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Artigo

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Application of Mexican Management Method for Uneven-aged Forests (MMOBI) to natural mixed stands in Asturias (northern Spain)

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Abstract The Mexican Management Method for Uneven-aged Forests or MMOBI (from the Spanish *Método Mexicano de Ordenación de Bosques Irregulares*) is the continuous cover forestry management system usually used in the state of Durango (Mexico). The silviculture system applied in the MMOBI is based on selective logging aimed at yielding a reverse “J-shaped” distribution.

The objective of the present study was to analyze the application of the MMOBI to natural mixed stands in Asturias (northern Spain). These stands are represented in strata numbers 4 and 9, defined in the third Spanish National Forest Survey, composed mainly of deciduous hardwoods.

The observed diameter distributions and the ideal diameter distributions obtained by the MMOBI for each genus were estimated. The percentage of felling intensity (*IC%*) was generally low in stratum 4, and was less than 20% for most genera except *Fraxinus* and *Acer,* for which *IC* > 50%. In stratum 9, *IC%* was generally higher than in stratum 4, although also low to intermediate, except for the genus *Tilia* (*IC* > 50%), whose trees are part of what commonly called Green Tree Retention.

The MMOBI is presented as an alternative forest management method in protective stands in this region.

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Key words forest management, natural mixed stands, deciduous hardwoods, De Liocourt, Green Tree Retention.

Resumen El Método Mexicano de Ordenación de Bosques Irregulares (MMOBI) es el sistema de gestión forestal de cubierta forestal continua empleado habitualmente en el estado de Durango (México). La selvicultura que se aplica en el MMOBI consiste en cortas de selección individual (o entresaca árbol a árbol), buscando una distribución diamétrica en forma de J invertida.

En este trabajo se analiza la aplicación del MMOBI en las masas naturales mixtas de Asturias (norte de España) representadas en los estratos números 4 y 9 del Tercer Inventario Forestal Nacional, formados mayoritariamente por frondosas caducifolias.

Se ha calculado para cada género la distribución diamétrica real y se ha estimado la ideal según el MMOBI. El porcentaje de intensidad de corta (*IC%*) fue generalmente bajo en el estrato 4, siendo inferior al 20% en la mayoría de los géneros excepto en *Fraxinus* y *Acer* con *IC* >50%. En el estrato 9 la *IC%* fue generalmente más alta que en el estrato 4, aunque también fue de baja a intermedia, excepto para el género Tilia con *IC* >50%, cuyos árboles se suelen incluir en el *Green Tree Retention*.

El MMOBI se presenta como una alternativa de gestión para masas con un carácter preferente protector.

Palabras clave gestión forestal, masas naturales, frondosas autóctonas, De Liocourt, Green Tree Retention.

Introduction

Uneven-aged silviculture systems promote forest management in stands in which multiple age classes or tree dimensions are included by using the continuous cover forestry (CCF) system. These methods, which are also known as close-to-nature forest management, are based on the principle of permanent maintenance of forest cover (Gadow, 2001). Reviews of the history, definitions, concepts, methods and application of the CCF are provided by Gadow et al. (2002) and Pommerening & Murphy (2004). Interest in this type of silviculture is growing in many parts of the world and it is presented as a viable alternative to the more usual even-aged system of management known as rotation forest management (RFM). The latter systems are characterized by the application of repetitive cycles of silvicultural treatments (planting or natural regeneration, clear felling and other treatments aimed at improving stands) with a defined rotation age (Gadow, 2001). Many areas that are currently managed by RFM systems in Europe and other parts in the world are being transformed to CCF systems (see e.g. Mason & Kerr, 2004).

Continuous cover forestry provides benefits such as more attractive stands, benefits for wild life, resistance to climate change, improved recreational activities, higher biodiversity of habits, lower cost (because the regeneration is natural), less risk of erosion with high precipitation and elimination of environmental impacts produced by timber harvesting in large areas (Gadow & Pukkala, 2012). Study of these forest systems in different areas of the world is of interest as the trees may be grouped in multiple age classes, dimensions classes or cohorts, included in pure or mixed stands (in this case referred as structures of complex stands) in boreal, temperate and tropical forests.

The Mexican Management Method for Uneven-aged Forests or MMOBI (from the Spanish *Método Mexicano de Ordenación de Bosques Irregulares*) is the CCF system applied to forest stands in temperate-cold climate regions in Mexico, mainly in the forests of the *Sierra Madre Occidental* in the state of Durango (SEMARNAT, 2008). These natural mixed pine-oak forests, which are often mixed with *Pseudotsuga*, *Arbutus* and *Juniperus*, represent a unique ecosystem with one of the highest species diversities in the world and are home to about 50% of all the known species of *Pinus* and *Quercus* (Shütz et al., 2012). The pine-oak forests cover 16% of the national territory in Mexico and occur throughout the major mountain ranges of the *Sierra Madre Occidental*, the *Sierra Madre Oriental*, the *Sierra Madre del Sur* and the *Transvolcanic Belt* (Rzedowski, 1978).

The MMOBI was formally developed in 1944 and first applied in the management plan of Atenquique forest in Jalisco (Rodríguez, 1958). The theoretical basis of the MMOBI system has been described in previous studies (e.g. Torres-Rojo, 2000). The silviculture applied in the MMOBI is based on selective logging aimed at yielding a reverse "J-shaped" (or negative exponential) diameter distribution, in which the harvest volume is estimated according the temporal growth of the forest stand so that cutting is distributed across all diameter classes (Rodríguez et al., 1960).

The objective of the MMOBI is to establish a balanced residual structure, in which tree competition is standardized by resources, development of the stand and natural regeneration are enhanced and the uneven-aged condition is maintained (Arellano, 2010). The management system considers the same harvesting areas as years of the cutting cycle (Prieto & Hernández, 2007). Specific applications of the MMOBI depend on local conditions (for more details, see Hernández-Díaz et al., 2008). The method is currently applied in 43% of the total managed forest surface in Mexico (Arellano, 2010).

The lack of application of silvicultural treatments in the natural mixed stands in Asturias (northern Spain) during the last few decades has led to the general abandonment of these stands, which impedes timber harvesting. Application of CCF systems such as the MMOBI is recommended in Asturias because of the steeply sloping topography of the area (which favors erosion processes), the lack of a timber industry, and the large protected natural areas where the stands are of high ecological, recreational and aesthetical value. The MMOBI was chosen because of the success of this method in Mexico and because the natural species of trees in Asturias and their characteristics are similar to those present in *Sierra Madre Occidental* in Mexico, with a predominance of slow growing deciduous hardwoods such as those of the genus *Quercus* and other genera with intermediate growth patterns. The characteristics of the natural deciduous forests in Asturias indicate predominance of a temperate climate, although there is a great diversity in microclimates and bioclimatic types and there are 28 different types of forest (Díaz-González, 2014).

The deciduous forests of Asturias, which include 95% of native forest and cover 20% of the surface area of the region, are predominated by pedunculate oak (*Quercus robur*), sessile oak (*Quercus petraea*), chestnut (*Castanea sativa*), birch (*Betula pubescens*), maple (*Acer pseudoplatanus*), small-leaved lime (*Tilia cordata*), large-leaved lime (*Tilia platyphylla*) and river bank forests formed mainly by black alder (*Alnus glutinosa*), ash (*Fraxinus excelsior*) and willow (*Salix atrocinerea*). Beech (*Fagus sylvatica*) and wild cherry (*Prunus avium*) are also important timber species in the natural forest in Asturias. The non-timber species in these forests include hazel (*Corylus avellana*), hawthorn (*Crataegus monogyna*), rowan (*Sorbus* spp.) and willow (*Salix atrocinerea*). On the other hand, trees with persistent leaves and that are associated with Mediterranean microclimates, such as holm oak (*Quercus ilex* and *Quercus rotundifolia*), cork oak (*Quercus suber*), the non-timber holly (*Ilex aquifolum*), Pyrenean oak (*Quercus pyrenaica*) and Portuguese oak (*Quercus faginea*), only represent 5% of the total forested area in the region and cover 1.1% of the land (Díaz-González & Vázquez, 2004).

The main objective of this study was to analyze the application of the MMOBI to natural mixed forests in Asturias (northern Spain), which are included in strata numbers 4 and 9 defined in the third Spanish National Forest Survey (Ministerio de Medio Ambiente, 2006). The natural timber species of stratum 4 are *Quercus robur*, *Q. petraea*, *Q. pyrenaica*, *Q. ilex*, *Castanea sativa*, *Betula pubescens*, *Fraxinus excelsior*, *Acer pseudoplatanus*, *Alnus glutinosa*, *Prunus avium*, *Fagus sylvatica*, *Tilia* spp. and *Pinus pinaster*. The natural timber species of stratum 9 are *Q. robur*, *Q. petraea*, *Q. pyrenaica*, *Castanea sativa*, *Fagus sylvatica*, *Alnus glutinosa*, *Betula pubescens*, *Fraxinus excelsior*, *Prunus avium*, *Tilia* spp. and *Acer pseudoplatanus*.

Materials and Methods

Data

The data used in the present study were obtained from the database of the third Spanish National Forest Survey (IFN3) (Ministerio de Medio Ambiente, 2006). The plots were selected by stratified sampling and the number of plots was weighted according to the surface area of the strata, to yield a systematic distribution with a random beginning. Finally, the plots were sited at the intersection points of the kilometric UTM lines of the Topographic National Map 1:50000 classified as forestry use.

The total volume was calculated for each species and stratum. The representative strata 4 and 9 were chosen for this study because they include most of the natural mixed forest species present in Asturias. For each species and diameter class, the following stand variables measured in the third Spanish National Forest Survey were considered: Density (*N*), Basal Area (*G*), Volume with Bark (*VCC*), Volume without Bark (*VSC*), Annual Increment in Volume with Bark (*IAVC*) and Firewood Volume (VLE). The mean values of these stand variables for strata 4 and 9 are shown in Tables 1 and 2.

Data processing

From the inventory data, the following characteristic variables of the MMOBI were calculated: Total Real Volume (*ERT*), Mean Annual Increment (*IMA*), Current Annual Increment (*ICA*), Percentage of the Current Annual Increment (*%ICA*), Felling Intensity (*IC*), Basal Area to Extract (*GREMO*), Residual Basal Area (*GRESI*) and Volume to Extract (*REMO*):

Total Real Volume (ERT). The total volume for each diameter class and species ($m^3 \cdot ha^{-1}$) correspond to the Volume with Bark (*VCC*) from the database of the Third National Forest Inventory (IFN3) (Ministerio de Medio Ambiente, 2006). The total values for each species in strata 4 and 9 are shown in Tables 1 and 2.

Mean Annual Increment (IMA). This was calculated ($m^3 \cdot ha^{-1} \cdot year^{-1}$) for each diameter class and species, also from the IFN3 database (Ministerio de Medio Ambiente, 2006).

*Current Annual Increment (ICA).*This is a characteristic MMOBI variable and is calculated ($m^3 \cdot ha^{-1} \cdot year^{-1}$) using the following equation:

$$ICA = \frac{(ERT \cdot CC)}{(Tp \cdot D)}$$

where *ERT* is the Total Real Volume ($m^3 \cdot ha^{-1}$); *CC* is the felling cycle (years), which was established as 10 years because this is a common value for ensuring the continuous effect of the silviculture while also being separated enough to secure the profitability of the harvest, considering in this case the intermediate value of the step times between diameter classes of all species; *Tp* is the recruitment period or step time from one diameter class to the next (years), estimated as explained further below; and *D* is the mean diameter.

*Percentage of the Current Annual Increment (%ICA).*This was estimated using the following equation:

$$\%ICA = \frac{(ICA \cdot 100)}{ERT}$$

where *ICA* is the Current Annual Increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$), and *ERT* is the Total Real Volume ($m^3 \cdot ha^{-1}$).

Felling Intensity (IC). The felling intensity (%) was calculated by comparing the real diameter distribution with the theoretical or target diameter distribution, which was obtained by applying the De Liocourt criterion (1898), as indicated further below. The excess number of trees regarding the target distribution indicates the number of trees to fell in each diameter class, which represents the percentage of felling in relation to the total number.

Basal Area to Extract (GREMO). This variable was calculated ($m^2 \cdot ha^{-1}$) using the following equation:

$$GREMO = \frac{G \cdot IC}{100}$$

where *G* is the Basal Area ($m^2 \cdot ha^{-1}$) and *IC* is the Felling Intensity (% trees to extract).

Residual Basal Area (GRESI). This was calculated (in $m^2 \cdot ha^{-1}$) as follows:

$$GRESI = G - GREMO$$

where *G* is the Basal Area ($m^2 \cdot ha^{-1}$) and *GREMO* is the Basal Area to Extract ($m^2 \cdot ha^{-1}$).

Volume to Extract or Removal (REMO). This was obtained ($m^3 \cdot ha^{-1}$) using the following equation:

$$REMO = \frac{(ERT \cdot IC)}{100}$$

Where *ERT* is the Total Real Volume ($m^3 \cdot ha^{-1}$) and *IC* is the Felling intensity.

Diameter distribution graphs

Theoretical ideal distribution or target distribution

The theoretical ideal distribution or target distribution was established according to the De Liocourt (1898) criterion, based on the exponential distribution for uneven-aged stands. In this diameter distribution, the increment in trees between successive diameter classes is based on a constant *q*, which depends on the class diameter interval, the species and the site index (De Liocourt, 1898), according to the following equation:

$$Ni = Ni{+}1 \cdot q$$

where N_i is the number of trees of diameter class "*i*", N_{i+1} is the number of trees of diameter class immediately above "*i*", and *q* is a constant used to define the progression.

The *q* values are always larger than 1 and are usually between 1.2 and 1.8. High values of *q* indicate an increase in the number of trees of the smallest diameter classes and a reduction in the largest for the same number of trees per unit of surface area.

The *q* value and the target distribution were calculated for each genus according to the principles of the MMOBI. The *q* value was estimated for each genus from the IFN3 data as the average of the values provided by two consecutive diameter classes when the value obtained was within the usual range (between 1.2 and 1.8).

Timber species	*N* (trees·ha^{-1})	*G* (m^2·ha^{-1})	*VCC* (m^3·ha^{-1})	*VSC* (m^3·ha^{-1})	*IAVC* (m^3·ha^{-1}·year^{-1})	*VLE* (m^3·ha^{-1})
Castanea sativa	37.000 (25.92%)	0.629 (29.54%)	2.741 (28.00%)	2.235 (28.55%)	0.261	0.381
Betula spp.	15.081 (10.56%)	0.133 (6.24%)	0.731 (7.47%)	0.637 (8.13%)	0.069	0.123
Fraxinus spp.	8.633 (6.05%)	0.121 (5.68%)	0.607 (6.20%)	0.393 (5.02%)	0.075	0.064
Quercus robur	7.458 (5.22%)	0.219 (10.31%)	0.887 (9.06%)	0.671 (8.57%)	0.042	0.110
Acer spp.	6.991 (4.90%)	0.076 (3.55%)	0.396 (4.05%)	0.348 (4.44%)	0.034	0.049
Quercus pyrenaica	4.871 (3.41%)	0.065 (3.07%)	0.248 (2.54%)	0.134 (1.71%)	0.019	0.033
Alnus glutinosa	3.843 (2.69%)	0.048 (2.28%)	0.369 (3.77%)	0.331 (4.22%)	0.015	0.023
Prunus spp.	2.538 (1.78%)	0.078 (3.69%)	0.324 (3.31%)	0.240 (3.07%)	0.009	0.056
Pinus radiata	2.104 (1.47%)	0.064 (2.99%)	0.340 (3.47%)	0.266 (3.40%)	0.056	0.026
Salix spp.	2.074 (1.45%)	0.048 (2.27%)	0.337 (3.44%)	0.272 (3.48%)	0.057	0.030
Fagus sylvatica	1.519 (1.06%)	0.035 (1.64%)	0.266 (2.72%)	0.240 (3.07%)	0.007	0.017
Eucalyptus globulus	1.290 (0.90%)	0.053 (2.49%)	0.386 (3.94%)	0.318 (4.07%)	0.043	0.025
Pinus pinaster	1.284 (0.90%)	0.040 (1.87%)	0.239 (2.44%)	0.169 (2.16%)	0.036	0.011
Quercus ilex	0.822 (0.58%)	0.011 (0.50%)	0.044 (0.45%)	0.025 (0.32%)	0.001	0.008
Tilia spp.	0.215 (0.15%)	0.008 (0.40%)	0.039 (0.4%)	0.035 (0.45%)	0.002	0.005
Quercus petraea	0.059 (0.04%)	0.036 (1.68%)	0.208 (2.13%)	0.186 (2.38%)	0.002	0.021
Pinus sylvestris	0.030 (0.02%)	0.005 (0.21%)	0.025 (0.26%)	0.018 (0.24%)	0.001	0.002
Other deciduous hardwoods	2.734 (1.92%)	0.062 (2.92%)	0.138 (1.41%)	0.112 (1.43%)	0.011	0.029
Other coniferous	0.244 (0.17%)	0.014 (0.68%)	0.056 (0.57%)	0.041 (0.53%)	0.003	0.016
Non-timber species	***N* (trees·ha^{-1})**	***G* (m^2·ha^{-1})**	***VCC* (m^3·ha^{-1})**	***VSC* (m^3·ha^{-1})**	***IAVC* (m^3·ha^{-1}·year^{-1})**	***VLE* (m^3·ha^{-1})**
Corylus avellana	23.245 (16.28%)	0.180 (8.46%)	0.642 (6.56%)	0.536 (6.85%)	0.088	0.122
Ilex aquifolum	14.896 (10.43%)	0.143 (6.69%)	0.429 (4.38%)	0.364 (4.65%)	0.057	0.094
Sorbus spp.	3.607 (2.53%)	0.047 (2.20%)	0.177 (1.81%)	0.154 (1.97%)	0.016	0.025
Crataegus spp.	2.22 (1.56%)	0.013 (0.63%)	0.155 (1.58%)	0.100 (1.28%)	0.007	0.007
Salix spp.	2.074 (1.45%)	0.048 (2.27%)	0.337 (3.44%)	0.272 (3.48%)	0.057	0.029
Total Stratum 4	**142.764**	**2.130**	**9.791**	**7.827**	**0.913**	**1.279**

N: trees/ha; *G*: basal area; *VCC*: volume with bark; *VSC*: volume without bark; *IAVC*: annual increment in volume with bark; *VLE*: firewood volume.

Table 1.- Mean values (and percentage of the total) of the main dasometric variables in stratum 4 for each species

Timber species	N (trees·ha-1)	G (m2·ha-1)	VCC (m3·ha-1)	VSC (m3·ha-1)	IAVC (m3·ha-1·year-1)	VLE (m3·ha-1)
Fagus sylvatica	125.115 (23.10%)	9.011 (46.30%)	49.884 (47.48%)	45.898 (50.03%)	0.945	5.684
Quercus petraea	44.812 (8.27%)	2.741 (14.08%)	18.201 (17.32%)	15.203 (16.57%)	0.424	1.554
Castanea sativa	27.405 (5.06%)	1.263 (6.49%)	6.343 (6.04%)	5.364 (5.85%)	0.270	0.700
Betula spp.	25.475 (4.70%)	0.720 (3.70%)	3.335 (3.17%)	3.006 (3.28%)	0.185	0.258
Quercus robur	19.481 (3.60%)	1.160 (5.96%)	7.121 (6.78%)	5.867 (6.39%)	0.230	0.597
Quercus pyrenaica	6.659 (1.23%)	0.454 (2.33%)	2.539 (2.42%)	2.041 (2.22%)	0.074	0.268
Fraxinus spp.	5.819 (1.07%)	0.268 (1.38%)	1.703 (1.62%)	1.394 (1.52%)	0.120	0.219
Prunus spp.	4.537 (0.84%)	0.119 (0.61%)	0.665 (0.63%)	0.504 (0.55%)	0.016	0.082
Acer spp.	3.968 (0.73%)	0.250 (1.29%)	1.357 (1.29%)	1.241 (1.35%)	0.044	0.142
Tilia spp.	1.480 (0.27%)	0.137 (0.70%)	0.659 (0.63%)	0.602 (0.66%)	0.024	0.077
Alnus glutinosa	0.857 (0.16%)	0.070 (0.35%)	0.400 (0.38%)	0.366 (0.4%)	0.016	0.031
Other deciduous hardwoods	3.751 (0.69%)	0.127 (0.65%)	0.642 (0.61%)	0.500 (0.55%)	0.050	0.057
Other coniferous	1.436 (0.27%)	0,166 (0.85%)	0.574 (0.55%)	0.419 (0.46%)	0.009	0.235
Non-timber species	***N* (trees·ha-1)**	***G* (m2·ha-1)**	***VCC* (m3·ha-1)**	***VSC* (m3·ha-1)**	***IAVC* (m3·ha-1·year-1)**	***VLE* (m3·ha-1)**
Ilex aquifolum	118.642 (21.91%)	1.430 (7.35%)	3.702 (3.52%)	3.121 (3.4%)	0.468	0.931
Corylus avellana	94.671 (17.48%)	0.674 (3.46%)	2.637 (2.51%)	2.202 (2.40%)	0.360	0.461
Crataegus spp.	28.937 (5.34%)	0.431 (2.21%)	2.607 (2.48%)	1.809 (1.97%)	0.097	0.218
Sorbus spp.	16.969 (3.13%)	0.240 (1.23%)	1.039 (0.99%)	0.915 (1.00%)	0.087	0.126
Salix spp.	11.586 (2.14%)	0.204 (1.05%)	1.651 (1.57%)	1.292 (1.41%)	0.314	0.131
Total Stratum 9	**541.604**	**19.465**	**105.058**	**91.744**	**3.736**	**11.772**

N: trees/ha; *G*: basal area; *VCC*: volume with bark; *VSC*: volume without bark; *IAVC*: annual increment in volume with bark; *VLE*: firewood volume.

Table 2.- Mean values (and percentage of the total) of the main dasometric variables in the stratum 9 for each species

Step time and maximum cutting diameter

For application of the MMOBI, it is necessary to define the maximum cutting diameter, which must be established according to the demands of the industry for which the felling products are destined. In the present study, it was assumed that the final destination of the products was the saw industry, which in northern Spain uses trees of minimum diameter 30-35 cm. The veneer industry, which demands diameters above 40 cm, was not considered because the lack of silvicultural treatments has led to production of a small number of trees of these dimensions, and because the growth of natural stands is rather slow, which implies long rotation ages to reach this size. Furthermore, this industry is not consolidated in the region and the demand for this type of wood is limited.

Application of the MMOBI also requires knowledge of the so called “step time” between two consecutive diameter classes (considering an interval of class of 5 cm and a first diameter class of 10 cm). In the present study, due the impossibility of sampling the trees with increment borer (the data came from the IFN3), the step times were estimated for each species by considering the maximum and minimum growth and the mean values of the yield tables available for some species (Madrigal et al., 1999; Diéguez-Aranda et al., 2009).

Target or final Basal Area

Another characteristic variable of the MMOBI is the target basal area (G_{final}). As it is known that the Current Annual Increment (ICA) and the basal area are related, the target basal area ($m^2 \cdot ha^{-1}$) was calculated using the following expression:

$$G_{final} = G_{actual} \cdot \left(\frac{\%ICA}{100} + 1\right)^{cc}$$

where G_{actual} is the Basal Area of the stand ($m^2 \cdot ha^{-1}$), *%ICA* is the percentage of the Current Annual Increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$), and *CC* is the felling cycle (considered as 10 years).

Estimating the number of trees in each diameter class Ni

The normal section of each tree (m^2) in relation to the total basal area ($m^2 \cdot ha^{-1}$) according to the diameter class in which it is included is: $\pi \cdot (d\ (cm)/200)^2$. This expression enables calculation of the coefficients for each diameter class in equations [1] and [2], which include the final or target basal area (G_{final}) calculated in the previous section.

The following equation was used to calculate the number of trees of the highest diameter class N_m and thus the target distribution in the stands with maximum cutting diameter of 35 cm:

$$0.007854 \cdot N_m \cdot q^5 + 0.017671 \cdot N_m \cdot q^4 + 0.031416 \cdot N_m \cdot q^3 + 0.04987 \cdot N_m \cdot q^2 + 0.070686 \cdot N_m \cdot q^1 + 0.096211 \cdot N_m \cdot q^0 = G_{final} \quad [1]$$

This equation only depends on N_m, because the De Liocourt constant *q* was calculated as indicated previously. In this case there are only 6 diameter classes that correspond to the values of *q* elevated to 0, 1, 2, 3, 4 and 5, from the highest diameter class to the lowest, where the mean diameter of the first diameter class is 10 cm.

For stands with maximum cutting diameter of 30 cm, the following equation was used:

$$0.007854 \cdot N_m \cdot q^4 + 0.017671 \cdot N_m \cdot q^3 + 0.031416\ N_m \cdot q^2 + 0.04987 \cdot N_m \cdot q^1 + 0.070686 \cdot N_m \cdot q^0 = G_{final} \quad [2]$$

Solving these equations, we obtained the value of N_m, which correspond to the number of trees of the highest diameter class, and the other values were calculated using the following sequence (Serrada, 2007):

N_m: Trees in the highest diameter class;

$$N_{m-1} = N_m \cdot q;\ N_{m-2} = N_m \cdot q^2;\ .....;$$

$$N_{m-i} = N_m \cdot q^i\ ;....;\ N_1 = N_m \cdot q^{(m-1)}$$

When the target structure is defined, we can calculate the volume to extract (or removal in the MMOBI) in each management unit. This volume is defined by the excess of the observed diameter distribution in relation to the target structure. Although it would be desirable to define the target structure for each stand and species, this is actually done for each stratum and group of species (Musalem, 1998).

Results

The values of the De Liocourt constant *q* calculated for each species in the two strata studied are shown in Table 3. The step times between diameter classes estimated for each species and the maximum cutting diameter are shown in Table 4. The values of the variables used in the MMOBI defined previously for the genera in stratum 4 are shown in Table 5. The same variables for the genera in stratum 9 are shown in Table 6.

The real total volume is lower in stratum 4 than in stratum 9 because the density (considering both timber and non-timber species) is lower in the former (only 142.76 trees$\cdot$ha^{-1}) than in the latter (541.60 trees$\cdot$ha^{-1}). The most abundant timber species in stratum 4 is chestnut (*Castanea sativa*), which represents 25.9% of all trees in the stratum, followed by birch (*Betula pubescens*), which accounts for 10.6% of all of the trees. In stratum 9, the most abundant species is beech (*Fagus sylvatica*), representing 23.1% of all trees in the stratum, followed among the timber species by the sessile oak (*Quercus petraea*), representing 8.3% of all trees. Due the higher density of trees and total real volume in stratum 9, the mean annual increments (*IMAs*) and the current annual increments (*ICAs*) are higher than in stratum 4. However, the percentage of the current annual increment (*%ICA*) is higher in the less dense (stratum 4), with values between 4.3% and 13.5% corresponding to larger trees, in contrast with values between 2.8% and 8.5% in the more dense (stratum 9). Logically the number of trees to extract is also higher in the stratum in which volume and density are highest (stratum 9).

Stratum 4		Stratum 9	
Genus	*q*	Genus	*q*
Quercus	1.2	*Quercus*	1.5
Castanea	1.4	*Castanea*	1.4
Betula	1.8	*Betula*	1.5
Fraxinus	1.2	*Fraxinus*	1.5
Acer	1.2	*Acer*	1.5
Alnus	1.2	*Alnus*	1.2
Prunus	1.5	*Prunus*	1.8
Fagus	1.2	*Fagus*	1.3
Pinus	1.2	-	-
Tilia	1.2	*Tilia*	1.2

Table 3.- Values of the De Liocourt constant q for the genera in strata 4 and 9

Species	Step time (years)	Maximum diameter (cm)
Castanea sativa	6	35
Quercus robur	15	35
Quercus petraea	15	35
Quercus pyrenaica	12	35
Quercus ilex	15	35
Betula spp.	7	30
Acer spp.	8	35
Alnus glutinosa	7	30
Fraxinus spp.	10	35
Pinus pinaster	5	35
Prunus spp.	8	35
Fagus sylvatica	8	35
Tilia spp.	10	30

Table 4.- Estimated step time between diameter classes and maximum diameter at felling for each species

The percentage of felling intensity (*IC%*) was generally low in stratum 4, and was less than 20% for most genera except *Fraxinus* and *Acer,* for which IC >50%. In stratum 9, IC% was generally higher than in stratum 4, although also low to intermediate, except for the genus *Tilia* (IC > 50%). The values of basal area to extract (*GREMO*), the residual basal area *(GRESI)* and the volume to extract (*REMO*) are also higher in stratum 9 in consonance with the larger volumes ($m^3 \cdot ha^{-1}$).

Figure 1 and 2 show the observed diameter distributions and the target or final diameter distributions estimated with the De Liocourt (1898) criterion for the genera in stratum 4 and stratum 9 respectively. Many observed distributions have the typical reverse “J-shaped” diameter distribution corresponding to natural stands. Only the genus *Tilia* in stratum 4 and the genera *Acer*, *Alnus* and *Tilia* in stratum 9 do not show this type of diameter distribution.

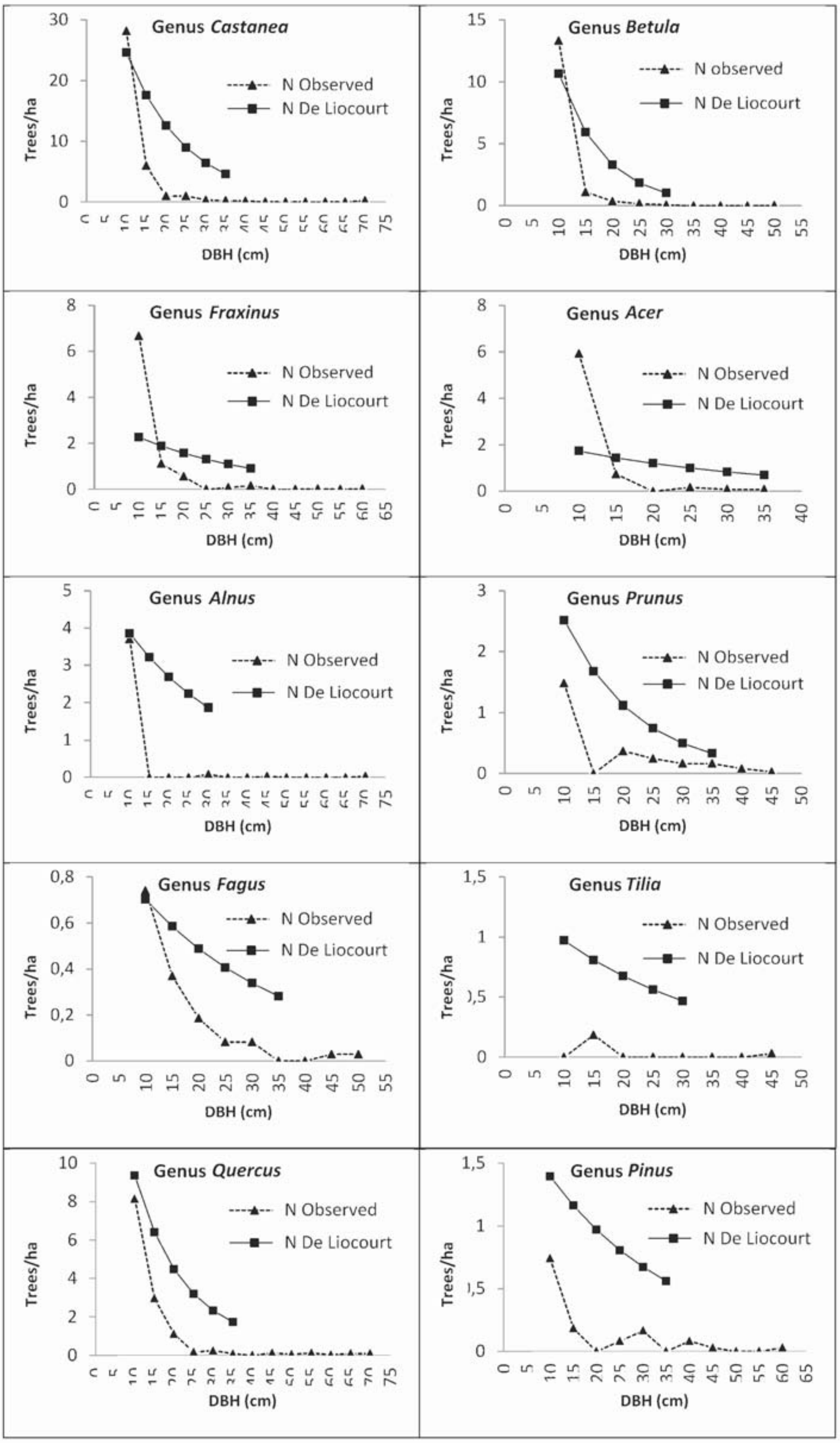

Figure 1.- Observed and target distributions in stratum number 4

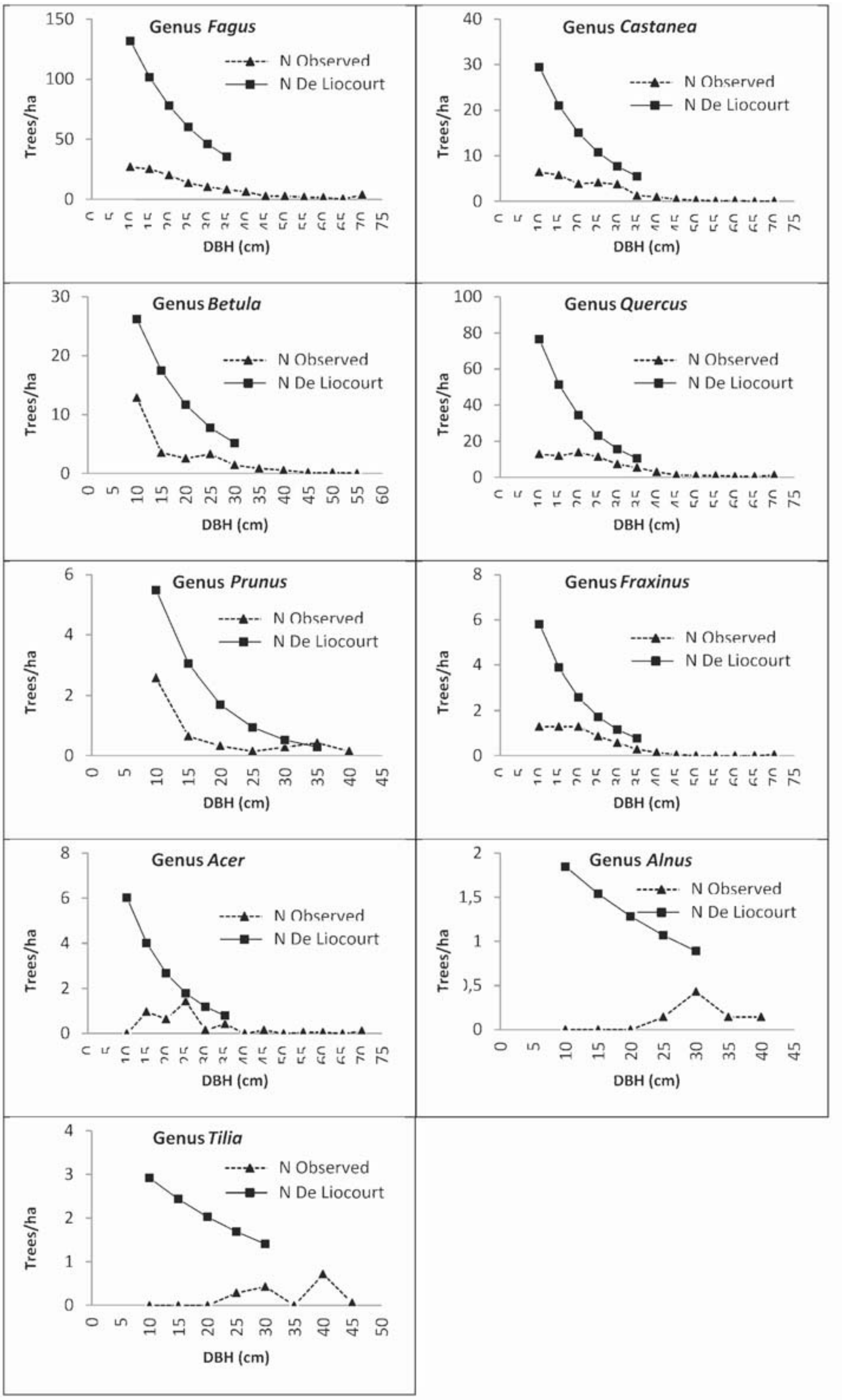

FIgure 2.- Observed and target distributions in stratum number 9

Discussion

We applied the MMOBI to natural mixed stands represented in stratum 4 and stratum 9 of the Spanish IFN3 for Asturias (Ministerio de Medio Ambiente, 2006). These strata are representative of natural mixed stands in Asturias because they differ in relation to their dasometric variables and they include many genera (after ruling out non-natural species with testimonial presence). In total, 10 timber genera and 5 non timber genera were considered in stratum 4, and 9 timber genera and 5 non timber genera were considered in stratum 9. The great diversity provides different cases for estimating the target diameter distributions from the observed diameter distributions.

As the stands are natural, almost all of the observed diameter distributions present the typical reverse "J shaped" curve similar to the first mathematical model for diameter distributions for uneven-aged stands developed by De Liocourt (1898). This distribution was considered as the target distribution because it enables application of the close-to-nature silvicultural system included in the CCF concept. Field studies in virgin and old-growth forest have confirmed the utility of the negative exponential model (Meyer & Stevenson, 1943; Meyer, 1952; Lorimer, 1980; Leak, 1996), although small changes in the decreasing curve occasionally occur (Westphal et al, 2006).

Genus	ERT	IMA	ICA	%ICA	Trees to extract	IC (%)	GREMO	GRESI	REMO
Castanea	2.741	0.261	0.369	13.47	4.026	10.90	0.068	0.561	0.243
Betula	0.731	0.069	0.095	13.03	2.701	17.91	0.024	0.109	0.131
Fraxinus	0.607	0.075	0.049	8.16	4.458	51.64	0.062	0.058	0.313
Acer	0.396	0.034	0.043	10.95	4.193	59.98	0.045	0.030	0.238
Alnus	0.369	0.016	0.047	12.80	0.059	1.54	0.001	0.048	0.006
Prunus	0.324	0.009	0.023	7.26	0.112	4.41	0.003	0.075	0.014
Fagus	0.266	0.007	0.021	7.92	0.098	6.42	0.002	0.033	0.017
Tilia	0.039	0.002	0.002	5.22	0.030	13.79	0.001	0.007	0.005
Quercus	1.388	0.064	0.059	4.26	0.498	3.77	0.012	0.319	0.052
Pinus	0.264	0.037	0.028	10.67	0.141	10.77	0.012	0.096	0.065

ERT: Total real volume ($m^{3} \cdot ha^{-1}$); *IMA*: Mean annual increment ($m^{3} \cdot ha^{-1} \cdot year^{-1}$); *ICA*: Current annual increment ($m^{3} \cdot ha^{-1} \cdot year^{-1}$); *%ICA*: % of the current annual increment; *IC*(%): % of felling intensity; *GREMO*: Basal area to extract ($m^{2} \cdot ha^{-1}$); *GRESI*: Residual basal area ($m^{2} \cdot ha^{-1}$); *REMO*: Removal, or volume to extract ($m^{3} \cdot ha^{-1}$).

Table 5.- Estimated variables of the MMOBI for stratum 4

Genus	ERT	IMA	ICA	%ICA	Trees to extract	IC (%)	GREMO	GRESI	REMO
Fagus	49.884	0.945	2.570	5.15	28.300	22.62	2.038	6.973	11.287
Castanea	6.343	0.270	0.491	7.74	2.183	7.98	0.101	1.162	0.506
Betula	3.335	0.185	0.283	8.49	1.789	7.02	0.050	0.669	0.234
Fraxinus	1.703	0.120	0.084	4.93	0.246	4.22	0.011	0.257	0.072
Prunus	0.665	0.016	0.051	7.59	0.281	6.20	0.007	0.112	0.041
Acer	1.357	0.044	0.066	4.84	0.360	9.07	0.023	0.228	0.123
Tilia	0.659	0.024	0.019	2.91	0.766	51.74	0.071	0.071	0.341
Alnus	0.400	0.016	0.021	5.26	0.286	33.33	0.023	0.046	0.133
Quercus	27.861	0.729	0.793	2.85	8.505	11.99	0.522	3.832	3.341

ERT: Total real volume ($m^{3} \cdot ha^{-1}$); *IMA*: Mean annual increment ($m^{3} \cdot ha^{-1} \cdot year^{-1}$); *ICA*: Current annual increment ($m^{3} \cdot ha^{-1} \cdot year^{-1}$); *%ICA*: % of the current annual increment; *IC* (%): % of felling intensity; *GREMO*: Basal area to extract ($m^{2} \cdot ha^{-1}$); *GRESI*: Residual basal area ($m^{2} \cdot ha^{-1}$); *REMO*: Removal or volume to extract ($m^{3} \cdot ha^{-1}$).

Table 6.- Estimated variables of the MMOBI for stratum 9

With respect to stand diameter distributions, the term "sustainable" can be interpreted in two ways (Rubin et al., 2006). First, in the absence of major disturbance, some uneven-aged stands are managed sustainably on the basis of reverse "J-shaped" distributions (Nyland, 2002; O'Hara, 2002). Second, some conceptual ecological models predict that old-growth stands should reach equilibrium or quasi-equilibrium where ecosystem structure and processes become more or less constant, or are naturally sustained (Bormann & Likens, 1979).

All observed stands in stratum 4 have a diameter distribution structure tending to the reverse "J shape" curve, and appropriate management enables the target distribution of De Liocourt (1898) to be reached. The only exception is the genus *Tilia*, which has a small number of trees that do not enable the target distribution to be reached. In this and other similar cases in stratum 9, these trees can be maintained in the stand without management. One of the concepts included in the CCF is the Green Tree Retention (GTR) system, which proposes maintaining trees or small woodlots in the stand after felling as wildlife refuges and to help preserve and increase the biodiversity in forest areas (see e.g. Rose & Muir, 1997; Zenner, 2000; Vanha-Majamaa & Jalonen, 2001; Valkonen et al., 2002). The economic viability of this silvicultural method is demonstrated even for Scots pine forest in northern Spain (Bravo & Díaz-Balteiro, 2004). The World Wildlife Fund has proposed (on the basis of scientific studies) that to enhance biodiversity, and as more than 30% of forest dwelling species depend on old trees and dead wood (dead trees that have not been felled and have not fallen), maintenance of between 20 and 30 $m^3 \cdot ha^{-1}$ of dead wood (or between 3% and 8% of the total volume of wood) should be an objective in boreal and temperate forests in Europe for the year 2030 (WWF, 2004).

Several different distributions are observed in the other genera in stratum 4. In the genera *Castanea*, *Betula*, *Alnus*, *Fagus* and *Quercus*, the observed distribution of trees in the smallest diameter class is similar to the target distribution, thus ensuring that future demand for all trees in the other diameter classes will be covered. Management is thus limited to eliminating the excess trees that would be incorporated into the subsequent diameter class in each cutting cycle. In the genera *Fraxinus* and *Acer*, there is an excess of trees in the smallest diameter class, and thus the felling intensity was the highest in these classes (sometimes more than 50% of trees). In this case it may be necessary to reduce the high regeneration density to allow incorporation of the required number of trees in successive diameter classes. Finally, in two genera, *Prunus* and *Pinus*, the number of trees in the smallest diameter class is slightly lower than the ideal value. Both genera present some trees with diameter bigger than the maximum cutting diameter established. Felling of these trees would open up large clearings, which would benefit colonization by regeneration and increase the number of trees in the first diameter class (Boudru, 1989; Madrigal, 1994).

The diameter distributions of the stands in stratum 9 also present a similar structure to the reverse "J shaped" curve, which would enable the target distribution of De Liocourt to be reached. The only exceptions are the genera *Tilia*, *Alnus* and *Acer* because of the smaller number of trees involved. These trees could be maintained as part of the aforementioned GTR system. The other genera present a similar structure, with a lack of trees in the smallest diameter classes and sometimes an excess of trees of diameter larger than the maximum cutting diameter. As already explained, to reach the proposed distribution, these large trees would have to be felled, thus opening up clearings that would be colonized by regeneration and increasing the density of the smallest diameter class (Madrigal, 1994).

Uneven-aged forest management is not included in the Spanish legislation because this type of forestry is hardly practiced. For example, in Galicia all forests are managed as even-aged forests. However uneven-aged forestry seems a very convenient future option for many mixed natural stands in Asturias, for the reasons given in this paper.

In conclusion, we applied the Mexican Management Method for Uneven-aged Forests (MMOBI) to natural mixed stands represented in two strata defined in the Spanish IFN3 for Asturias (Ministerio de Medio Ambiente, 2006). The MMOBI is presented as a continuous cover forestry system (CCF) with possible application to other strata of natural mixed stands in Asturias (included in the IFN3) and an alternative management method for protective stands, which are abundant in Asturias because of the physical characteristics of the land and the presence of numerous protected natural areas.

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