewes spent the most of their grazing activity on the improved pasture (exceeding 0.70). These proportions varied seasonally, especially in the case of cows and goats. The proportion of grazing time on the improved pasture decreased over the grazing season, from 0.96 in June to 0.70 in December for cows, and from 0.64 to 0.28 for goats. Sheep hardly varied their behaviour, as they only reduced their utilisation of the improved area during a short period in the summer (from 0.90 in July to 0.78 in September), with a new increase in autumn. Goat was the only species browsing on pines, with a maximum grazing time of 0.06 registered in August and isolated records in other controls.

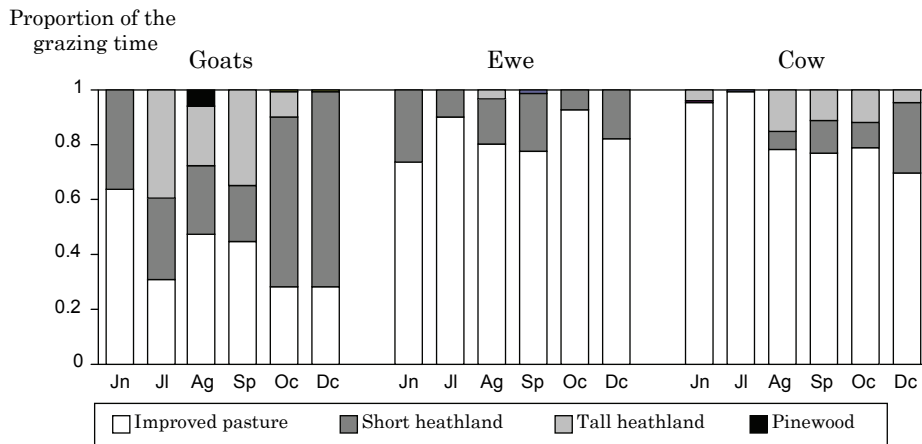


Figure 7.2.2. Proportion of the grazing time spent on each vegetation type by lactating cows, ewes and goats during the grazing season in a partially (24%) improved heathland plot.

The diurnal grazing pattern exhibited by the animals changed during the grazing season, depending on the available sward height in the improved pasture area, meteorological conditions and daylight hours (Figure 7.2.3). In spring and summer, both cattle and sheep rested during two main breaks, at midday and in the afternoon. Goats' behaviour was more variable within the herd, i.e. it was less synchronic between individuals. During autumn, with shorter sward height and daytime length, resting times decreased, especially in sheep. Grazing time of ewes on heathlands was mainly restricted to the evening on their way to their resting area.

Table 7.2.1. Chemical composition of the main plant components in a partially improved gorse-heathland across the grazing season.

Variable	Season				s.e.m.	Significance		
	Spring	Summer	Autumn	Mean		P	S	P x S
CP (g kg ⁻¹ DM)	133.3	118.7	93.8		5.32	***	***	**
Heather	78.6	71.6	68.1	72.7c	5.22			
Gorse	172.0	112.0	100.4	128.1b	6.27			
Heath grass	105.2	115.8	85.2	102.1b	6.97			
Improved pasture	177.6	175.5	121.6	158.2a	6.15			
NDF (g kg ⁻¹ DM)	573.7	623.9	642.1		15.31	***	*	ns
Heather	561.4	611.1	606.2	592.9b	15.04			
Gorse	636.3	668.3	652.3	652.3ab	18.07			
Heath grass	649.3	700.1	741.1	696.8a	20.08			
Improved pasture	447.9	516.2	568.6	510.9c	17.71			
ADF (g kg ⁻¹ DM)	387.3	420.2	431.7		13.33	***	+	ns
Heather	439.4	516.7	512.9	489.7a	13.10			
Gorse	506.3	526.7	511.4	514.8a	15.73			
Heath grass	345.2	351.8	411.0	369.3b	17.49			
Improved pasture	258.2	285.7	291.6	278.5c	15.42			
ADL (g kg ⁻¹ DM)	153.1	167.7	181.1		14.65	***	ns	ns
Heather	346.9	382.9	387.4	372.4a	14.40			
Gorse	192.2	200.5	236.9	209.9b	17.30			
Heath grass	32.2	50.4	42.3	41.6c	19.22			
Improved pasture	41.4	37.0	57.7	45.3c	16.95			

CP: crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber; ADL: acid detergent lignin. P: plant, S: season. + $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns not significant ($P > 0.10$).

Means with different letters within each chemical variable are significantly different ($P < 0.05$).

Diet composition

The estimated composition of the diet selected by each animal species during the grazing season is presented in Table 7.2.2. The herbaceous species were the main dietary component of cattle and sheep throughout the grazing season, ranging from a minimum of 0.81 (August-December) to a maximum of 0.92 (June) in cattle, and from a minimum of 0.66 (August) to a maximum of 0.95 (July) in sheep. The proportion of this vegetation component in the diet of these two animal species was only significantly ($P < 0.01$) different in July (0.90 vs. 0.95 in cattle and sheep, respectively) and August (0.81 vs. 0.66 in cattle and sheep, respectively). The inclusion of herbaceous species in the diet of goats was

significantly ($P < 0.01$) lower throughout the whole season, achieving a minimum value (0.16) in November and a maximum (0.69) in July (Table 7.2.2).

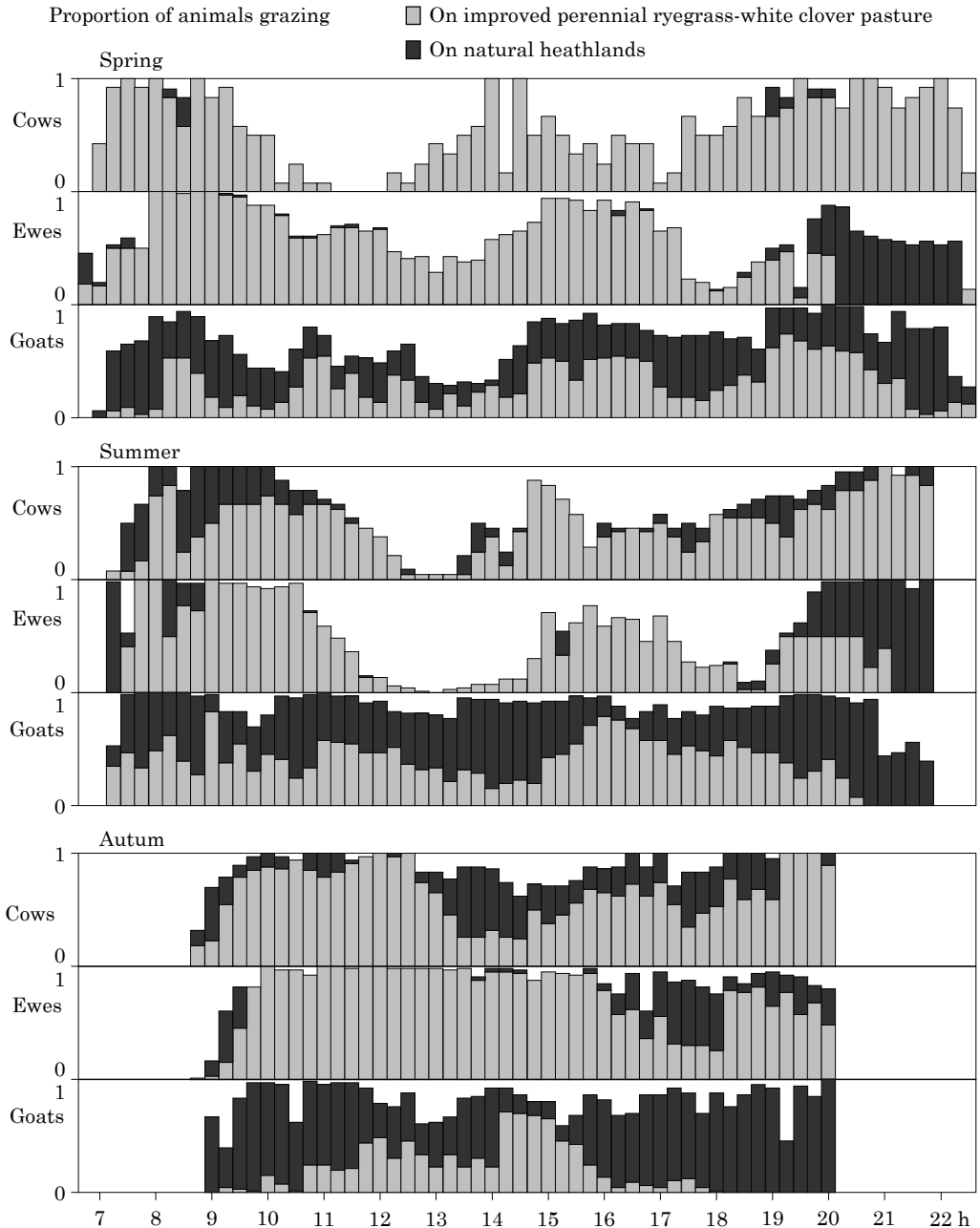


Figure 7.2.3. Diurnal variation in the grazing use by lactating cows, ewes and goats in a partially (24%) improved heathland plot. Spring: June-July; Summer: August-September; Autumn: October-December.

Table 7.2.2. Diet composition of cattle, sheep and goats across the grazing season on a gorse-heathland with 24% of improved pasture.

Month	Plant component	Cattle	Sheep	Goats	s.e.m.	sign
June	Herbaceous	0.916a	0.935a	0.687b	0.014	**
	Gorse	0.084b	0.065b	0.278a	0.013	**
	Heather	0.000b	0.000b	0.035a	0.008	**
July	Herbaceous	0.905b	0.951a	0.693c	0.012	***
	Gorse	0.009b	0.000b	0.100a	0.009	***
	Heather	0.086b	0.049c	0.207a	0.010	***
August	Herbaceous	0.806a	0.655b	0.187c	0.022	***
	Gorse	0.000	0.000	0.000	-	ns
	Heather	0.194c	0.345b	0.813a	0.022	***
November	Herbaceous	0.807a	0.829a	0.162b	0.037	***
	Gorse	0.023ab	0.000b	0.063a	0.018	**
	Heather	0.170b	0.171b	0.775a	0.040	***
December	Herbaceous	0.809a	0.849a	0.206b	0.038	***
	Gorse	0.000b	0.000b	0.091a	0.025	***
	Heather	0.191b	0.151b	0.703a	0.039	***

** $P < 0.01$; *** $P < 0.001$; ns not significant; means with different letters in each row are significantly different ($P < 0.05$).

Gorse was essentially selected by goats at the beginning of the grazing season (0.28 and 0.10 in June and July, respectively) and in November (0.09). In contrast, cattle and sheep tended to reject it, with the exception of June when gorse accounted for 0.08 and 0.06 of their diets, respectively.

Differences in the estimated proportion of heather in the diet among livestock species were also registered. The selection of heather increased significantly in every animal species from June, with proportions in the diet close to zero (0 for cattle and sheep and 0.04 for goats), to August when they reached maximum values of 0.19, 0.34 and 0.81 for cattle, sheep and goats, respectively. Afterwards, the selection of this plant component decreased, especially in sheep and goats, even though heather continued as the main component of goats' diet until the end of the grazing season.

Vegetation type and diet selection

According to the Jacobs' electivity index (S), all livestock species showed positive selection to graze on improved pasture, but the indexes for goats during summer-autumn were consistently lower (0.11-0.48) than those for cattle and

sheep (0.76-0.95) (Table 7.2.3.). Short heathlands, covering the greatest surface, had the lowest (negative) S indexes (from -1.00 to -0.71 for cattle and sheep; from -0.78 to 0.07 for goats). However, tall heathlands reached positive indexes in cows (from August to October) and goats (from July to October).

With respect to the diet selection, herbaceous plants were positively selected by cattle and sheep in all sampled periods, whereas goats presented negative Jacobs' indexes from August to December. Gorse was rejected from July onwards by both cattle and sheep, while goats selected it positively in June ($S = 0.57$), and consumed it in proportion to its availability in July ($S = 0.01$). Both cattle and sheep selected against heather, though in August this rejection was stronger for cattle than for sheep (-0.66 vs. -0.38; $P < 0.001$). In contrast, goats showed positive selection for heather from August to December (Table 7.2.3.).

Table 7.2.3. Jacobs's electivity index for each livestock species according to the vegetation use (grazing time) and diet composition.

Grazing time	Improved pasture			Short heathland			Tall heathland		
	Cattle	Sheep	Goat	Cattle	Sheep	Goat	Cattle	Sheep	Goat
June	0.97	0.80	0.70	-0.99	-0.71	-0.57	-0.37	-1.00	-1.00
July	0.99	0.94	0.17	-1.00	-0.90	-0.66	-0.82	-0.96	0.77
August	0.84	0.86	0.48	-0.93	-0.83	-0.73	0.36	-0.43	0.54
September	0.83	0.84	0.44	-0.88	-0.78	-0.78	0.19	-0.70	0.72
October	0.85	0.95	0.11	-0.91	-0.93	-0.13	0.23	-0.99	0.11
December	0.76	0.87	0.12	-0.72	-0.81	0.07	-0.27	-1.00	-0.90

Diet selection	Herbaceous plants			Gorse			Heather		
	Cattle	Sheep	Goat	Cattle	Sheep	Goat	Cattle	Sheep	Goat
June	0.93a	0.94a	0.69b	-0.10b	-0.23b	0.57a	-1.00b	-1.00b	-0.94a
July	0.92a	0.96a	0.69b	-0.87b	-1.00b	0.01a	-0.85b	-0.92b	-0.63a
August	0.82a	0.65a	-0.30b	-1.00	-1.00	-1.00	-0.66c	-0.38b	0.57a
November	0.82a	0.84a	-0.40b	-0.68ab	-1.00b	-0.38a	-0.70b	-0.70b	0.49a
December	0.82a	0.86a	-0.27b	-1.00b	-1.00b	-0.37a	-0.66b	-0.74b	0.34a

For diet selection, means with different letters in each row within each plant component are significantly different ($P < 0.05$).

Grazing overlap between livestock species

The degree of grazing overlap between livestock species assessed by the Kulczynski similarity index (KSI) was higher between cattle and sheep compared to that found between sheep and goats or between cattle and goats (Table 7.2.4.) , considering either the grazing time spent on each vegetation type (KSI mean values from June to December of 0.86, 0.58 and 0.56 for cattle-sheep, sheep-goat

and cattle-goat, respectively) or the diet composition (respective means of 0.76, 0.53 and 0.47). In general, dietary overlap between species decreased over the grazing season, but this trend was less noteworthy for the indexes derived from the grazing time, with an overlapping between cattle and sheep exceeding 0.86 from July onwards.

Table 7.2.4. Overlapping level (Kulczynski similarity index) between livestock species in the vegetation use (grazing time) and diet composition.

Month	Grazing time			Diet composition		
	Cattle-Sheep	Cattle-Goat	Sheep-Goat	Cattle-Sheep	Cattle-Goat	Sheep-Goat
June	0.74	0.64	0.89	0.94	0.68	0.70
July	0.91	0.31	0.40	0.79	0.65	0.74
August	0.88	0.69	0.67	0.65	0.33	0.53
September	0.90	0.67	0.67			
October ⁽¹⁾	0.86	0.47	0.35	0.60	0.34	0.31
December	0.87	0.55	0.46	0.81	0.35	0.36
Mean	0.86	0.56	0.58	0.76	0.47	0.53

⁽¹⁾ Sampling date at November 12th for diet composition.

Animal performance

Daily LW changes of mothers

Individual LW changes differed significantly ($P < 0.001$) between animal species in any period of the grazing season, and significant ($P < 0.05$) interactions between animal species and year for these LW changes were also observed in all periods that comprised the grazing season (Table 7.2.5.). Thus, autumn-calving cows (2003) gained 1159 g day⁻¹ during the spring while spring-calving cows (2006) recovered only 421 g day⁻¹. During summer, autumn-calving cows, which were at the end of lactation, maintained LW (6 g day⁻¹), whereas spring-calving cows, in the middle of lactation, lost 557 g day⁻¹. In autumn, cows belonging to both calving seasons lost near a half a kilo per day (540 and 455 g day⁻¹ in autumn- and spring-calving cows, respectively).

Small ruminants showed different trends in their individual LW changes in comparison with cows. Ewes and goats increased their LW at 63 and 49 g day⁻¹ respectively ($P < 0.05$) during the spring, without significant differences among years. Conversely, significant ($P < 0.001$) differences between years were observed

during summer; in 2003 ewes and goats gained LW at the same level as in spring, 67 and 51 g day⁻¹ respectively, but in 2006 ewes and goats lost 32 and 8 g day⁻¹, respectively. During autumn ewes lost only 5 g day⁻¹ and goats 24 g day⁻¹ ($P < 0.001$) without significant differences between years.

On the overall grazing season (from May to December), cows lost LW, particularly spring-calving cows (260 g day⁻¹), while ewes and does increased their LW in 14 and 7 g day⁻¹, respectively.

Body condition score

Changes in body condition of mothers were closely related to the live weight changes. Thus, small ruminants maintained or improved their body condition throughout the grazing season while for cows it worsened (Table 7.2.5).

Table 7.2.5. Daily live-weight (LW) changes per Livestock Unit (LU) and body condition score (BCS) changes in suckler cows, ewes and goats grazing on partially improved heathlands during two grazing seasons (from May to December).

Year (Y)	2003			2006			Significance level			
	Species (Sp)	Cattle	Sheep	Goat	Cattle	Sheep	Goat	Sp	Y	Sp x Y
Initial LW (kg)		590	44	38	462	41	38	***	***	***
LW change (g day ⁻¹)										
Spring		1159	62	40	421	64	57	***	***	***
Summer		6	67	51	-556	-32	-8	***	***	***
Autumn		-540	-10	-18	-455	0	-31	***	*	*
Overall		-26	22	14	-260	6	-1	***	***	***
BCS change										
Spring		0.42	0.34	0.25	0.05	0.26	0.21	ns	*	ns
Summer		-0.04	0.01	0.05	-0.35	-0.34	-0.01	***	***	*
Autumn		-0.88	0.13	-0.16	-0.30	0.09	-0.21	***	*	**
Overall		-0.50	0.26	0.14	-0.60	0.03	-0.01	***	+	ns
Initial LW per LU (kg LU ⁻¹)		590	305	263	462	288	264	***	**	**
LW change (g day ⁻¹ per LU)										
Spring		1159	437	282	421	447	402	***	**	***
Summer		6	468	360	-556	-227	-57	***	***	*
Autumn		-540	-71	-124	-455	2	-216	***	ns	**
Overall		-26	156	98	-260	45	-4	***	***	ns

+ $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns not significant ($P > 0.10$).

Daily LW gains of offspring

During spring, calves' daily LW gains (1016 g) were obviously higher than those for lambs (193 g) and kids (99 g). During summer, considerable reduction in calves LW gains were observed, resulting in 591 and 626 g day⁻¹ for autumn- and spring-born calves, respectively. The reduction was also important for lambs, 85 g

day⁻¹, while kids practically keep their gains (80 g day⁻¹). For the overall spring-summer grazing season, mean daily LW gains for each species were 790, 125 and 89 g day⁻¹ in calves, lambs and kids, respectively. Nevertheless, autumn-born calves had significantly ($P < 0.001$) higher LW gains (904 g day⁻¹) than those born in spring (676 g day⁻¹) (Table 7.2.6).

Table 7.2.6. Daily live-weight (LW) gains per Livestock Unit (LU) in calves, lambs and kids grazing on partially improved heathlands during two grazing seasons (from May to December).

Year (Y)	2003			2006			Significance level		
Species (Sp)	Cattle	Sheep	Goat	Cattle	Sheep	Goat	Sp	Y	Sp x Y
Initial LW (kg)	228.3	13.7	8.1	50.1	11.0	10.2	***	***	***
LW change (g day ⁻¹)									
Spring	1295	191	102	737	195	97	***	***	***
Summer	591	131	102	626	38	58	***	*	**
Overall	904	155	102	676	95	75	***	***	***
Initial LW (kg) per LU	228	96	57	50	77	71	***	***	***
LW change (gday ⁻¹ per LU)									
Spring	1295	1335	713	737	1362	677	***	**	**
Summer	591	919	717	626	264	403	ns	***	***
Overall	904	1082	715	676	665	525	***	***	*

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; NS not significant ($P > 0.05$).

LW changes of mothers expressed on a LU basis

LW changes per LU differed significantly ($P < 0.001$) between animal species, varying the difference level over the grazing season (Table 7.2.5). In spring, the highest LW gains per LU corresponded to autumn-calving cows (1159 g day⁻¹ per LU) and the lowest figures to does (342 g day⁻¹ per LU). Ewes' LW changes per LU (442 g day⁻¹ per LU) were similar to spring-calving cows (421 g day⁻¹ per LU) and higher ($P = 0.067$) than goats' LW gains (Figure 7.2.4).

In summer, small ruminants had positive LW gains per LU with significant ($P < 0.001$) differences between years because all the species lost weight in 2006, but in a lesser extent in the case of small ruminants. Averaging both years, cows lost 275 g day⁻¹ per LU while ewes and does recovered 121 and 152 g day⁻¹ per LU, respectively. The balance of LW changes for the spring-summer grazing season was not significantly different between the three animal species although the interaction year x species was highly significant ($P < 0.001$).

During autumn, all animal species lost weight, but cows did at significant ($P < 0.001$) higher level (-497 g day⁻¹ per LU) than goats (-178 g day⁻¹ per LU) and

ewes (-49 g day^{-1} per LU), with a significant ($P < 0.001$) interaction between year and species, even though year effect was not significant.

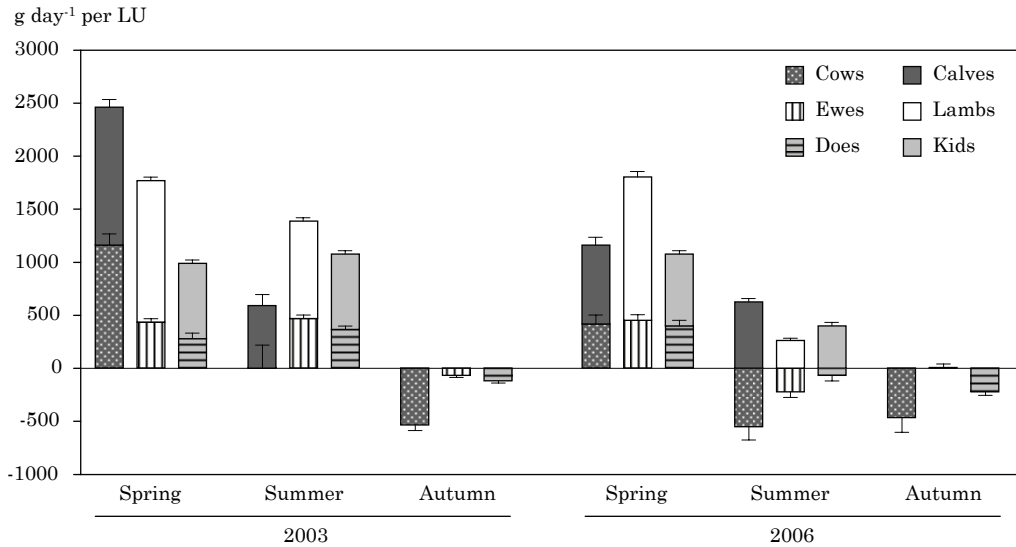


Figure 7.2.4. Daily live-weight changes per Livestock Unit (LU) of lactating cattle, sheep and goats grazing on partially improved heathlands. Vertical lines show standard errors of means.

Considering the whole grazing season, cows had a negative balance (-143 g day^{-1} per LU) while ewes and goats gained 101 and 47 g day^{-1} per LU respectively ($P < 0.001$). In this case, the year \times species interaction was not significant, while year effect was highly significant ($P < 0.001$) (Table 7.2.5.).

LW gains of offspring expressed on a LU basis

LW production per LU during spring was higher ($P < 0.001$) in lambs (1348 g day^{-1}) than in spring-born calves (737 g day^{-1}) and kids (695 g day^{-1}), and similar to that achieved by autumn-born calves in 2003 (1295 g day^{-1}) (Table 7.2.6). During summer, the production per LU was more similar between the three species, but with significant ($P < 0.001$) interaction between year and species, due to the lower performance of lambs and kids in the second year (Figure 7.2.4). On the overall spring-summer grazing season of both years, higher ($P < 0.001$) LW production was achieved by lambs (874 g day^{-1} per LU), followed by calves (790 g day^{-1} per LU).

day⁻¹ per LU) and kids (620 g day⁻¹ per LU); year effect was highly significant ($P < 0.001$) and the interaction year x species was significant ($P < 0.05$) (Table 7.2.6.).

Total production per LU

Analysing the total production (mothers + offspring) from each animal species, a similar production between cattle and sheep during the spring grazing was observed, with significant ($P < 0.001$) differences between years in the case of cattle, related to some extent with the different calving season. In summer the total production was significantly ($P < 0.001$) higher in small ruminants (712 g day⁻¹ per LU) than in cattle (333 g day⁻¹ per LU).

In the spring-summer grazing period, the highest production was achieved by sheep (1110 g day⁻¹ per LU) followed by cattle (990 g day⁻¹ per LU), and the lowest corresponded to goats (857 g day⁻¹ per LU). However, during the whole grazing season (from May to December) the lowest production was from cattle (647 g day⁻¹ per LU) while goats had 667 g day⁻¹ per LU and sheep achieved 975 g day⁻¹ per LU. Figure 7.2.4 shows the contribution of mothers and offspring to that production during the different periods of the two studied grazing seasons.

Nematode parasites

In general, gastrointestinal nematode FECs increased during the grazing season in 2006, although differences among the livestock species were recorded (Figure 7.2.5.).

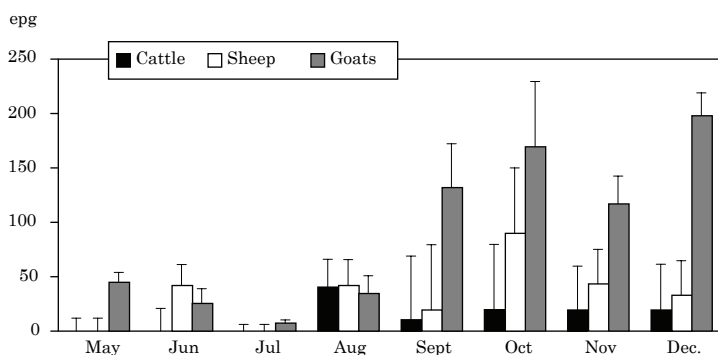


Fig. 7.2.5.

Gastrointestinal nematode faecal egg counts in cattle, sheep and goats across the grazing season on partially improved heathlands. Data are shown as mean \pm s.e.

There were also considerable differences between individuals within species. The FEC increase was higher in goats when compared to cattle and sheep, mainly

from September to December (with a mean figure ranging from 110 to 200 epg). The mean FECs were lower in cattle (14 epg) and sheep (34 epg) during all grazing season, with a maximum of 40 (in August) and 90 epg (in October), respectively. Significant ($P < 0.001$) differences were observed in the last control (December) with higher mean FECs in goats (197 epg) compared to cattle (20 epg) and sheep (33 epg).

Nematode genera identified were *Ostertagia* in cattle and *Teladorsagia* and *Trichostrongylus* in sheep and goats. The percentage of *Trichostrongylus* (from 30% in June to 75% in December) increased during the grazing period, while that of *Teladorsagia* decreased.

Discussion

Nutritive value of vegetation

The CP, NDF, ADF and ADL contents of the different plant components were quite similar to those found in a previous work in the same location (Celaya et al., 2007b) and revealed the low nutritive value of the natural components, even the herbaceous ones, compared to the ryegrass-clover pasture. The general trends of the chemical parameters over the grazing season also agreed with the aforementioned work, indicating that the nutritive value of the available vegetation decreased from spring to autumn.

Grazing behaviour and diet selection

Results showed that cattle and sheep grazed preferentially on the improved ryegrass-clover pasture area, regardless of the available sward height or nutritive quality of the herbage in that area. Although goats showed a similar behaviour in spring they readily shifted to woody vegetation when the available sward height decreased below 7 cm in July. Many studies have reported a higher willingness of goats to browse on woody plants compared to other domestic ruminants (Lu, 1988; Narjisse, 1991).

Previous works showed that goats consume gorse (*Ulex europaeus*) at a higher proportion than sheep (Clark et al., 1982; Radcliffe, 1986). Also Bullock (1985) found a higher consumption of heather by goats than by sheep as observed in the present study. However, the differences between sheep and goats in heather

selection were less clear in previous studies, depending on the heather species (Bartolomé et al., 1998) or season (Celaya et al., 2007b).

It is known that sheep graze more intensively on ryegrass-clover pastures than goats (Grant et al., 1984). In the present work, as sward height in the improved area did not decrease below 4 cm until November, sheep continued grazing on the improved pasture without apparently limiting their intake. They consumed lower proportions of heather than in a previous work (Celaya et al., 2007b) under similar experimental conditions with non-lactating animals, in which the mean sward height during autumn was 2.7 cm, and thus the ewes selected diets with more than 0.4 heather from September to December.

In contrast, cattle are known to hardly consume these woody plants (Aldezabal, 2001; Celaya et al., 2007b) in spite of their higher intake limitation as sward height decreases when compared to sheep (Baker et al., 1981; Forbes & Beattie, 1987). This feature of cattle may be related to their inability to select efficiently the green shoots of shrubs due to their muzzle anatomy (Illius & Gordon, 1993).

The lower dietary overlap between goats and cattle or sheep as opposed to that between cattle and sheep has also been observed in other works under very different conditions (i.e. Lechner-Doll et al., 1995; Aldezabal, 2001). This indicates a lower interspecific competition between goats and other animal species, and a more efficient use of heterogeneous plant resources (Wright & Connolly, 1995).

Animal performance

The results of this experiment showed that in spring, when available sward height was higher than 7-8 cm, LW gains per LU of autumn-calving cows were higher than in spring-calving cows and small ruminants. In this season, goats' LW gains per LU were 20-35% lower than in sheep but similar to those achieved by spring-calving cows. However, the LW changes per LU of small ruminants in summer were generally higher than in cattle. In this season, goats' LW gains were as high as in sheep, partly because sheep achieved a high performance level in spring and, therefore, the gain rates during summer were reduced as a consequence of the good body condition at the end of spring.

On overall spring-summer LW changes per LU were similar between sheep and autumn-calving cows, but higher than in spring-calving cows. Goats' LW

changes per LU were even higher than in spring-calving cows. In autumn, after weaning their calves, spring-calving cows lost significantly more LW per LU than goats, while ewes were able to maintain their LW. These interactions between livestock species and season were the result of variations on pasture availability, intake capacity and grazing behaviour among years and animal species. In fact, previous studies (Wright & Whyte, 1989) showed that suckler cows achieve maximum intake and production when available mean sward height is around 8 cm. However, when grass availability decreases to 5-6 cm, herbage intake and milk production are significantly reduced in cows. Therefore, calves' milk intake decreased affecting negatively their growth rates (Baker et al., 1981). In contrast, ewes are able to maximize growth rate in ryegrass-clover pastures with 5-6 cm mean sward height (Orr et al., 1990; Osoro et al., 2002), and in natural vegetation communities with very short sward they are able to maintain their body weight (Osoro et al., 2000a). Nevertheless, the animal responses to sward height are affected by the initial body condition, with higher LW gains achieved by those animals with previous poorer condition.

The LW changes recorded under the present conditions showed better response to the sward height than that found under lowland conditions in the case of cattle (Osoro et al., 2000d) and goats (Osoro & Martínez, 1995), and similar in the case of sheep (Osoro et al., 2002). Different reasons may explain these differences. Higher pasture density has been observed in mountain pastures compared to lowland pastures (Celaya et al., 2002), and thus higher intakes per bite could be obtained in the former, increasing total intake (Hodgson, 1985). In the case of goats, a better performance was observed when they had heather available, due to a lower parasitism (Osoro et al., 2007b) and a more efficient protein utilization (Frutos et al., in press).

Moreover, the interaction between body size, intake capacity and nutrient requirements with the quantity and quality of available vegetation is known (Fitzhugh, 1978). Illius and Gordon (1993) indicated that small herbivores generally require more energy relative to their gut capacity than large ones and thus have to select higher quality foods. In contrast, larger animals with comparatively larger gut capacity relative to their metabolic requirements can retain digesta in the gastrointestinal tract for longer time and thus digest it more thoroughly. In spite of such beneficial capacity, and in contrast with sheep and

goats, cattle are unable to maintain their required intake consuming only the components of the natural vegetation in heathlands, due to their poor ability to select them and limited intake rate when sward height of the improved pasture area decreases, as stated above.

Higher performance of autumn-calving than spring-calving cows during the spring-summer grazing season have been previously observed in lowland pastures (Russel et al., 1986) but also with higher costs of winter feeding for the former (Chestnutt, 1984). It would be related to the different lactation status of cows during the spring-summer, and to the development of intake capacity by calves, which will be higher in autumn-born calves than in those younger calves born in winter-spring (Russel et al., 1986).

Parasite burden

Although the gastrointestinal nematode infection was only studied during 2006, data obtained showed the infection level in the three ruminant species and their contribution to pasture contamination by these parasites. Results showed that goats tended to shed more nematode eggs in faeces than sheep and cattle. Firstly, the differences in FEC between cattle, sheep and goats could be related to their development of immunity to gastrointestinal nematodes, and secondly, to their nutrition level. It is known that goats are mainly browsers and have evolved the lowest levels of immunity, and both young and adult animals usually require anthelmintic treatment to maintain their health in grazing conditions (Hoste et al., 2008). In change, adult sheep develop a higher level of immunity than goats as they are naturally grazers. Unless they got a heavy burden of parasite nematodes, treatment of adults may not be necessary. On the other hand, adult cattle generally do not require treatment for nematodes, although treatment may enhance the productivity (Vercruyssen & Claerebout, 2001). Nevertheless, the FECs found in goats in the current study (i.e. maximum values of 197 epg in December) are much lower than those (> 8000 epg) found at the end of the grazing season in goats grazing on ryegrass-clover pastures with no available heather (Osoro et al., 2007b). In such report, a significant effect of heather supplementation on FEC reduction was observed.

Conclusions

In conclusion, on these heterogeneous vegetation communities (heathlands with areas of improved pasture) and management conditions, sheep achieved the best performance if the entire grazing season is considered (from May to December), despite the good level of production in spring from autumn-calving cows. Goats would be a good complement for an efficient use of the natural vegetation, achieving production levels as high as those from spring-calving cows without compromising parasitic infection rates between animal species. Therefore, considering LW gains per LU and complementarity in their grazing behaviour, mixed flocks of sheep and goats would be the most appropriate to achieve sustainable systems from the animal production and vegetation use points of view. Anyway, market meat values should be considered to settle the best ways to operate at a profit in each particular condition.

8. Tools for land use planning

8.1. Geostatistical modelling of air temperature in a mountainous region of Northern Spain

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Abstract

Air temperature is one of the most important factors affecting vegetation and controlling key ecological processes. Air temperature models were compared in a mountainous region (Asturias in the North of Spain) derived from five geostatistical and two regression models, using data for January (coolest month) and August (warmest month). The geostatistical models include the ordinary kriging (OK), developed in the XY plane and in the X, Y and Z axis (OKxyz), with zonal anisotropy in the Z axis (variogram fitting procedure developed in this study), and three techniques that introduce elevation as an explanatory variable: ordinary kriging with external drift (OKED) and universal kriging, using the Ordinary Least Squares residuals to estimate the variogram (UK1) or the Generalised Least Squares residuals (UK2). The OKED, UK1 and UK2 techniques were more satisfactory than OK in terms of standard prediction error and mean absolute error, which were inferior by 1 °C, but OKxyz improved the results obtained with those techniques. Moreover, OKxyz, OKED, UK1 and UK2 improved slightly the results of a regression model with UTM coordinates and elevation data as independent variables in terms of bias (R1); whereas a complex

regression model, which includes altitude, latitude, distance to the sea and solar radiance as independent variables (R2), showed better results in terms of mean absolute error, under 0.16°C for both months. A second validation carried out with stations discarded for the interpolation showed a greater similarity between the efficiency of R2 and the geostatistical techniques.

Keywords: Climate; Kriging; Mapping; Regression Analysis; DEM.

Introduction

Air temperature is one of the input variables for land evaluation and characterisation systems, as well as hydrological and ecological models. These models use air temperature to drive processes such as evapotranspiration, soil decomposition, and plant productivity (Dodson & Marks, 1997). Hence, forest management and research need this climatic variable as a basis for understanding many processes, as it is the main factor affecting vegetation distribution, in the sense that its action is felt over wide areas of the earth's surface (De Phillips, 1951).

Air temperature is an important site characteristic used in determining site suitability for agricultural and forest crops (Hudson & Wackernagel, 1994), and it is used in parameterizing the habitat of plant species (Rubio et al., 2002; Sánchez-Palomares et al., 2003) and in determining the patterns of vegetational zonation (Richardson et al., 2004). Moreover, air temperature is a factor related to plant productivity, as it is connected with the length of the vegetative period and evapotranspiration. Different indexes have been developed for relationships between components of climate and quantitative variables of vegetation communities. These indexes are known as potential productivity indexes, and they are reviewed in Serrada (1976), Hägglund (1981) and Del Valle (2004). Finally, temperature can be also considered as a limitation factor, and many studies have been carried out with temperature as a threshold for different processes, *e.g.* the minimum temperature which may lead to lethal damage of tissue or whole tree seedlings under different situations of stand density, topography or soil preparation (Blennow, 1993, 1998).

Therefore, spatial modelling of climate variables, such as air temperature, is of interest for forestry science. However, these variables are not easy to obtain because they appear as measurements at discrete points. Consequently, many

different methods have been developed to generate regional maps from point data, based on the continuity of temperature and its strong dependency on elevation - on a global average, temperature decreases around $0.65^{\circ}\text{C} / 100 \text{ m}$ in altitude (Barry & Chorley, 1987; Gandullo, 1994; Lutgens & Tarbuck, 1995), although this rate may vary with the season and the geographic situation (Goodale et al., 1998), and in relation to diurnal effects (Richardson et al., 2004).

Different interpolation methods have been used to model the spatial distribution of air temperature; the most widely used being the inverse distance interpolation weighting, Voronoi tessellation, regression analysis or, more recently, geostatistical methods. Kurtzman and Kadmon (1999) compared different methods (splines, inverse distance weighting and multiple regression analysis) for daily mean minimum and maximum temperatures in Israel; Sánchez-Palomares et al. (1999) developed maps of climate variables with polynomial regressions based on the X and Y coordinates and elevation in Spain. Relationships have been derived between temperature and other topographic variables, together with elevations, such as exposure, continentality, latitude, and solar radiation. For example, Goodale et al. (1998) and Ninyerola et al. (2000, 2005) used regression analysis and GIS techniques to model different climate components in Ireland and Spain, respectively. Marquínez et al. (2003) related rainfalls in Asturias (Spain) with variables such as distance to the sea and to the West (due to the dominance of fronts from NW). Geostatistical techniques have also been used: Lapen and Hayhoe (2003) compared inverse distance weighting to geostatistical methods (ordinary kriging and cokriging, and ordinary kriging with external drift) to spatially model the seasonal and annual temperature and total precipitation normals in the Great Lakes (Ontario, Canada); Hudson and Wackernagel (1994) mapped air temperature of Scotland using ordinary kriging with external drift; and Ishida and Kawashima (1993) used different kriging estimators, specially cokriging estimators, to evaluate the usefulness of these approaches in temperature modelling in Japan. Approaches that include altitude (or depth) as a spatial dimension (as ordinary kriging with Z anisotropy) have been successfully applied for natural resources estimation (Ayalew et al. 2002; Montes et al. 2005), but these approaches have never been used for predicting climatic variables.

Air temperature modelling in mountainous regions is difficult and challenging (Li et al. 2005). Meteorological stations are often spread sparsely, especially at high elevation or in uninhabited areas (Rolland, 2002). Thus, it is difficult to obtain precise climatic maps (Carrega, 1995) because reconstruction of temperature fields involves interpolating sparse data over large distances (Dodson & Marks, 1997). The majority of studies made in places with complex topography have used regression models to obtain the lapse rates, with elevation data as the unique independent variable (Dodson & Marks, 1997; Rolland, 2002) or together with others, such as slope, exposure or distance to the sea (Carrega, 1995).

This study aimed to compare different geostatistical approaches and regression models to spatially predict mean air temperature in January (winter) and August (summer) in a mountainous region of Northern Spain.

Material and Methods

Study area

This comprised the Region of Asturias in Northern Spain, covering an area of 10,604 km². Its Northern boundary is the Cantabrian Sea (with a coastline of 519 km), and the Southern natural border is the Cantabrian Mountains (Figure 8.1.1.). This region is characterised by a steep relief, with altitudes ranging from sea level to 2,648 m within only 40 km, and with 80% of the land exceeding slopes of 20% and 34.5% of the territory over 50% (SADEI, 2005b).

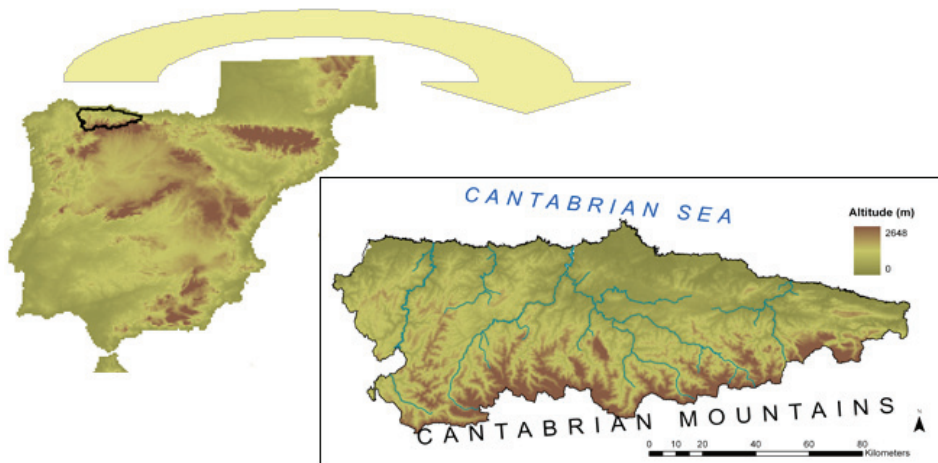


Figure 8.1.1. Location of the study area.

Data

Mean air temperature data in January (coolest month) and August (warmest month) were obtained from 96 meteorology stations of the National Meteorology Institute (INM) of the Spanish Government dispersed throughout Asturias. Most of them are located in the central part of the region, which is relatively flat and more populated, while a small number of stations were in areas of complex topography in the South, West and East of the region. Hence, the spatial distribution of the selected stations in the study area was strongly biased toward low elevations: about 85.9% of them are situated below 600m, around 9.4% between 600-1000 m, and only 4.7% over 1,000 m. The biased location of stations poses a problem in modelling temperature because almost 20% of the territory is located over 1,000 m. For this reason, another 60 stations in surrounding regions, belonging to the INM, were also considered to make up for the scarcity of data in some areas. Counting these stations of nearby provinces, the number of stations over 1,000 metres reached 24.7% of the total 156 stations (96 in Asturias and 60 in nearby provinces).

A digital elevation model (DEM) of Asturias was used as ancillary data, with an accuracy of 90 m, and it was obtained from the Department of Topography of the Forest Engineering College (Polytechnic University of Madrid). Prediction points have been obtained from this DEM, and belong to a grid of 500m x 500m, totalling 42,438 prediction points with its respective UTM coordinates and elevations. Thus, the accuracy of the resulting models was a pixel size of 0.25km². Most air temperature models use a pixel size of at least 1 km x 1km (Hudson & Wackernagel, 1994; Dodson & Marks, 1997; Goodale et al., 1998; Hayhoe & Lapen, 2001). However, elevation and temperature can vary dramatically within 1 km², particularly in mountainous regions, e.g. with a slope of 50%, 1 km means an altitude difference of 500 m, which results in a temperature difference of 3.25 °C (0.65 °C/100m x 5). Hence, in this study a smaller grid is chosen because of the steep slopes found in Asturias. Furthermore, this precision (500m x 500m) still brings an acceptable volume of data in terms of computing-time and capacity.

Filtering data

According to the definition of the World Meteorological Organisation (WMO), data for a 30-year period are recommended because they provide stable and reproducible monthly means (Fliri, 1975; Gafta & Pedrotii, 1996). Therefore, the mean temperatures used in this study were assessed from 1970-2000 data sets. Only 23 stations in August and 19 in January of the 156 stations had complete data series during that period of time. In order to select more appropriate stations for this study, two criteria were established for selection: 1) those stations with recorded data in at least 15 years of the series; and 2) those with data which had a Pearson correlation coefficient with the stations with complete data, of higher than 0.7. Only 77 stations in each month fulfilled these requirements, including the complete ones, so the air temperature models were built from the August and January monthly means of these 77 stations (Figure 8.1.2.).

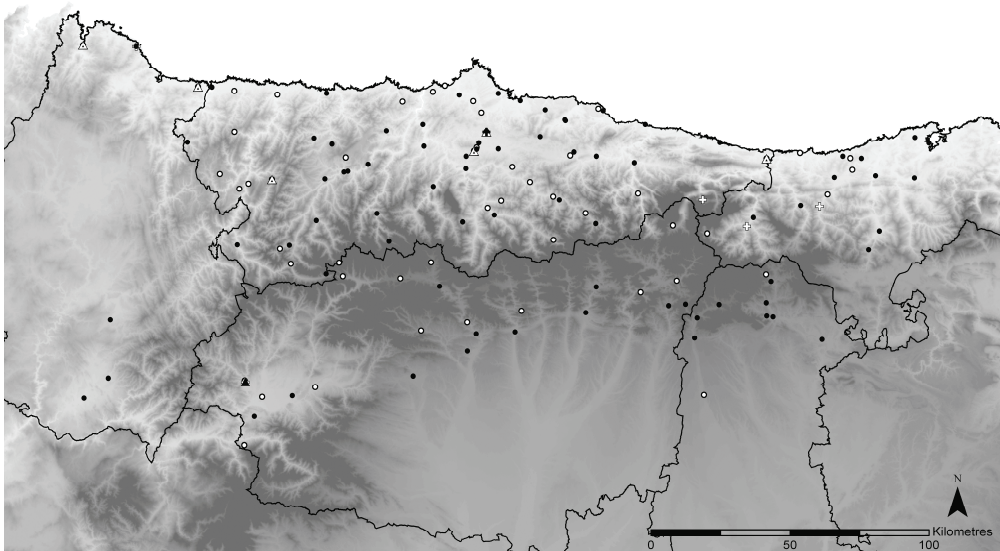


Figure 8.1.2. Location of the selected stations for mean temperature prediction (white) and stations used for data validation (black). Circles represent stations with data for January and August; triangles represent stations only with January data; crosses represent stations only with August data.

A Homogeneity or Runs Test (Thom, 1966) was used to determine whether the order of occurrence of two values of the variable was random, and the results showed that no temporal trends within the mean temperature series existed.

Once the suitability of the sample length and homogeneity had been checked, missing data during the study period were estimated. This was achieved by linear regression between stations with incomplete and complete data using the stepwise approach. This method has the advantage that one variable selected in one step can be eliminated in another step. The estimated data comprised 19.61% of the total data used in the interpolation methods.

Geostatistical methods

Geostatistics comprise a set of techniques and estimators which use the spatial variability and correlation of a continuous spaced-distributed phenomenon to predict at unsampled locations. They consist generally of two steps: a preliminary data exploratory and structural analysis of the information in order to describe the spatial variability of the variable, and the spatial prediction at unsampled points.

Spatial variance model: The variogram

The spatial autocorrelation was characterised through the experimental semivariogram. The semivariogram (usually abbreviated to variogram) measures the average dissimilarity between data separated by a lag h . It is calculated as half the average squared difference between the components of data pairs (semivariance):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{a=1}^{N(h)} [z(u_a) - z(u_a + h)]^2 \quad (1)$$

Where $N(h)$ is the number of pairs of data locations a vector h apart, $z(u_a)$ and $z(u_a+h)$ are measurements at locations u_a and u_a+h , respectively, which are considered as single realisations of the random function $Z(u)$ defined over the domain D of R^2 .

Then, the experimental variograms were modelled using the spherical model (Goovaerts, 1999), to which a nugget effect was added, and the gaussian model (Cressie, 1993).

The theoretical variogram model was fitted from the experimental variogram using the minimum weighted squares method (Cressie, 1993). The performance of the fitted variogram at small scales, which are the most important in the spatial prediction (Hudson & Wackernagel, 1994), was checked by comparing the plots of the theoretical model fitted and the experimental variogram.

Spatial prediction

Ordinary kriging in the XY plane (OK). The ordinary kriging prediction of $Z(u)$ at location u_a is given by the following equation:

$$z^*(u_a) = \sum_{i=1}^n \lambda_i(u_a) z(u_i) \quad (2)$$

Where $\lambda_i(u)$ is the assigned weight for data $z(u_i)$ from the n sampled locations, so that the estimation of error variance (Eq. (3)) was minimised, under the constraint of unbiasedness of the estimator (Eq. (4)).

$$\sigma_E^2 = \text{Var}\{Z^*(u_a) - Z(u_a)\} \quad (3) \quad \sum_{i=1}^n \lambda_i = 1 \quad (4)$$

Ordinary kriging in the X,Y and Z axis with zonal anisotropy on the Z axis (OKxyz). As occurs with depth in geosciences, when elevation is included in the kriging system the directional variograms show zonal anisotropy, i.e. the variogram for stations aligned through the XY plane show different sill (the semivariance value where the variogram gets stable) than for stations located at different elevation (Z axis).

When observations are available in all directions, as usually occurs with geological surveys, the anisotropy may be modelled directly from the directional experimental variograms (Gringarten & Deutsch, 2001). However, the terrain configuration impedes air temperature observations aligned through the vertical direction. Those pairs of stations forming an angle with the horizontal greater than 1.75° were selected to calculate the directional variogram for the Z axis, whereas those pairs of stations forming an angle with the horizontal smaller than 0.75° , and with elevation difference no greater than 300 m, were selected to calculate the XY variogram. For each lag, the vertical component of the distance

was averaged across all pairs of observations, both in the XY plane and in the Z direction variograms. The key step when dealing with zonal anisotropy is to build a strictly negative definite model (Rouhani & Myers, 1990; Myers & Journel, 1990). Both directional variograms were modelled as the sum of an isotropic spherical variogram and a gaussian variogram for the Z axis, which constitutes a valid model (De Iaco et al., 2002):

$$\gamma(d) = \gamma_{spherical}(x, y, z) + \gamma_{gaussian}(z) \quad (5)$$

Ordinary kriging was carried out calculating the sum variogram for each pair of observations for each observation-prediction point.

Ordinary Kriging with External Drift (OKED). The spatial prediction was carried out over the residuals ($\delta(u)$) of a regression model of $Z(u)$ as a function of the explanatory variable $Y(u)$:

$$z(u_a) = a_0 + a_1 y(u_a) + \delta(u_a) \quad (6)$$

The predicted values are the addition of the regression estimates of $Z(u)$ at each location and the residuals estimated through ordinary kriging at each location.

Universal Kriging (UK). $Z(u)$ is given by the following linear model of p known functions $f_k(u)$:

$$z(u_a) = \sum_{k=0}^p \beta_k f_k(u_a) + \delta(u_a) \quad (7)$$

The Eq. (2) holds, and the unbiasedness condition becomes:

$$\sum_{i=1}^n \lambda_i f_{j-1}(u_i) = f_{j-1}(u_a) \quad (8)$$

To obtain the λ_i coefficients in Eq. (2) the error variance given by Eq. (9) is minimised:

$$\sigma_E^2 = \left(\sum_{k=0}^p \beta_k f_k(u_a) + \delta(u_a) - \sum_{i=1}^n \left(\lambda_i \sum_{k=0}^p \beta_k f_k(u_i) \right) - \sum_{i=1}^n \lambda_i \delta(u_i) \right)^2 \quad (9)$$

Two different procedures have been carried out to estimate the variogram for UK. The first variogram estimation (UK1) was based on the residuals of Ordinary Least Squares (OLS) β_k estimates of Eq. (7) (which in turn coincides

with the variogram used in the OKED method). Thereafter, the universal kriging estimator will be carried out with these variogram's parameters to kriging the values of the variable. Unfortunately, the variogram computed with the OLS residuals yields a biased estimator of the true variogram (Cressie, 1993). The second procedure, referred to as UK2 and developed by Neuman and Jacobson (1984), consists of iteratively fitting the variogram (starting with the variogram based on the OLS residuals) and obtaining the Generalised Least Squares (GLS) estimates of the β_k coefficients through Eq. (10):

$$\hat{\beta}_{GLS} = \left(X' \Sigma(\hat{\theta})^{-1} X \right)^{-1} X' \Sigma(\hat{\theta})^{-1} Z \quad (10)$$

Where $\hat{\beta}_{GLS}$ is the vector of the coefficients, X is an $n \times (p+1)$ matrix whose (a,j) element is $f_{j-1}(u_a)$, Z is the column vector of the $z(u_a)$ values in the n sampled locations and $\Sigma(\hat{\theta})$ is the VAR(Z) matrix based on the parameters $(\hat{\theta})$ of the fitted variogram. The variogram based on the GLS residuals does not solve the bias problem, although this bias usually has little effect on the spatial prediction (Cressie, 1993).

Regression models

The first regression model for the Iberian Peninsula (R1) was developed by Sánchez-Palomares et al. (1999) and it was based on stepwise multiple regression analysis, which was carried out for each month and for each of the 10 main basins previously described in the Iberian Peninsula. The models of the mean temperature for January (T_J) and for August (T_A) presented these forms for Asturias:

$$T_J = 2490.96 - 5.66 \left(\frac{e}{10^3} \right) - 104.46 \left(\frac{Y}{10^5} \right) + 1.10 \left(\frac{Y}{10^5} \right)^2 \quad (11)$$

$$T_A = -2157.01 - 4.05 \left(\frac{e}{10^3} \right) + 0.89 \left(\frac{X}{10^5} \right) + 93.57 \left(\frac{Y}{10^5} \right) - 0.11 \left(\frac{X}{10^5} \right)^2 - 1.01 \left(\frac{Y}{10^5} \right)^2$$

Elevation (e) and UTM coordinates in metres (X is the UTM coordinate in the x-axis, and Y in the y-axis).

The other used model (R2) was developed by Ninyerola et al. (2005). In this model, together with elevation (e) and UTM coordinates, in this case latitude (L), they introduced new independent variables, thanks to the Geographical

Information Systems (GIS) techniques. These were the continentality (C) measured as the linear distance to the sea, the solar radiance (obtained from a DEM and astronomical equations) (R), and the geomorphology or curvature radius of the terrain also derived from the Digital Elevation Model (DEM) and which was used to develop the continentality variable. It presented the following expression:

$$T = b_0 + b_1e + b_2L + b_3C + b_4R \quad (12)$$

Then, a correction of the estimated residuals was accomplished. Temperature values at the sampled points are obtained directly from the Digital Climatic Atlas of the Iberian Peninsula, available free on-line (<http://opengis.uab.es/wms/iberia/mms/index.htm>).

Validation and techniques comparison

To compare the performance of the five geostatistical methods, the results of the leave-one-out cross-validation were analysed (Stone, 1974; Geiser, 1975), as well as the distribution of the prediction errors in the estimation points. Besides, data from the stations, which were rejected for the interpolation, were also used to verify the goodness of our models, above all in faraway locations.

The leave-one-out cross-validation or jackknifing is a commonly applied method in geostatistics (Isaaks & Srivastava, 1989; Cressie, 1993; Nalder & Ross, 1998) because no reserved data are required for the data validation. The number of sampled sites with climatic data is usually not very large and they are sparse throughout the study area, so all the sampled data are used for the spatial prediction in order to improve the precision of the predictions. The cross-validation procedure was carried out as follows: each datum was removed and predicted from its neighbours ($\hat{Z}_{-a}(u_a)$). Then, estimated and observed values were compared. The Normalised Mean Error or NME (E_1) was used to check whether the kriging prediction was approximately unbiased (the NME should be approximately 0):

$$E_1 = \frac{1}{n} \sum_{a=1}^n \left\{ \frac{(Z(u_a) - \hat{Z}_{-a}(u_a))}{\sigma_{-a}(u_a)} \right\} \quad (13)$$

The Normalised Root Mean Squared Error or NRMSE (E_2) was used to check whether the kriging prediction error based on the fitted variogram was satisfactory, in which case the NRMSE should be approximately 1:

$$E_2 = \left[\frac{1}{n} \sum_{a=1}^n \left\{ \frac{(Z(u_a) - \hat{Z}_{-a}(u_a))}{\sigma_{-a}(u_a)} \right\}^2 \right]^{1/2} \quad (14)$$

Cross validation only provides information on areas associated with observed data (Robeson, 1994), so it should not be used for confirmatory data analysis, such as standard error estimation. Thus, the kriging standard error ($\sigma_{OK}(u_a)$ and $\sigma_{UK}(u_a)$, given by Eq. (15) and Eq. (16), respectively) was assessed at the prediction points, which quantifies the uncertainty in the predicted surface.

$$\sigma_{OK}^2(u_a) = \sum_{i=1}^n \lambda_i \gamma(u_a - u_i) - (1 \cdot I' \Gamma^{-1} \boldsymbol{\gamma})(I' \Gamma^{-1} I) \quad (15)$$

$$\sigma_{UK}^2(u_a) = \boldsymbol{\gamma}' \Gamma^{-1} \boldsymbol{\gamma} - (\mathbf{x} - \mathbf{X} \Gamma^{-1} \boldsymbol{\gamma})(\mathbf{X}' \Gamma^{-1} \mathbf{X})(\mathbf{x} - \mathbf{X} \Gamma^{-1} \boldsymbol{\gamma}) \quad (16)$$

Where I is the column matrix of ones, I' is the row matrix of ones, $\boldsymbol{\gamma}$ is the column vector of the semivariogram values between u_a and u_i ($\gamma(u_a - u_i)$), Γ is the matrix with the $(i, j)^{th}$ ($\gamma(u_i - u_j)$), \mathbf{x} is the vector of the p $f_k(u_a)$ values and \mathbf{X} is the $n \times (p+1)$ matrix whose (a, j) element is $f_{j-1}(u_a)$.

For the geostatistical and the regression models the mean error (ME) - M_1 - and the mean absolute error (MAE) - M_2 - at the observed points were computed to determine the accuracy of the different estimation approaches:

$$M_1 = \frac{1}{n} \sum_{a=1}^n (Z(u_a) - \hat{Z}_{-a}(u_a)) \quad (17)$$

$$M_2 = \frac{1}{n} \sum_{a=1}^n |Z(u_a) - \hat{Z}_{-a}(u_a)| \quad (18)$$

Stations not used for the spatial model, with at least 5 years data, were selected to carry out a validation over an independent data set (52 stations in January and 51 in August). The prediction error, ME and MAE were calculated for the different techniques. Many of these stations were located in areas with sparse data (Figure 8.1.2.), and the proportion of these stations over 600m exceeded the proportion of those used in the interpolation (42.3% for January and 43.1% for August). Accordingly, the independent data set was used to check the

performance of the different prediction techniques in areas with few observations or at high altitudes.

Results

Geostatistical models

The correlation between temperature (T) and elevation (e) in the OLS regression model was negative and significant at 0.01 level, 2-tailed ($\rho = -0.75$ for August temperatures and $\rho = -0.93$ for the mean temperature of January). The OLS regression was the following:

$$T_j = 90.85 - 0.065e \qquad T_A = 196.99 - 0.026e$$

The iterative approach used to fit the variogram and the GLS estimates of the β_k coefficients, Eq. (10), resulted in $\beta_0 = 99.051$ and $\beta_0 = 164.161$ (the intercept) and $\beta_1 = -0.077$ and $\beta_1 = -0.009$ (coefficient of the elevation variable) for January and August, respectively.

Figure 8.1.3. shows the experimental variogram for the air temperature and the spherical model fitted for OK, and the directional variograms in the XY plane and Z axis, as well as the fitted spherical plus gaussian model for the OKxyz. The variogram for the OLS and the GLS residuals and the fitted spherical models (for OKED and UK1, and for UK2 respectively) can also be seen. The parameters for the fitted theoretical variogram models are shown in Table 8.1.1. It can be observed that there was negligible nugget effect, i.e. distance near nought means variogram -variance- close to nought, which agreed with the continuous nature of this variable; and the sill or variance value in January was higher than in August, according to a higher variability of the data in winter.

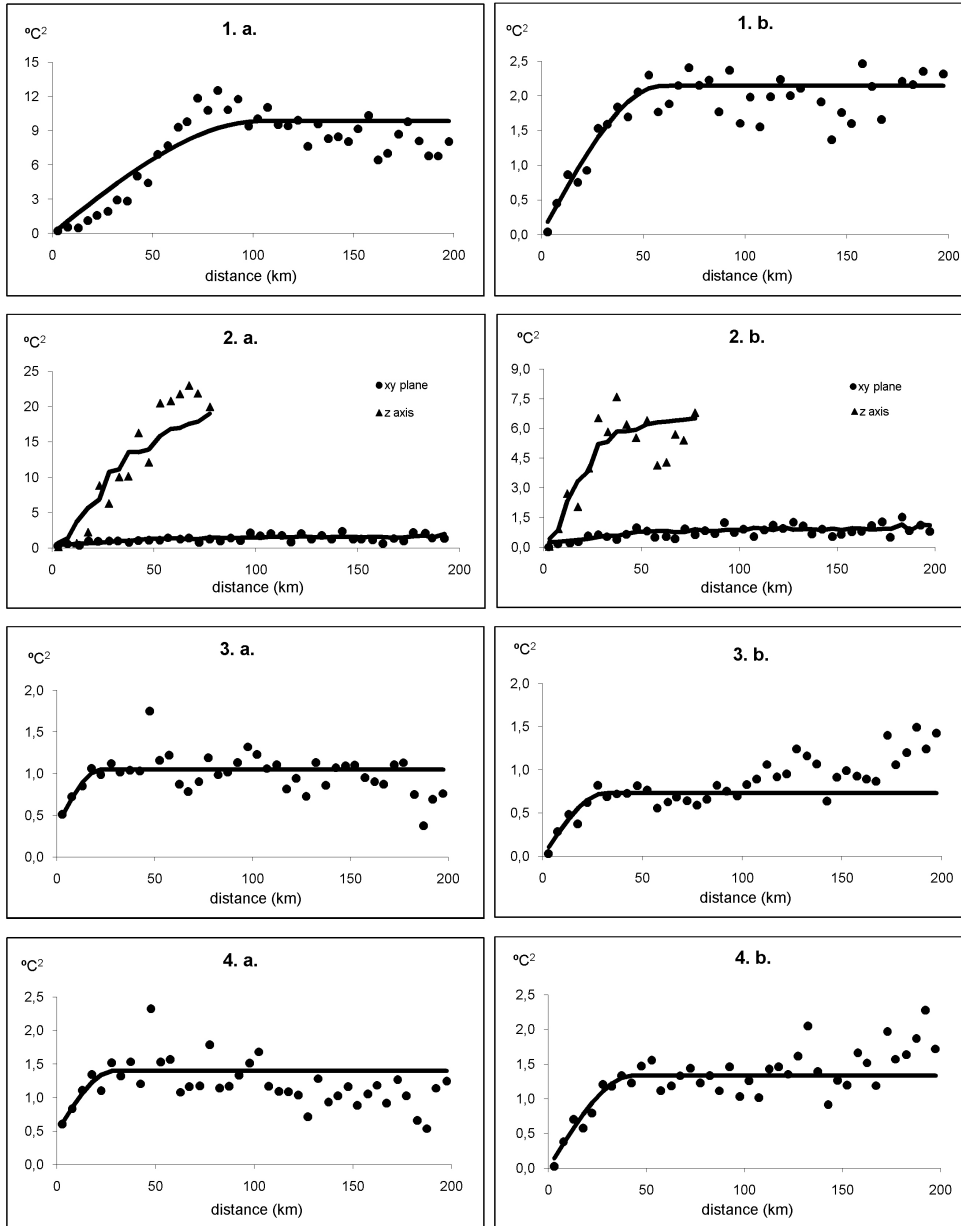


Figure 8.1.3. Variograms of (a) January and (b) August: 1) for mean temperatures with ordinary kriging, 2) for mean temperatures with ordinary kriging in 3D, 3) for ordinary least squares residuals (ordinary kriging with external drift and universal kriging 1), 4) for generalised least squares residuals obtained for universal kriging 2.

Table 8.1.1. Parameters of the fitted variograms for January and August data with the different methods.

	Type of adjustment	Month	Nugget (°C ²)	Sill (°C ²)	Range (km)
Ordinary Kriging	Spherical	January	0.000	9.855	104.7
		August	0.021	2.146	59.3
Ordinary Kriging XYZ with zonal anisotropy in the Z axis	Spherical (xyz)	January	0.489	1.205	144.3
		August	0.243	0.644	136.9
	Gaussian (z)	January	0.000	21.764	0.9
		August	0.000	6.039	0.6
Ordinary Kriging with External drift and Universal Kriging 1	Spherical	January	0.370	1.050	22.4
		August	0.000	0.732	31.4
Universal Kriging 2	Spherical	January	0.493	1.403	28.6
		August	0.000	1.337	43.1

Prediction and modelling of mean temperature

The maps of January and August mean temperature derived from the five geostatistical and the two regression methods are shown in Figures 8.1.4. and 8.1.5., respectively. A progressive cooler gradient can be observed when moving from the coast line to the South (to the mountains), and some exceptional cooler areas can be found near the coast due to the high altitudes of some sierras which are very close to the coast. Warm areas occurred in middle-high parts of the main basins.

In winter, the Western coast was warmer than the Eastern coast. This is probably due to the Eastern part of Asturias which is more affected by the European Anticyclone in winter, which brings cold, dry air. In the Western part of Asturias, the climate is often influenced by subtropical winds from the SW, which bring clouds and rain (García & Reija, 1994). In summer, the warm interior regions coincided with the warmest areas. This phenomenon points the “muffle effect” of the sea.

Comparing the techniques, there were great differences between ordinary kriging and the other techniques, which accommodate elevation data, as shown in Figures 8.1.4. and 8.1.5. and Table 8.1.2. These differences were higher in winter, when the correlation between mean temperature and altitude was higher.

The January mean temperature with OK was around 2°C higher than the rest. This differential increased, reaching nearly 4 °C, when only stations over 600 m were considered, and exceeding 8 °C for the minima. The three-dimensional OK (OKxyz) presented seemingly similar results to the multivariate ones on average

terms. However, the minimum temperatures of OKxyz at high altitudes, and similarly to OK, showed noticeable differences with the multivariate techniques.

Table 8.1.2. Descriptive statistics of the predicted temperatures. The first regression model is the one developed by Sánchez-Palomares et al. (1999) and the second one by Ninyerola et al. (2005).

	°C	January			August		
		Stations			Stations		
		< 600 m	≥ 600 m	All	< 600 m	≥ 600 m	All
Ordinary Kriging	min	4.5	2.8	2.8	16.6	14.7	14.7
	max	10.0	9.3	10.0	20.6	20.5	20.6
	mean	8.1	6.1	7.1	19.0	18.6	18.8
	Std. dev.	1.0	1.4	1.5	0.5	1.1	0.9
Ordinary Kriging in 3D	min	4.7	1.7	1.7	17.1	14.2	14.2
	max	9.4	7.5	9.4	20.2	18.7	20.2
	mean	7.5	3.6	5.7	18.8	16.4	17.7
	Std. dev.	1.0	1.1	2.2	0.5	0.9	1.4
Ordinary Kriging with External Drift	min	4.5	-6.7	-6.7	16.6	12.8	12.8
	max	9.9	6.5	9.9	20.6	19.8	20.6
	mean	7.3	2.7	5.1	18.9	17.2	18.1
	Std. dev.	1.2	2.1	2.8	0.6	1.2	1.2
Universal Kriging 1	min	4.5	-6.3	-6.3	16.6	12.2	12.2
	max	9.9	6.7	9.9	20.6	19.7	20.6
	mean	7.3	2.8	5.2	18.9	17.0	18.0
	Std. dev.	1.1	2.0	2.8	0.6	1.3	1.3
Universal Kriging 2	min	4.5	-6.1	-6.1	16.6	11.8	11.8
	max	9.9	6.7	9.9	20.6	19.6	20.6
	mean	7.3	2.9	5.2	18.8	16.9	17.9
	Std. dev.	1.1	2.0	2.7	0.6	1.3	1.4
Regression Model 1	min	5.2	-5.1	-5.1	16.5	10.6	10.6
	max	9.4	5.7	9.4	20.0	18.1	20.0
	mean	7.3	3.0	5.3	18.3	16.0	17.3
	Std. dev.	1.1	1.9	2.6	0.6	1.2	1.5
Regression Model 2	min	3.4	-5.0	-5.0	16.3	10.6	10.6
	max	10.3	8.0	10.3	21.0	19.9	21.0
	mean	7.3	3.3	5.4	18.6	16.4	17.6
	Std. dev.	1.1	1.9	2.5	0.6	1.2	1.5

In August, differences were less, although OK continued estimating higher mean temperatures (around 1°C), and both OK and OKxyz predicted higher minima at high altitudes (around 2°C) than OKED, UK1 and UK2.

The regression models estimated mean temperatures similar to those of the multivariate spatial models in January, although the minimum temperatures were smoothed. In August, the regression models gave slightly lower mean and minimum temperatures than the multivariate spatial models.

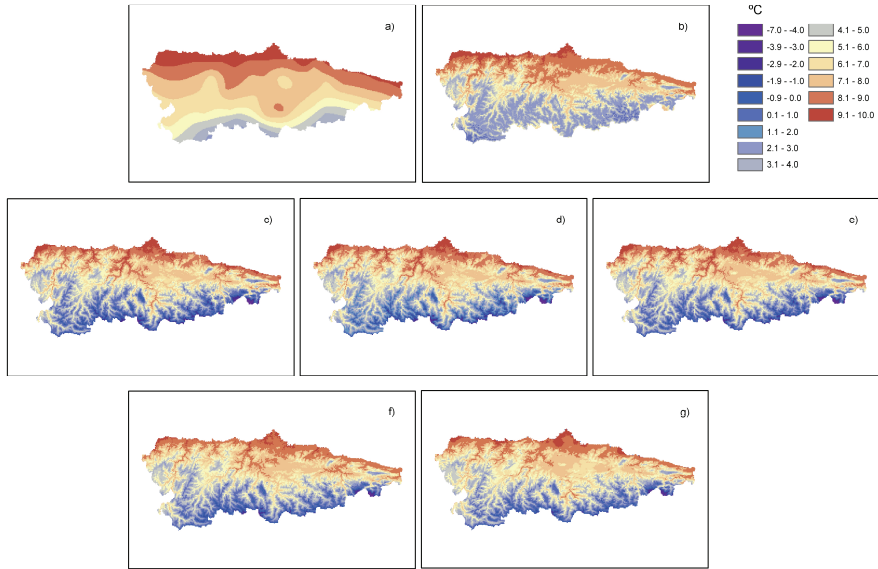


Figure 8.1.4. Models of predicted mean air temperature in January: a) Ordinary kriging, b) Ordinary kriging in 3D, c) Ordinary kriging with external drift, d) Universal kriging 1, e) Universal kriging 2, f) Sánchez-Palomares' regression model, g) Ninyerola's regression model

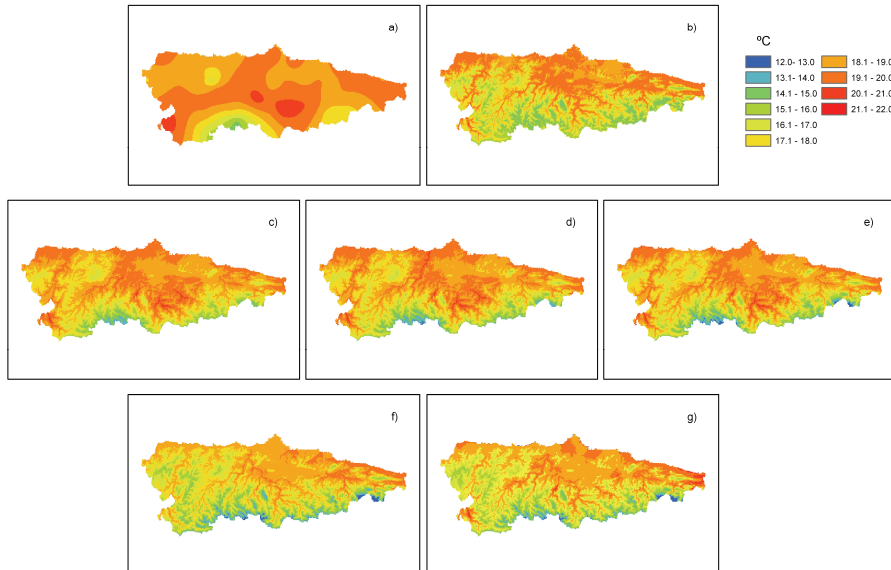


Figure 8.1.5. Models of predicted mean air temperature in August: a) Ordinary kriging, b) Ordinary kriging in 3D, c) Ordinary kriging with external drift, d) Universal kriging 1, e) Universal kriging 2, f) Sánchez-Palomares' regression model, g) Ninyerola's regression model.

Validation and kriging error distribution

Table 8.1.3. shows the NME and NRMSE resulting from the cross-validation for the OK, OKxyz, OKED, UK1 and UK2 methods. The NME was approximately 0 for every kriging technique, which indicated that air temperature estimations were approximately unbiased. The NRMSE of every procedure was approximately 1, which indicated that the fitted variogram and the consequent kriging standard error were satisfactory. An exception appeared in January with OKxyz, with a low NRMSE, which indicated that the kriging variance tend to overestimate the true error.

Table 8.1.3. Normalised Mean Error (NME) and Normalised Root Mean Squared Error (NRMSE) of the values inferred by Cross-Validation, for each technique (OK: Ordinary Kriging; OKxyz: Ordinary Kriging in 3D; OKED: Ordinary Kriging with External Drift, UK: Universal Kriging), and during January and August.

	January					August				
	OK	OKxyz	OKED	UK1	UK2	OK	OKxyz	OKED	UK1	UK2
NME	0.025	0.003	0.017	0.011	0.009	0.016	0.008	0.028	0.030	0.026
NRMSE	0.737	0.320	0.994	0.996	0.875	1.190	1.136	1.181	1.156	0.955

The OKED, UK1 and UK2 showed prediction models with similar ranges in the kriging standard error maps (Figure 8.1.6.). Nonetheless, the OKxyz, which takes into account the spatial variability in three dimensions, compiled better results than the other models, especially in January and for low altitudes.

In general, August predictions showed smaller errors than January ones, according to a smaller variability of the summer's data. The highest residuals were found in those areas with no or sparsely distributed stations, such as in Navia basin (in the West) and in the Southern mountainous region. In the case of OKxyz, the distribution of the errors was remarkably regular throughout the region, and large errors were recorded only in the Southern ranges, over 1400 m above sea level. However, they comprised a very small area. They reached very high values because of the high semivariance values reached in the Z variogram.

Table 8.1.4. shows the mean error and mean absolute error for the kriging and the regression models considering every prediction point, as well as the kriging standard error for the kriging models. The OK showed higher mean

kriging standard error than the multivariate spatial models, and the latter showed poorer results than OKxyz, at every turn. The UK2 presented the highest mean kriging standard error among the multivariate models, although the low value of its NRMSE (Table 8.1.3.) indicates that $\sigma_{UK}(u_a)$ may overestimate the true error for UK2.

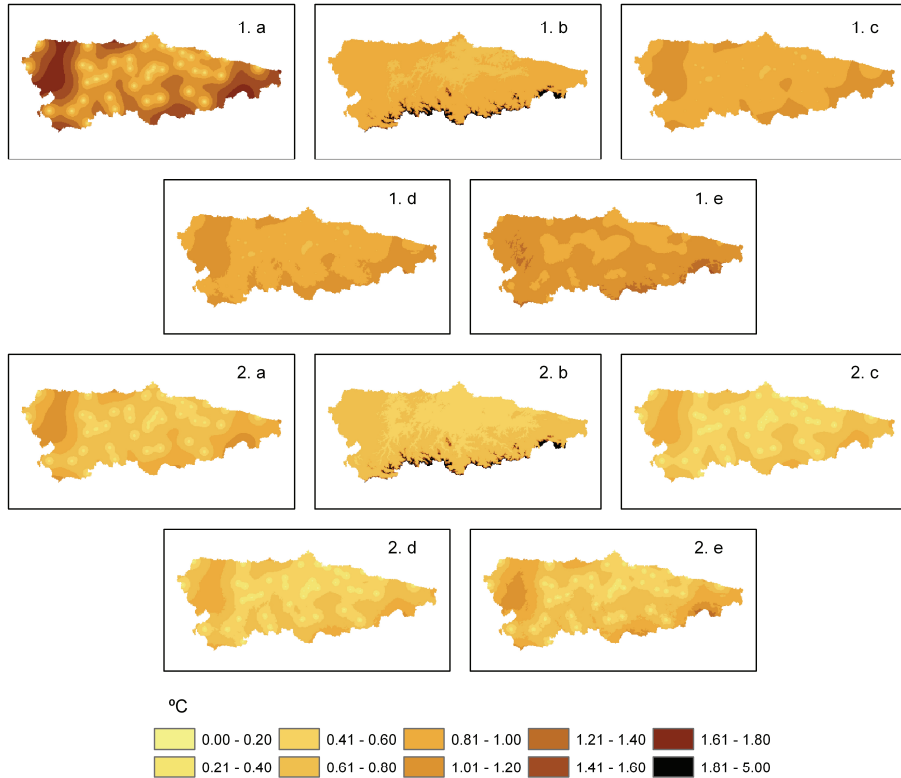


Figure 8.1.6. Maps of the kriging (prediction) standard errors: 1. January, 2. August. a) Ordinary kriging, b) Ordinary kriging in 3D, c) Ordinary kriging with external Drift, d) Universal kriging 1, e) Universal kriging 2.

High altitude prediction is of great interest, as Asturias encompasses a large area at high elevations and as this prediction involves much complexity and difficulty. In Table 8.1.4. errors are also studied separately at low and high elevation (<600 m and ≥ 600 m above sea level). The range of MAE was below 1°C in every technique which considered the elevation data. However, the ME indicated that the OKED had a larger bias than the UK1 and the UK2 at high elevations. The model R1 showed generally poorer results than the geostatistical

models in terms of ME and MAE, meanwhile the R2 model showed the lowest MAE, both for high and low elevations and January and August temperatures.

Table 8.1.4. Mean Errors (ME), Mean Absolute Errors(MAE) and Kriging Standard Error Estimates (KSE) resulting of the cross validation for the geostatistical methods and ME and MAE for regression models (R1 is the model developed by Sánchez-Palomares et al. (1999) and R2 is the model developed by Ninyerola et al.(2005)) for all the sampled locations.

		ME (°C)	MAE(°C)	KSE (°C)
All stations	OK January	0.052	0.731	1.158
	OKxyz January	0.018	0.668	0.898
	OKED January	0.024	0.774	0.947
	UK1 January	0.020	0.791	0.958
	UK2 January	0.018	0.778	1.068
	R 1	-0.087	0.796	
	R 2	0.070	0.377	
	OK August	0.029	0.788	0.742
	OKxyz August	0.009	0.567	0.664
	OKED August	0.032	0.624	0.590
	UK1 August	0.033	0.617	0.602
	UK2 August	0.032	0.608	0.701
	R 1	0.232	0.640	
	R 2	-0.024	0.240	
Stations equal and over 600 m	OK January	-0.386	0.788	1.227
	OKxyz January	0.100	0.678	0.995
	OKED January	0.094	0.841	0.966
	UK1 January	0.026	0.881	0.987
	UK2 January	0.006	0.846	1.105
	R 1	-0.305	0.952	
	R 2	-0.029	0.147	
	OK August	-0.518	1.022	0.786
	OKxyz August	-0.012	0.638	0.756
	OKED August	-0.225	0.762	0.629
	UK1 August	-0.111	0.734	0.654
	UK2 August	-0.055	0.755	0.766
	R 1	0.025	0.552	
	R 2	-0.096	0.152	
Stations below 600m	OK January	0.251	0.706	1.098
	OKxyz January	-0.019	0.664	0.814
	OKED January	-0.007	0.744	0.931
	UK1 January	0.018	0.750	0.932
	UK2 January	0.023	0.747	1.036
	R 1	0.012	0.725	
	R 2	0.115	0.482	
	OK August	0.277	0.682	0.704
	OKxyz August	0.018	0.535	0.585
	OKED August	0.149	0.561	0.556
	UK1 August	0.098	0.565	0.558
	UK2 August	0.071	0.542	0.644
	R 1	0.326	0.680	
	R 2	0.009	0.280	

Table 8.1.5. shows the results of the independent validation. As high altitude and low sampled areas were relatively more frequent in the data set used for the independent validation, the mean estimated temperatures were lower than for the entire study area, and the errors and biases were higher than for the cross-validation. However, the MAE was smaller than 1°C for all the interpolation techniques except for OK. The R1 regression model showed smaller bias and MAE in January than the other techniques, whereas the OKxyz and R2 were the techniques which performed better in August. It was remarkable that the difference between the MAE made with R2 and the rest of techniques disappeared. Even in January, we can see that R2 presented poorer results than the geostatistical performances.

Table 8.1.5. Mean Temperature (T), Mean Errors (ME), Mean Absolute Errors (MAE), Kriging Standard Error Estimates (KSE), Normalised Mean Error (NME) and Normalised Root Mean Squared Error (NRMSE) for the independent validation data set (R1 is the model developed by Sánchez-Palomares et al. (1999) and R 2 is the model developed by Ninyerola et al. (2005))

		T (°C)	ME (°C)	MAE (°C)	KSE (°C)	NME	NRMSE
January	OK	6.3	-0.373	1.049	1.277	-0.276	1.283
	OKxyz	5.7	0.178	0.863	0.835	0.119	1.124
	OKED	5.8	0.120	0.866	0.953	0.104	1.116
	UK1	5.8	0.107	0.862	0.959	0.064	1.119
	UK2	5.8	0.074	0.856	1.076	0.183	1.118
	R 1	5.8	0.051	0.831			
	R 2	5.7	0.188	0.867			
August	OK	18.6	-0.348	1.041	0.830	-0.460	1.857
	OKxyz	18.3	-0.082	0.771	0.428	-0.204	1.070
	OKED	18.5	-0.244	0.897	0.649	-0.456	1.218
	UK1	18.4	-0.213	0.888	0.652	-0.413	1.215
	UK2	18.4	-0.197	0.884	0.768	-0.335	1.198
	R 1	18.1	0.146	0.879			
	R 2	18.1	0.100	0.753			

Discussion

Geostatistical techniques have been used to infer reasonable models, from accuracy and time-capacity computing points of view, of the mean air temperature in January and August. Air temperature is one of the main external factors affecting ecological processes. The three analysed geostatistical methods that included elevation as an auxiliary variable to estimate the distribution of

mean monthly air temperature, showed similar patterns with reasonable estimation errors, as well as error estimations, which indicates the adequacy of the spatial models developed. Furthermore, a new approach based on XYZ kriging with zonal anisotropy in the Z direction has been applied with promising results. The absence of an underlying deterministic relationship between elevation and temperature constitutes the main difference between this approach and the multivariate geostatistical techniques and the regression models analysed.

August predictions had generally smaller errors than in January. This is in accordance with the higher variability in January data and the higher variances found in January variograms. This is similar to the trend found by Rolland (2002), where the air temperature interpolation error was higher in January than in July (the warmest month in its study region). As previously reported (Hudson & Wackernagel, 1994; Dodson & Marks, 1997), correlations between temperature and elevation may change seasonally, and were higher in this study in January than in August. A similar trend appeared in Israel (Kurtzman & Kadmon, 1999) where the regression coefficient between the January mean daily temperature and altitude reached $R^2=0.84$, meanwhile with June temperatures this coefficient was $R^2=0.57$. Besides, in Scotland (Hudson & Wackernagel, 1994), mean temperature of July held the weakest correlation coefficient with elevation of every studied month (January, April, July and October), because of the strong correlation with latitude in summer.

Taking into account these correlation coefficients, it is not surprising that the models inferred with the elevation data brought about more accurate predictions, because altitude plays a major part in climatic spatial changes in mountainous areas (Stoutjesdijk & Barkman, 1992). OKxyz, UKs and OKED improved the temperature estimations made with OK. In Figure 8.1.6. and in Table 8.1.4., the kriging errors and mean errors at sampled locations decreased when elevation was considered (on average 15% in kriging error terms). This improvement was greater in winter time (January) at high elevations (≥ 600 m). Recall that January temperatures showed higher correlation with altitude data.

The impressive differences in the prediction maps and the prediction errors between the OK and OKxyz techniques show the importance of the variogram model in the kriging prediction. In fact, the only difference between both approaches was the variogram computing method. With OKxyz, the kriging

weights were drastically reduced when the altitude difference increased. Surprisingly, the prediction maps derived through OKxyz were very similar to those derived from the OKED, UK1, UK2 and the regression models, which assumed a deterministic linear relationship between temperature and elevation. However, the highest point prediction errors were recorded with the seemingly more accurate geostatistical technique, the OKxyz, with figures around 5°C in January, and nearly 3°C in August. In Figure 8.1.6. these large prediction errors encompassed a small area with only 6.7% (January) and 4.8% (August) of the surface exceeding the prediction error by 1°C. Moreover, they matched up with the highest elevations (over 1400 m), due to the high altitude differences between the nearest stations.

UK2 showed larger kriging errors than the other multivariate kriging methods (1.4°C for both months), which is in accordance with the highest variogram sill value (Table 8.1.1.). Nevertheless, $\sigma_{UK}(u_a)$ for UK2 may be a more reliable estimator of the true kriging variance, as the NRSME indicates. In fact, the variogram estimate based on the OLS (Ordinary Least Squares) residuals had larger bias than the estimate based on the GLS (Generalised Least Squares) residuals (Cressie, 1993).

Conversely, although the OKED and the UK1 techniques were based on the residuals of the same regression model, the UK1 included the elevation of the prediction points and the sampled points in the kriging system. Hence, UK1 must give more precise predicted error estimates (as the NME and the NRMSE indicate) than OKED, which does not incorporate the uncertainty within the internal model.

For stations at altitudes above 600 m, the MAE with OK was similar to the MAE with OKED, UK1 and UK2, but the ME indicated that OK estimates were strongly biased towards higher temperatures (Tables 8.1.4. and 8.1.5.), probably because of the non-homogeneous altitudinal distribution of the stations. The inclusion of the variability on the Z direction in the OKxyz seemed to solve the bias problem, and this approach held the best results in terms of MAE in both months. For the high altitude stations, the UK2 showed a smaller bias, specially in January, when the correlation between elevation and temperature was higher. Conversely, the OKED showed larger bias (mean error) than the other multivariate kriging methods, towards lower temperatures in January, and

specially towards higher temperatures in August, when the correlation between elevation and temperature is lower. In fact, for August, the absolute value of the coefficient in the regression model was quite low, so the regression may overestimate high altitude temperatures, whereas the ordinary kriging may smooth the residuals at these altitudes. In January, it seems to occur conversely. The biased August temperature estimations with OKED were also corroborated by the independent validation.

The regression model with elevation as a unique independent variable showed a strong bias towards low temperatures at low altitudes in August and towards high temperatures at high altitudes in January, smoothing the extreme temperature values. The decrease in efficiency of simple regression analysis for assessing temperature with elevation was also confirmed by Rolland (2002). The model developed by Ninyerola et al. (2005), which included other variables such as the distance to the sea or the curvature radius of the terrain, showed much better performance in bias terms and was the most precise in MAE terms, particularly at higher elevations where MAE was under 0.16°C for both months. Nonetheless, the R2 model gave more biased estimations than OKxyz and UK2, and its implementation was more complex than the rest as it requires a solar radiance model and some GIS development to derive the independent variables. Surprisingly, the independent validation, that mainly reflects the model's performance in poorly sampled areas, did not show better results for the regression models than for the kriging techniques. In fact, all the techniques except OK gave similar figures in terms of MAE. When accounting for the bias, the UK2 and R1 techniques showed slightly better results in January, when the correlation between elevation and temperature was higher, whereas in August the OKxyz and R2 regression model gave the best results.

Conclusions

In spite of the scarce and irregularly distributed number of sampled data, the models derived from geostatistical techniques with elevation as an auxiliary variable were quite accurate, especially the ordinary kriging XYZ with zonal anisotropy in the Z direction. The variogram fitting procedure of the OKxyz has been developed in the frame of this research, and with the same independent variables (UTM-coordinates and elevation data) improved the regression models.

These techniques were satisfactory, since other predictive models had lower predictive power (OK and R 1) or they mean a complex analysis such as R2, which required technical resources that are not always available, and more time and computing-capacity. Also, it has been shown that predictions with R2 in places elsewhere do not necessarily provide the best results. Future directions of this research include the use of other variables in the multivariate kriging methods, continuing the trend followed by regression techniques, and the use of geostatistical techniques to study the temporal variability of ecological variables, a key aspect for every natural resources management.

8. Tools for land use planning

8.2 Potential productivity of forested areas based on a biophysical model. A case study of a mountainous region in Northern Spain

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Abstract

The potential productivity was modelled in a mountainous region of Spain. The model combined climatic, topographic and lithological data using a variant of a traditional biophysical model: the Paterson index. In a first approach, the climatic productivity was assessed modelling the required parameters using different geostatistical techniques and softwares supported by GIS. A second approach involved using a lithological map to reclassify the different types of *facies* into 8 productive classes, and a correction coefficient was then assigned to each one. The potential forest productivity model involved the integration of both models (climatic productivity and lithological correction). Finally, data from the III National Forest Inventory (NFI) (annual increment in wood volume) were used to compare the real and potential yield data within different regions of the studied area. The results of these analyses demonstrated the usefulness of the model, particularly in mountainous regions, where no significant differences were found between the data from the III NFI and the model, but they also showed the discrepancies between the estimates and real data when the latter are considered for different tree species, age or management.

Keywords: Geostatistics; GIS; land use planning; modelling; yields

Introduction

Today's forest managers face a number of important challenges. One of the most critical is the need to provide forest products for an increasing world population despite a shrinking natural-resource base challenged by climate change, desertification, environmental pollution, loss of biodiversity and other stresses. Forests have acquired a renewal and special significance due to their key role in environment conservation, recreation and sustainable production as one of the base of rural development. In current forest science research, the requirement to encompass this new paradigm involves an increasing need for precise estimates of forest structure and biomass, potential productivity or forest growth (Tickle et al., 2001), and modelling at different scales, from stand to landscape level. In this regard, a deep knowledge of forest productivity of the states is essential to develop forestry and land use plans and policies (Lansberg, 2003).

Different criteria and methods have been used to evaluate forest sites productivity (Vanclay, 1994). A traditional classification divides the variety of approaches into phytocentric, considering the phytomass production as the ultimate measure of site's productivity, or geocentric methods, asserting the dependence of site productivity upon soil and climatic variables. Among phytocentric approaches, the use of site index is broadly accepted as a surrogate of the potential productivity for pure even-aged stands (Wang et al., 2005). However, there are some cases in which the site index seems to be an inappropriate tool since it is linked to a specific species and forest structure (Monserud & Sterba, 1996; Bravo & Montero, 2003). Hence, it is impossible to obtain this index where there are no trees, where the species concerned is not present (Ung et al., 2001) or with some specific species, e.g. *Quercus* spp. (Adame et al., 2006) due to their traditional management techniques (coppice or pruning) or their slow growth rate. Furthermore, site index should not be used for young stands, since a slight error in estimation at this age could lead to a much larger error, as the curves tend to join at age zero (Goelz & Burk, 1992). Thus, alternative methods to phytocentric ones for site productivity assessment are important.

The prediction of site index from site attributes (geocentric) has been researched thoroughly, although it is difficult to test them against the true site productivity (Daniel et al., 1979). Main approaches have developed models based

in climatic, topographic, soil and biotic factors (Vanclay, 1994). The best known climatic index of forest growth is Paterson's CVP index (Paterson, 1956) which was designed to predict the maximum growth potential in terms of volume production (Hägglund, 1981; Johnston et al., 1967). Traditionally, this index has been used for large areas, even at global scales (Lemieux, 1961; Sánchez Palomares & Sánchez Serrano, 2000). Nevertheless, with the aid of new technologies and the existence of more and better data sets, this index can be applied at regional scales. In spite of its limitations, it can be very useful for comparing zones located within the same region, regardless of the presence or absence of trees, the age of the stand or the species (Vanclay, 1994).

Simulation modelling has been proven as a practical and effective approach for forest dynamics and yield research throughout the time and space. In fact, it is an economically efficient way -maybe the only one- to investigate the implications of different management strategies (Bravo & Díaz-Balteiro, 2004; Rodríguez Soalleiro et al., 2004), or the upscaling of productivity estimates from individual sites to larger areas (Bernier et al., 1999; Landsberg & Waring, 1997). Besides, some other "Digital Forestry" techniques as Geographic Information Systems (GIS) have become one of the most useful and widespread tools in forestry and information management (Shao & Reynolds, 2006).

The aim of this study is to review a model of potential productivity initially developed by Serrada (1976), and later revised by Sánchez Palomares and Sánchez Serrano (2000) for mainland Spain. This model is based on a modified bioclimatic index: the Paterson Index, weighted according to lithology. It has been widely used by forest managers in Spain with acceptable results at regional scales. In this study we propose new approaches for the required inputs, using Geographical Information Systems (GIS) and other statistical tools such as geostatistical techniques to improve base climatic models. In addition, results of this geocentric approach is tested for the first time using actual yield data, applying this methodology to a complex and mountainous region in the North of Spain, Asturias.

Material and Methods

The study area

The study area comprises the region of Asturias in North Spain, covering an area of 10,604 km². Its Northern boundary is the Cantabrian Sea (with a coastline of 354 km), and the Cantabrian Mountains form a natural border to the South (Figure 8.2.1). This region is characterised by steep topography, with altitudes ranging from sea level to 2,648 m in just 40 km. Thus, 80% of the territory has slopes greater than 20% and 34.5% exceeds 50%.

Data

The initial data were the mean monthly temperatures and rainfall obtained from the meteorological stations of the National Meteorology Institute located in Asturias and nearby provinces. According to the World Meteorological Organization, a 30-year period is required to establish the climatic baseline. Therefore, the 1970-2000 data set was used for the modelling, previously completing the missing data through regression analyses. A Digital Elevation Model (DEM) was taken as ancillary data, with an accuracy of 50 m.

Data obtained from the III National Forest Inventory of Spain (NFI) (Ministerio de Medio Ambiente, 2003) were compared to the model. The forestry database in Asturias comprises a total number of 1,877 plots that means one plot every 240 ha. For this study a total of 872 plots were selected, being those which were most significant in terms of forestry and productive species (Figure 8.2.1). These species were *Pinus sylvestris* L., *Pinus radiata* D. Don, *Pinus pinaster* Aiton., *Eucalyptus globulus* Labill., *Betula* spp., *Fagus sylvatica* L., *Castanea sativa* Mill., *Quercus robur* L. and *Quercus petraea* (Mattuschka) Liebl., and a minimum canopy closure of 15% of any of these species was required for the selection. Production data (Annual Increment of Volume of Wood per hectare, henceforth AIVW, defined as m³ ha⁻¹ yr⁻¹) and the UTM coordinates of every plot were obtained using the BASIFOR software (Del Río et al., 2002) developed by the University of Valladolid (Spain). Productive data for the different tree species and diameter classes (sorted out every 10 cm) were recorded in each plot.

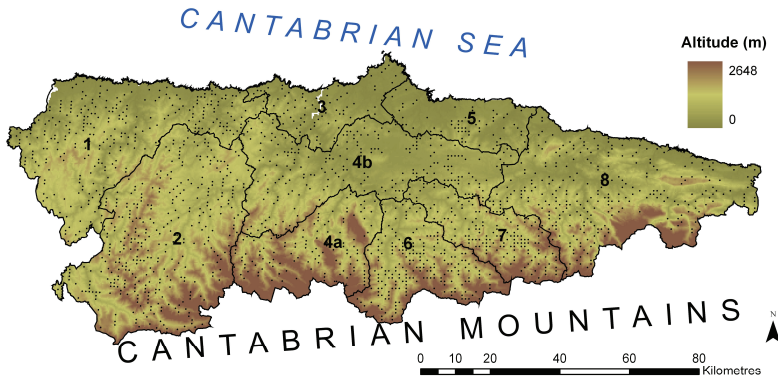


Figure 8.2.1. Location of the study area, with its regions and the locations of the selected plots from the III National Forest Inventory.

Climatic Productivity

The Paterson Index (PI) used in this work is a variant developed by Serrada (1976).

$$PI = \frac{V.P.G.f}{A.12} \quad (1)$$

Where V is the mean monthly temperature of the warmest month ($^{\circ}\text{C}$), A is the difference between the mean maximum temperature of the warmest month and the mean minimum temperature of the coldest month (both in $^{\circ}\text{C}$), P is the mean annual rainfall (in mm), G is the length (number of months) of the growing period according to the Gaussen criteria (Gaussen, 1954), that is the total number of months in which rainfall (mm) was more than double the mean temperature (in $^{\circ}\text{C}$), as long as this temperature was equal to or exceeded a minimum threshold of 6°C . Finally, f is the insolation factor proposed by Gandullo (1994):

$$f = \frac{2500}{(n + 1000)} \quad (2)$$

Where n is the number of sun hours in one year.

To assess these ecological variables, several techniques were used, all of them supported by ArcGis 9.0 (ESRI, Inc., Reedlands, 2004).

The insolation factor f decreases when the number of sun hours increases. It is considered that the growth of forest covers in the Iberian Peninsula, with

frequent summer droughts and with a high number of annual sun hours, is favoured by low insolation, which reduces evapotranspiration and increases height growth. The number of sun hours was estimated through an approach based on the model developed by Kumar et al. (1997). The original model consisted of a program that was capable of estimating the ground radiation, even in mountainous regions, because it took into account both slope and aspect, and was supported by formulas which incorporated latitude, day of the year, the time of the day and the azimuth. In any case, this model only considered radiance in cloudless conditions. In the variant used in this study, the hours per day when radiation measurements exceeded 120 W m^{-2} (minimum threshold detected by heliographs) were computed. Estimates were assessed every 20 minutes.

To obtain the parameters V , A , P and G , it was necessary to model the monthly rainfall and mean temperatures, and the mean maximum and minimum temperatures of the warmest and the coolest months, respectively. The modelling was carried out using geostatistical techniques, attempting to identify the approach which gave the least estimation errors. Full details of the techniques applied can be found in Benavides et al. (2007), in which 5 geostatistical methods were compared for estimating the mean January and August temperatures in Asturias. In the present study, the five geostatistical techniques were compared for the monthly rainfall and temperature estimates. The methods included ordinary kriging (OK), developed in the XY plane and in the X, Y and Z axis (OKxyz), with zonal anisotropy in the Z axis, along with three techniques that included elevation from the DEM as an explanatory variable: ordinary kriging with external drift (OKED) and universal kriging, using the Ordinary Least Squares residuals to estimate the variogram (UK1) or the Generalised Least Squares residuals (UK2). The accuracy of the resulting models was a pixel size of 0.25km^2 . Once the models were mapped, the mean error or bias (ME) and the mean absolute error (MAE) at the observed points were computed to determine the accuracy of the different approaches.

Potential *versus* real forest productivity

Apart from climate, soil is another important factor related to plant growth and as such, should be taken into account (Milner et al., 1996; Wang et al., 2005). Hence, a correction of the climatic productivity was carried out based on the

lithology map of Asturias on a 1:25,000 scale (Centro de Cartografía Ambiental y del Territorio de Asturias). The different types of *facies* were sorted into eight productive classes, according to the productive characteristics of the soils normally derived from them. Next, each productive class was given a correction coefficient (*C*) according to the values given in Table 8.2.1. (Sánchez Palomares & Sánchez Serrano, 2000). These coefficients resulted from a study of the yield tables of native species under similar management regimes, inferring that yield variations were attributable to differences in soils.

The relationship between the PI and the real productivity is assessed through Eq(3), an algorithm developed by Paterson and validated for mainland Spain by Serrada (1976). Hence, the map of potential forest productivity for Asturias was obtained through Eq(4), with the previously modelled inputs. The land was then classified into different productive classes (Table 8.2.1.) according to the resulting figures.

$$P = 5.3 \cdot \log IP - 7.4 \quad (3)$$

$$P = C \cdot 5.3 \cdot \log\left(\frac{VPGf}{A12}\right) - 7.4 \quad (4)$$

Once the potential productivity model was mapped, their values in every plot previously selected from the NFI were compared to the real figures. In the present study, Asturias was divided into 8 regions (Figure 8.2.1.). Each region is similar in terms of the environment, population, main economic sectors, the quality and quantity of infrastructure, equipment and communications. Region 4 was subdivided since the area was very large and had two very distinct regions: a mountainous part (4a) and an inner part (4b).

Correlations and univariate analyses of variances were carried out in each of the 9 regions, using the SPSS software (SPSS, Inc., Chicago, 2004). The analysis of variance made it possible to identify where the real data, with all the main species pooled together, and the potential productivity data were similar, and where it did not. Then, correlation analyses were carried out to identify the factors which contributed to the dissimilarities between both data sets, considering the type of species (low and fast growing species), the diameter classes and the stems per hectare.

Table 8.2.1. Description of the productive classes and sub-classes, with their lithologic correction coefficient (C) and productivity ranges ($\text{m}^3 \text{ha}^{-1} \text{year}^{-1}$) (Serrada, 1976).

Class	C	Subclass	Production	Description
I	1.66	Ia	>9.0	No limitation for productive forests growth
		Ib	8.25-9.0	
		Ic	7.5-8.25	
II	1.44	IIa	6.75-7.50	Slight limitations for productive forests growth
		IIb	6.0-6.75	
III	1.22	IIIa	5.25-6.0	Moderate limitations for productive forests growth
		IIIb	4.50-5.25	
IV	1	IVa	3.75-4.5	Moderately severe limitations for productive forests growth
		IVb	3.0-3.75	
V	0.77	Va	2.25-3.0	Severe limitations for productive forests growth
		Vb	1.5-2.25	
VI	0.55	VIa	1.0-1.5	Very severe limitations for productive forests growth
		VIb	0.5-1.0	
VII	0.33	VII	<0.5	Enough limitations to hinder the growth of any productive forest
VIII	0	VIII	0	Unproductive lands

Results

Modelling the ecological variables

The monthly rainfall, mean temperatures, and mean maximum and minimum temperatures of the extreme months were modelled using the five geostatistical techniques. The errors associated with the different methods can be seen in Table 8.2.2. The estimates were more precise when elevation data were taken into account. Hence, OKxyz was proven to be the best and selected to model the temperatures and UK2 for rainfall modelling. The mean rainfall of August was an exception because no correlation was found between the variable and the elevation, therefore, OK was run with the lowest error.

It should be noted that temperature errors were inferior to 1°C and were fairly unbiased since the mean errors were very close to zero. In general, the errors in summer predictions were smaller than those for winter. With regard to rainfall, the absolute residuals were lower in summer, coinciding with the drier season. However, errors in spring and autumn were proportionally inferior as the rainfall was more regular during these months. On average, the value of MAE was 10% of the predicted rainfall.

Once the kriging techniques had been selected and the monthly climate models developed, the parameters A , V , P and G (required for the Paterson Index)

were mapped (Figure 8.2.2). This figure also shows the insolation factor (Gandullo, 1994) assessed after calculating the number of annual sun hours. It can be noticed that the flat regions and South facing hillsides presented the lowest f value since they received the highest number of sun hours. Finally, by implementing Eq(1), we obtained the potential climatic productivity map (Figure 8.2.3.).

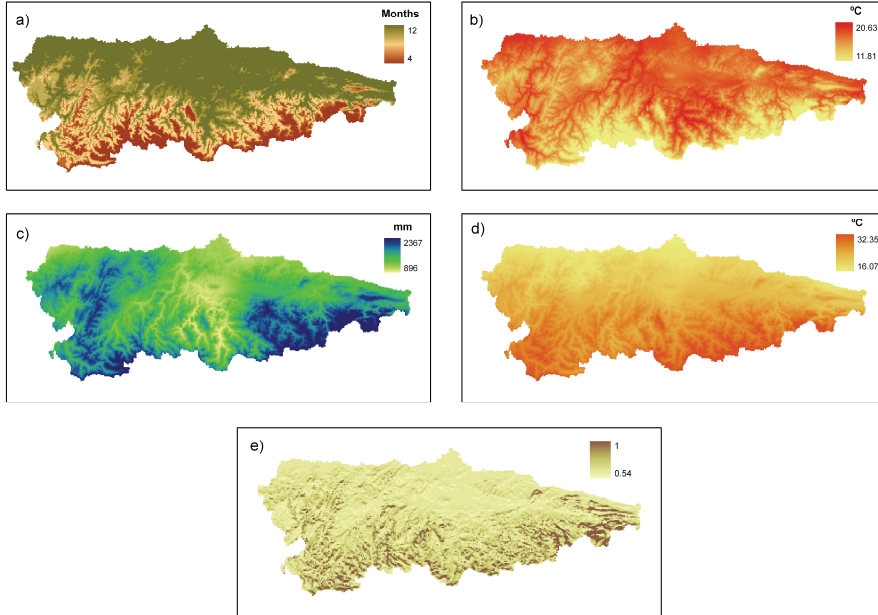


Figure 8.2.2. a) Number of vegetation active months; b) Mean temperature of August, in °C; c) Annual rainfall, in mm; d) Thermic fluctuation, in °C; e) Insolation coefficient.

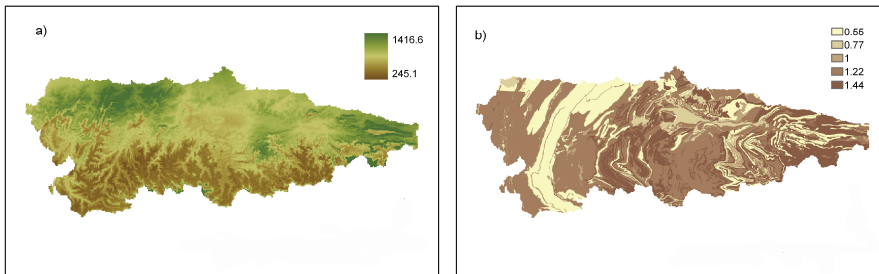


Figure 8.2.3. a) Map of the Paterson Index model; b) Map of the correction coefficients due to lithology.

Table 8.2.2. Mean Error (ME) and Mean Absolute Error (MAE) obtained estimating mean monthly temperatures (T) and rainfall (R), and the mean minimum temperature of January (MinJ) and mean maximum temperature of August (MaxAg), with different techniques: ordinary kriging (OK) in the XY plane, and with anisotropy in the Z axis (OKxyz), ordinary kriging with external drift (OKED) and two variants of universal kriging (UK1 and UK2).

	Jan	Febr	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	MinJ	MaxAg	
T (°C)	ME	0.05	0.03	0.05	0.04	0.02	0.06	0.03	0.03	0.04	0.05	0.05	0.10	0.03	
	OK	0.02	0.02	0.00	0.03	0.02	0.01	0.05	0.01	0.04	0.03	0.04	0.03	0.02	-0.01
	OKxyz	0.02	0.01	0.02	0.02	0.02	0.03	0.04	0.03	0.03	0.03	0.02	0.04	0.02	-
	OKED	0.02	0.01	0.02	0.02	0.02	0.03	0.04	0.03	0.04	0.03	0.02	0.03	0.02	-
	UK1	0.02	0.01	0.02	0.02	0.02	0.03	0.04	0.03	0.04	0.03	0.02	0.03	0.02	-
	UK2	0.02	0.01	0.03	0.03	0.02	0.09	0.05	0.03	0.03	0.03	0.03	0.03	0.03	-
MAE	OK	0.73	0.74	0.76	0.83	0.82	0.80	0.79	0.76	0.71	0.69	0.69	0.87	1.05	
	OKxyz	0.67	0.57	0.55	0.52	0.49	0.51	0.57	0.51	0.54	0.57	0.77	0.67	0.80	
	OKED	0.77	0.62	0.55	0.53	0.55	0.61	0.67	0.48	0.51	0.65	0.58	1.09	-	
	UK1	0.79	0.60	0.55	0.54	0.53	0.61	0.65	0.51	0.52	0.65	0.79	1.09	-	
	UK2	0.78	0.62	0.56	0.57	0.53	0.63	0.57	0.61	0.53	0.66	0.61	1.00	-	
	R (mm)	ME	0.13	0.10	0.17	0.19	0.08	0.09	0.25	0.18	0.37	-0.07	-0.18	-	-
OKxyz		-0.42	-0.28	-0.22	-0.13	-0.11	-0.06	0.13	0.21	-0.05	0.15	-0.10	-0.33	-	
OKED		-0.04	-0.12	-0.02	0.06	-0.05	-0.01	0.17	-	-0.06	0.17	-0.20	0.16	-	
UK1		-0.06	-0.14	-0.02	0.12	0.06	-0.02	0.16	-	-0.08	0.15	-0.25	-0.33	-	
UK2		0.02	0.04	-0.06	-0.03	-0.08	-0.02	-0.02	-	0.06	0.19	-0.24	-0.32	-	
MAE		13.42	13.44	13.73	14.59	11.89	7.33	6.84	7.73	9.03	11.85	15.32	18.29	-	
OKxyz	13.31	12.92	13.96	16.44	11.03	7.02	6.83	8.36	8.83	11.66	15.76	17.21	-		
OKED	12.76	12.62	13.48	14.12	10.65	6.76	6.56	-	9.21	10.59	14.67	17.81	-		
UK1	12.82	12.76	13.48	14.68	11.97	6.80	6.60	-	8.66	10.67	14.81	17.21	-		
UK2	12.80	12.71	13.12	13.89	10.47	6.67	6.22	-	8.59	10.67	14.81	16.89	-		

Potential Forest Productivity

The correction factor derived from the lithology was mapped (Figure 8.2.3.) according to Table 8.2.1. The final step was to represent the potential productivity estimates (Figure 8.2.4.) generated by using Eq(4) with the modelled inputs. The productivity figures ranged from 2.91 to 13.11 $\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$.

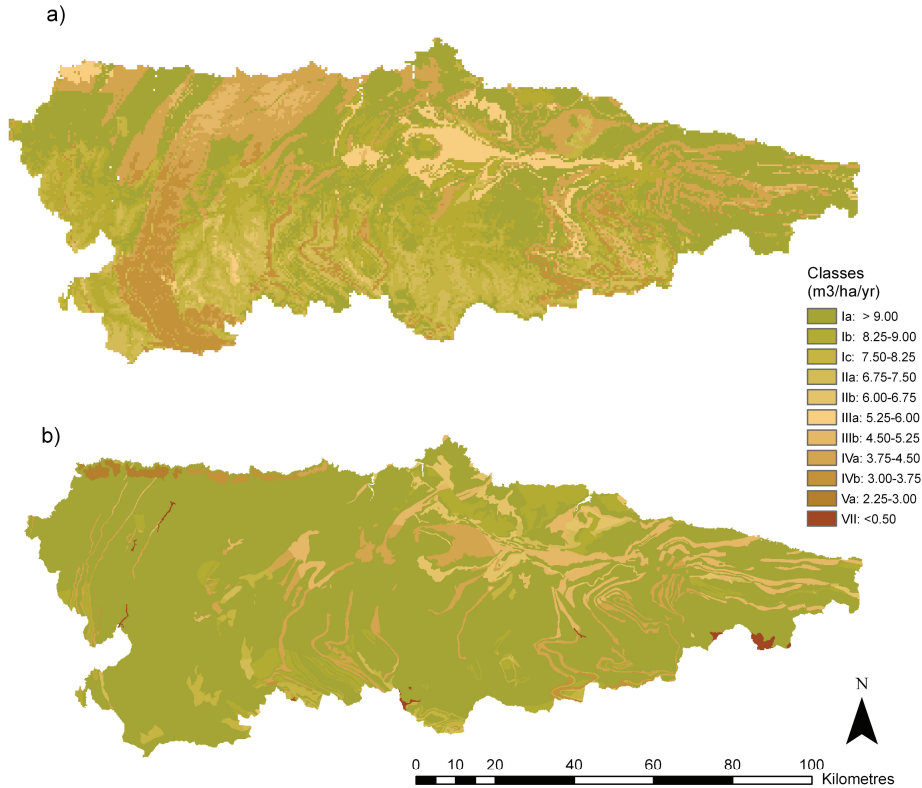


Figure 8.2.4. a) Potential Forest Productivity model, b) Potential Forest Productivity model assessed by Sánchez-Palomares and Sánchez Serrano (2000).

Data from the III National Forest Inventory

The Analysis of Variance analysis showed that the production data ($\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$) did not differ significantly ($p < 0.05$) when comparing the actual values with those of our model for regions 2, 4a, 6 and 8 (Table 8.2.3.). These four regions comprised all the mountainous regions with high altitudes and steep slopes. Region 7 was the only mountainous region missing from this list.

A detailed study of the remaining regions showed that the differences between paired data (real *vs.* potential productivity) may be the result of

management factors. It was found that the type of species, the age and the stocking rate were factors which significantly influenced the real production (Table 8.2.4.). The main factor affecting the AIVW was the stocking rate, with a positive correlation coefficient of $\rho=0.803^{**}$ when data of whole Asturias were pooled together. The type of tree species (fast *vs.* low growing) and the diameter classes showed also significant correlation with IAVW, but negative ($\rho=-0.602^{**}$ and $\rho=-0.537^{**}$, respectively). When regional data were considered separately, tree species were more homogeneous in terms of growth and the stocking rate acquired even more relevance.

Table 8.2.3. Effect of the origin of data (National Forestry Inventory *vs.* model) on the productivity ($\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$), in the different regions of Asturias.

Region	Mean		s.e.m.	Sig. (p-value)
	NFI	Model		
1	11.066	7.108	0.733	0.000
2	6.647	5.546	0.627	0.215
3	17.366	8.103	1.325	0.000
4a	5.856	6.452	0.646	0.516
4b	11.714	7.373	0.914	0.001
5	14.260	7.997	1.544	0.005
6	6.215	7.888	0.588	0.051
7	3.912	7.967	0.485	0.000
8	9.213	7.739	0.753	0.168

s.e.m.: standard error of the mean

It was found that regions 1, 3 and 4.b (less mountainous and closer to the coast) have a real productivity higher than potential one, with negative values resulting from the subtraction between real and potential averages (Table 8.2.5.). Higher AIVW was correlated with the existence of high yielding trees (mainly eucalyptus), with high stocking rates and low diameter classes.

As regards region 7, the real values also differed significantly from the potential values (Table 8.2.3.) although in this case the former were lower (Table 8.2.5.). This appears to be due to the complex orography of the region and the influence this has on the species found in the plots (only slow growing species)

When real yield figures are considered separately for different species and at different ages, the analysis of variance showed no similarities with the values of the model. That is because we can not extract from the model information for different age classes or tree species as it shows potential productivity yields.

Table 8.2.4. Correlation coefficients between the AIVW and main management factors: type of species (S, fast or low growing), stocking rates (N), and diameter classes (DC).

	Region	S	N	DC
AIVW (m ³ ha ⁻¹ yr ⁻¹)	1	-0.217**	0.745**	-0.136**
	2	-0.256**	0.834**	-0.200**
	3	-0.195**	0.764**	-0.191**
	4a	-0.156**	0.861**	-0.632**
	4b	-0.546**	0.803**	-0.520**
	5	-0.270**	0.755**	-0.201**
	6	-0.125**	0.856**	-0.124**
	7	-	0.883**	-0.187**
	8	-0.202**	0.835**	-0.221**
	total area	-0.602**	0.803**	-0.537**

Table 8.2.5. Descriptive statistics of the variables SUBTRACTION (between the potential productivity, PP, and the AIVW) and the RATIO (division between the AIVW and PP).

Region	Subtraction		Ratio	
	Mean	SD	Mean	SD
1	-1.63	7.08	1.43	1.22
2	0.89	4.54	0.88	0.91
3	-4.37	8.79	1.69	1.29
4a	1.72	5.81	0.78	0.71
4b	0.54	6.77	0.98	0.93
5	-2.24	7.88	1.32	1.03
6	1.87	5.95	0.78	0.76
7	3.88	3.18	0.53	0.41
8	1.87	5.65	0.82	0.81

SD: Standard deviation

Discussion

Productivity modelling

Most climatic models previously developed have used a pixel size of at least 1 km² (Goodale et al., 1998; Hudson & Wackernagel, 1994). However, as elevation and temperature can vary dramatically in mountainous regions a smaller grid, 0.25 km² pixel size, was chosen in this study.

The errors made with the geostatistics techniques were acceptable, especially considering the complex topography. It is remarkable that errors made in summer temperature predictions were smaller than those made in winter. This is due to the higher variability of the cold season data and agrees with a similar trend found by Rolland (2002) in Alpine regions, and by Benavides et al. (2007) in

Asturias. A visual appreciation of the variables related with air temperature figures (Figure 8.2.2.) reveals the well-known correlation between the temperature estimates and the altitude (Stoutjesdijk & Barkman, 1992). The estimates became progressive cooler when moving inland from the coast towards the mountains in the South, and the growing season was found to be longer and the thermic ranges smaller in coastal areas than in the Cantabrian Mountain range. However, the warmest regions in summer corresponded to the inner basin of the main rivers due to the “buffering effect” of the sea (Benavides et al., 2007).

The fact that rainfall is greatest in mountainous areas suggests that elevation again plays an important role. Other authors have already detected and quantified this phenomenon (Havesi et al., 1992; Goovaerts, 2000). It can also be observed that the Western part of the area registered higher values than the Eastern part. This is due to the predominance of weather fronts from the NW (Marquínez et al., 2003).

Bearing all this in mind, the figures for the climatic productivity index ranged from 245 to 1417, exceeding the value of 25 which is considered the threshold value for natural regeneration of a forest (Gandullo, 1994). The model developed indicated higher potential productivity in low, flat areas, closer to the sea, because these registered warmer temperatures, a smaller thermic range, and a longer growing season. There were also some differences between the East and West which may be due to the weather fronts predominantly entering.

The influence of lithology on the productivity map can be clearly seen. The climatic productivity appeared as a continuous variable, similar to the behaviour of the climatic and topographic variables (adjacent points registered similar values for the variables). However, the lithology presented abrupt transitions at our scale. A strip of land can be identified in the Western half of the region, crossing Asturias from North to South, where correction factor values were low. This was due to the characteristics of the lithology: quartzites that give rise to acid soils with many outcrop rocks.

Comparing these results with those of the previous model represented in Figure 8.2.4.b. and developed by Sánchez Palomares and Sánchez Serrano (2000), a more detailed performance of the newer model can be appreciated. On one hand, a more accurate scale of the lithology map has been used (from 1:50,000 to 1:25,000). On the other hand, the use of geostatistical interpolations and the

advantages offered by the GIS allow us to obtain more precise information on the ecological variables throughout the region, especially in mountainous regions where modelling is always difficult and challenging (Carrega, 1995). Hence, an altitudinal gradient can be distinguished in the present model, but not in the earlier study. In the old model, 77.4% of the Asturian surface was considered a region with maximum climatic productivity ($I_a > 9 \text{ m}^3\text{ha}^{-1}\text{yr}^{-1}$) compared to 27.3% in our case, and the lithology was the only clearly stated factor that resulted in lower productivity. However, this picture does not appear to reflect the real situation as it does not take into account the fall in temperature associated with altitude, an important variable affecting vegetation growth (Landsberg & Waring, 1997; Ni, 2004).

Usefulness for land use planning

This approach has been widely used for decades and its practical implementation has proved its worth for silvicultural planning. Its incorporation into the forest managers' decision making process is an important milestone which many productivity models do not attain (Battaglia & Sands, 1998). In spite of the usefulness of the model, its validation can be somewhat complex due to the lack of adequate data for directly testing the potential productivity estimates. It is difficult to separate the site, stocking, age, structure and species effects when analysing plot growth data, especially with mixed or uneven-aged stands (Milner et al., 1996). In a mountainous region the ecological variables may also differ significantly from the estimates because the samples are usually scarcer. The climatic variables in Asturias were tested with an acceptable level of errors by Benavides et al. (2007), particularly bearing in mind that the greatest errors were detected at the highest altitudes, above the altitudinal limit of the forest. The lithology was simply proposed as an approximate description of soil characteristic but the lack of correlation between the real productivity and the lithological coefficient (data not shown) suggests that other factors contribute greatly to the development of the soil, especially in mountainous regions. These factors include slope, altitude (Odeh et al., 1994), rainfall and historic and current land management practices, e.g. the existence or absence of vegetation cover, soil preparation or fertilisation particularly for fast growing species plantations, or the use of fire as a management tool (Fernández et al., 2005).

A significant correlation between both databases (real and potential) can be observed, thus partially validating our model. However, the value of the coefficient is small ($\rho=0.203^{**}$), highlighting the aforementioned difficulties involved in assessing potential productivity and the differences between both data sets. The statistical analysis showed that our model was capable of generating values similar to the real values in mountainous regions, when all the species and ages are pooled. This is especially relevant given the difficulty in modelling areas with complex topography. Conversely, in flat areas close to the sea, the real figures exceeded the potential ones due to the management practices and the existence of eucalyptus (*Eucalyptus globulus* Labill.) stands, which are exotic high yielding forest species, managed at high densities using short rotations.

Moreover, the evaluation of the coefficients of the potential productivity formula (Eq 3 and 4) may be biased when it is used in small areas, because Paterson (1956) included in the statistical analysis data from large areas with a great diversity of annual growth rates, and Serrada (1976) validated Paterson's approach using data from plots located all over the Iberian Peninsula, including the Mediterranean area, which in general terms has a lower productivity rates than Asturias (less favourable climatic conditions) but covers a larger surface area. In addition, the advances made in terms of Genetics (new clones with better yield rates) and the new technical knowledge (silvicultural performances) might also affect the results which were not contemplated when the original model was developed.

To sum up, it should be stated that this model has a number of limitations which should be borne in mind. The spatial interpolations are smoothing techniques, and therefore, introduce errors which can be propagated to the model output. Moreover, the accuracy of the prediction may improve using an accurate model for soil. However, where precise edaphic information is not available, it would be more costly to obtain this data *in situ* rather than using the lithology map.

Further research is required in order to refine and improve the assessment of potential productivity and its implementation as a management tool. In the meantime, the present model can be used, bearing in mind its limitations, to define the areas at regional scale where productivity is potentially the highest, regardless of the existing management practices (density, ages, silvicultural

actions) or tree species. It also allows us to evaluate the current state of the forest stands, defining areas, species and management methods which produce yields above or below the potential productivity figures. This possibility is very useful both for land use planning and for aiding forest managers to make appropriate decisions.

9. General Discussion

Advances in computer technology, particularly in relation to Geographic Information Systems (GIS) and statistics, are currently incorporated in land use planning and land management. In this study, geostatistics techniques were used to model the climatic variables which in turn were used to assess the site productivity for forested areas. The index used considers vegetation productivity as a reflection of the specific climate in the surrounding an area, in our case, weighted according to lithology. This index was previously used to predict potential productivity in mainland Spain, although greater detail can be appreciated in the newer model. The use of geostatistical interpolations along with advantages offered by the GIS allow us to obtain more precise information regarding the climatic variables across the region, especially in mountainous regions where modelling is always challenging (Carrega, 1995; Li et al., 2005). Hence, an altitudinal gradient can be distinguished in the present model since it takes into account the altitudinal variation in temperature and rainfall, both of which are important variables affecting vegetation growth (Landsberg & Waring, 1997; Ni, 2004).

It should also be stated that this model has a number of limitations which should be borne in mind. The spatial interpolations are smoothing techniques, and therefore, introduce errors which can be propagated into the model output. Moreover, the accuracy of the prediction is influenced by the resolution and the quality of the input data, which can often be deficient. For instance, meteorological stations are often spread sparsely, especially at higher altitudes or in uninhabited areas. However, by sorting the land into productive classes instead of considering precise values, the results are simplified and this effect is lessened. We believe that accurate models for soil characteristics and its thickness may also improve model estimations, amending the small correlation between real productivity and the considered lithological coefficients. It is widely known that other factors, apart from lithology, contribute greatly to the development of the soil, especially in mountainous regions. These factors include slope, altitude (Odeh et al., 1994), rainfall, temperature and historic and current land management practices, e.g. the existence or absence of vegetation cover, soil

preparation or fertilisation, particularly for plantations of fast growing species plantations, or the use of fire as a management tool (Fernández et al., 2005). However, where precise edaphic information is not available, it would be more costly to obtain this data *in situ* rather than using the lithology map.

Hence, bearing in mind its limitations, the present model can be used for two main purposes. Firstly, to evaluate the current state of the forests stands, defining areas, species and management methods which produce yields above or below the potential productivity; and secondly, to delimit the productive areas at regional scale, regardless of the existing management practices (density, ages, silvicultural actions) or tree species, in order to define land uses or territory management strategies.

Analysing the estimates of the model, we can see that 59.1% of the Asturian area and 55.8% of Western county are included in the Class I (no limitations for forest growth). Within this class, the highest production estimates (Ia) comprehend 27.3% of the area of Asturias. These figures are primarily associated with coastal areas, where the elevations are low and the climate is milder. We suggest that these zones should be devoted to forestry, together with some other productive agricultural activities. Forest managers must choose the best species and management practices based on specific information recorded in the field and according to the main objective of the plantation (sawlog timber, pulp, etc). It is also crucial to consider environmental conservation in the decision making process.

Eucalyptus globulus and *Pinus radiata* are currently the preferred species for plantations in Northwestern Spain due to their rapid growth and high productivity, thus generating relatively short term returns. They are managed at high stocking rates with short rotation periods. Much controversy has surrounded the introduction of eucalyptus stands since these trees appear to restrict the growth of the understorey (and consequently affect the biodiversity) more than other species as a result of certain terpenic compounds with anti-germination characteristics. In addition, other adverse effects associated with these trees are, on the one hand, that they can be responsible for drying out the soils and aquifers, and on the other that they seem to favour the acidification of soils (Carrasco-Letelier et al., 2004; Jobbágy & Jackson, 2004). The clear cutting/coppice management techniques applied also contribute to nutrient

extraction and the erosion of hillsides. (Fernández et al., 2004). The scientific literature, e.g. the research carried out in New Zealand, also contains references to the acidification of soils under pine stands (Davis & Lang, 1991; Parfitt et al., 1997; Alfredsson et al., 1998; Cossens & Hawke, 2000; Chang et al., 2002), stands where clear-cutting also tends to be used as part of their management. Hence, the advantages of pine over eucalyptus are not at all clear (Rodríguez, 1985). In any case, these intensive systems must be controlled, perhaps by making use of other native broadleaf trees or by employing alternative, less aggressive harvesting procedures such as the shelterwood system or thinning. In this way, the high quality of these regions is maintained, thus achieving greater sustainability and conserving the biodiversity.

In such productive areas, silvopastoral management can be considered complementary in stands that would otherwise be devoted exclusively to forestry. On the one hand, forest grazing in the early stages of the plantations can promote seedling growth by reducing competition with the pasture for water and nutrient. At this stage, tree protection methods should be considered to avoid browsing damage: single tube shelters, single fence or electrified strand around grouped trees/rows, foliar application of repellents such as denatonium benzoate, etc. (Sharrow, 2001; Lehmkueler et al., 2003; Leroy & Caraglio, 2003). The choice of method will depend on the species of tree, the species of animal (and its grazing behaviour), the financial cost, and the structure and size of the stand. However, in this type of stand with high stocking rates, the application of these techniques would hardly be economically viable. On the other hand, the use of tree species with longer rotations, aimed at the production of good quality timber for sawlogs (straight and knot-free stems) requires earlier thinning and pruning. These operations result in higher light transmission to the understorey, thus increasing pasture growth. Livestock can then be brought in to utilise the pasture, providing earlier financial returns. Fertilisation can also be applied to increase pasture production under these stands, as shown by the forest grazing trials conducted in Galicia, Northwestern Spain (Mosquera-Losada et al., 2006; López-Díaz et al., 2007; Rigueiro-Rodríguez et al., 2007).

Agriculture is an alternative land use which must also be considered in these highly productive areas. Due to the orography of Asturias, land use over the centuries has tended towards livestock breeding rather than agriculture. The

former accounts for 85.7% of the production (at base prices) within this economic sector. However, these fertile areas at lower altitude close to the coast can be also used as cultivated farmland. Due to the great importance given to stockbreeding in this region and the key role of livestock in landscape management and sustainable systems, we emphasized the need for forage crop cultivation to guarantee food for animals during seasons with pasture shortages.

In the studied county, only 9.6% of the land belongs to the most productive class (Ia), whilst the proportions of less productive land increase in comparison to Asturias as a whole, with 46.2% belonging to classes Ib and Ic. For these productive classes, together with those with slight or moderate limitations for forest production (classes II and III), silvopastoral systems might be the best option to efficiently exploit the resources. Forest grazing can also be introduced in the more productive areas, but in this case, as the limitations to forest growth appear, the livestock should acquire more importance in the system, limiting the tree stocking rates and canopies in order to guarantee good yields of pasture. The loss in quantity of wood production may be offset by the gains in pasture production (and consequent animal production) and in timber quality, e.g. silvopastoral systems such as those described by Dupraz and Newman (1997) using native broadleaf tree species which produce high quality timber such as oak, ash, walnut, chestnut, wild cherry or sycamore. In these systems, tree protection is an important issue due to the value of these trees and their reduced number.

These systems may present different structures: a mosaic landscape with trees in groups, wide-spaced trees on pasture or borderline tree distributions (Mosquera-Losada et al., 2005). Management of the tree canopy has an important influence on pasture productivity. Trees of an appropriate species/clone (with suitable architecture and tolerance to specific site limitations), at low stocking rate and pruned or pollarded regularly, will likely increase pasture production and enhance sward botanical composition. The trials conducted in New Zealand revealed negligible effects at the very beginning of tree planting and a more rapid reduction in pasture production under evergreen trees. These results agree with those obtained in Galicia (Northwestern Spain), close to our study site. Rozados-Lorenzo et al. (2007) asserted that after the first 7 years of tree establishments the effect on pasture production was imperceptible beneath deciduous trees

(*Betula alba* L., *Quercus rubra* L. and *Castanea sativa* Mill.) at different stocking rates. However, under conifers such as *Pinus radiata* and *Pseudotsuga mensiesii* (Mirb.), tree effects became noticeable sooner, especially with stocking rates over 500 stems ha⁻¹ (Rozados-Lorenzo et al., 2007).

For sites with severe limitations for forest production, stockbreeding would be the preferred land use. In Asturias, these areas are mainly determined by the topography and soil characteristics, while the climate is not usually a determining factor, apart from on the highest peaks above the altitudinal limit of the forest. These areas with severe limitations to forestry systems comprised 25% of the Asturian surface and 29.6% of our study site (Western county). In this case these areas are associated with lithologies that originate very poor, rocky, shallow and acid soils such as quartzite. Such areas are often covered by heathlands. A strip of land that can be identified in the Western half of the region, crossing Asturias from North to South (with low values of the correction factor), which coincides with a large area of heathlands dominated by *Erica australis* subsp. *aragonensis* (Alvarez et al., 2004) where precisely the assessed fire risk is highest (Marquínez et al., 2003).

The trials conducted for pastoral management analysis as part of this study, support the necessity to establish improved areas in heathlands, given the low nutritive values estimates also identified in previous studies (Hodgson & Eadie, 1986; Celaya et al., 2007b), in order to meet the requirements of livestock throughout the grazing season (Maxwell et al., 1986; Osoro et al., 1999). Moreover, in valleys or anywhere with greater soil thickness and nutrient levels, trees can be planted in order to provide shade and shelter for animals as well as for conservation purposes such as bioremediation for controlling soil acidification (Wall, 2006), or establishing a plantation of fast-growing species on erodible sites or in swampy soils (Wilkinson, 1999). When necessary, these trees can also be used as fodder.

The animals display different grazing behaviour resulting in different use of the resources. Cattle showed a clear preference (in terms of grazing time and diet selection) for herbaceous vegetation. This observation coincides with the previous literature on the grazing behaviour of cattle (Aldezabal, 2001; Celaya et al., 2007b). Therefore, cattle are not the most suitable livestock for use in heathland management, because they are unable to maintain their required

intake consuming only the components of the natural vegetation. This is due to their poor ability to select these components and limited intake rate, in contrast with horses (Ferreira et al., 2008), when the sward height of the improved pasture and grass species decreases.

Small ruminants, especially goats, are able to use woody species when the availability of the improved pasture decreases (Lu, 1988; Narjisse, 1991; Allan & Holst, 1996). In these experiments, a significant proportion of woody species in the goats' diet was recorded. Additionally, the amount of time they spent grazing in shrublands was greater than for the other two species. This agrees with the results from previous studies in which the browsing capacity of goats has been demonstrated (Clark et al., 1982; Radcliffe, 1986; Celaya et al., 2007b). Moreover, as also observed by Osoro et al. (2000a), this behaviour becomes more marked when goats are grazing in mixed flocks with other species. On the other hand, sheep hardly change their behaviour when other animal species are present (Osoro et al., 2000a). Sheep, like cattle, also prefer herbaceous plants. However, they are able to maintain their live weight at lower sward height (Forbes & Beattie, 1987; Hodgson et al., 1991; Osoro et al., 2000c), and are able to consume a large amount of heather when grass is scarce (from August onwards). These abilities mean that sheep achieve the best results in these communities if the entire grazing season is considered.

The lower dietary overlap between goats and cattle or sheep as opposed to between cattle and sheep, has also been observed in other studies under very different conditions (i.e. Lechner-Doll et al., 1995; Aldezabal, 2001). This suggests that the establishment of mixed management may result in a more efficient use of these heterogeneous plant resources (Wright & Connolly, 1995). In our experiment, when single and mixed grazing treatments were compared, the latter slowed more the shrub encroachment to a greater degree, particularly in the case of gorse. This in turn permitted more growth of herbaceous plants in these treatments compared to single grazing. This was due to the greater browsing ability of goats as stated above.

Finally, the last classes, with site production under $1 \text{ m}^3 \text{ ha}^{-1}$, should be managed only for conservation purposes and non-productive objectives. In our model, no surface was included in these classes, although this may be due to the lack of edaphic data, such as soil thickness or rocky places that limit tree growth.

All the results obtained from this dissertation suggest that the diversification of outputs in farmland is the best option to develop efficient and sustainable systems and conserve the biodiversity in heterogeneous resources such as the heathlands of Northern Spain. Hence, the management of these areas must be affronted using a multidisciplinary approach, armed with the necessary understanding of the topics involved. Theoretical modelling of spatial variables, supported by improvement in statistics, GIS or remote sensing, allow us elaborate an initial approach to evaluate the potential site and to address the land use planning. Where these figures are higher, forestry production should be favoured, although it can be complemented by the introduction of livestock to utilise the pasture growing beneath the trees (Hawke & Knowles, 1997). The lower the potential production, the greater the importance of livestock and therefore, mixed systems are proposed.

Through the literature review, a lot of information was gathered in relation to other experiments which should be used for reference in future studies. However, the knowledge acquired in the field is undoubtedly necessary to establish specific guidelines for land use. The first results obtained from this study show that small ruminants are more suitable for heathlands. In particular, in partially improved heathlands, were found to perform best (more productive), and they could be complemented by goats to achieve a more efficient use of the resource. In natural heathlands, without improved areas, goats and horses would bring better results than sheep and cattle (Osoro et al., 2008). Thus, mixed grazing with goats could have beneficial effects on the future management of these marginal areas, with improving the nutritive quality of the available vegetation for other livestock species, and reducing the fire risk through a lower accumulation of combustible woody phytomass.

Future trials should focus on the establishment of silvopastoral systems in these marginal areas, by planting trees where this is possible, considering different tree species, purposes (timber, shade, erosion control, fertility improvement, fodder), management (stocking rates, silvicultural actions) or structures (wide-spaced, alley-cropping, in groups or in shelterbelt), together with different animal performances (type of flock, stocking rate, grazing management). At the same time, obstacles should be identified and any financial changes or variations in the vegetation dynamics should be monitored.

10. Conclusions

1. The study county is an example of a less-favoured, rural area in abandonment. Young people migrate to the cities in order to increase their scope of opportunities. The remaining people are ageing and less educated, and consequently there are less entrepreneurial initiatives. The likelihood of modernizing farms by introducing new knowledge and technology also decreases with the loss of the younger generations.

2. The studied region has a livestock farming tradition that has involved the deforestation of many areas over the centuries. Today, with the abandonment of the agrarian activities, shrub encroachment is increasing (especially heathlands), and in turn the risk of fire and erosion is rising. New plans and policies should be considered in order to create better conditions for their inhabitants, and to reorganize farms into sustainable systems.

3. Silvopastoral systems are suggested as a land use management solution for these marginal areas. The choice of the tree species along with adequate knowledge regarding their establishment and management is crucial. This will depend on the particular characteristics of the site, and on the targeted farm outputs. Therefore, *Pinus radiata* plantations are primarily used for large scale erosion control and/or timber production. However, *Populus* and *Salix* are more appropriate when livestock enterprises are the primary aim and other tree functionalities are required (minimising the suppression of pasture growth, soil protection and stabilisation, shade/shelter, and supplementary fodder).

4. Management of the tree canopy has an important influence on pasture productivity, and consequently on the performance of the system. Trees of an appropriate species/clone (with suitable architecture and tolerance to specific site limitations), at low stocking rate and pruned or pollarded regularly, will likely increase pasture production and enhance sward botanical composition.

5. Within the first five years after establishing the trees, there are negligible effects on pasture, regardless of the tree species.

6. During the first part of the rotation, the effects of trees on pasture dynamics are usually slight at low stocking rates. In any case, the effects of deciduous trees on pasture yields seem inferior to those caused by evergreen species, with reductions of pasture around 10-20% for young *Populus*-pasture system, and 20-40% for young *Pinus radiata*-pasture systems, at 100 sph in both cases. This is due to the partial recovery which takes place during the leafless period with deciduous trees, and higher pasture smothering by needles of evergreen species.

7. As tree density increases and/or in the second part of the rotation, the reduction in pasture yield caused by tree shade increases dramatically, especially with *P. radiata*. Reductions for trees of this species aged 18-20 years were estimated around 75% at 100 sph, 83% at 200 sph and 100% at 400 sph.

8. A decline in pasture quality occurs with increasing levels of shade. There is a general decrease in the proportion of legumes (e.g. *Trifolium* spp.) and grasses (e.g. *Lolium* spp.), and an increase in the proportion of dead matter and other grasses proportions with lower nutritive value such as *H. lanatus*.

9. For the development of sustainable systems, the recommendation of establishing adjacent areas of improved pasture to meet the nutritional requirements of livestock is supported.

10. Distinct foraging behaviour was recorded among cattle, sheep and goats. Cattle and sheep preferentially grazed on the improved area, selecting herbaceous species (grazers), while goats utilised woody species to a higher degree (browser).

11. The presence of goats may lead to a higher control of gorse encroachment (lower accumulations of combustible woody phytomass), permitting in turn a higher presence of herbaceous plants in the canopy.

12. Sheep performed best if the entire grazing season is considered (from May to December), despite the good level of production in spring from autumn-calving cows. They were able to maintain their live weight throughout the grazing season, in spite of the reduction in pasture availability.

13. Regarding the complementary grazing behaviour between goats and cattle or sheep, mixed flocks can be a good option to achieve a more efficient resource use. In particular, mixed flocks of sheep and goats would be the most efficient along with production management.

14. In spite of the scarce, scattered and irregular distribution of sampled data, the models derived from geostatistical techniques with elevation as an auxiliary variable were quite accurate when modelling air temperature in mountainous regions. Especially, the ordinary kriging with zonal anisotropy in the Z direction.

15. The modelling of ecological variables with geostatistical techniques can be very useful for the development of other more complex models. In this study, the use of interpolations and the advantages offered by the GIS, allow us to improve an existing approach for site productivity, traditionally used by forest managers in decision making process.

16. This model is useful for defining the most potentially-productive zones within a specific area, regardless of the present management practices (stocking rates, species, silvicultural actions...). Thus, this model provides an analytical tool for studying the spatial variation of climatic and lithological variables, and their effect on forest production at a regional scale, above all in mountainous regions where modelling and predictions are always more complex. It can also be useful to evaluate the current state of stands.

17. Finally, it can be concluded that to achieve sustainable systems in heterogeneous landscapes such as these, aggravated by an awkward socioeconomic scene, a multidisciplinary approach must be followed involving the use of management practices which draw upon a solid understanding of all the issues.

11. References

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