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Can we get an operational indicator of forest carbon sequestration? A case study from two forest regions in Spain

C. Herrero*, F. Bravo

Sustainable Forest Management Research Institute UVa-INIA, ETS Ingenierías Agrarias, University of Valladolid, Avda, Madrid 44, 34071 Palencia, Spain

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ABSTRACT

Indicators for sustainable forest management are considered to be key tools for the implementation of regional, national and international forest policies. The Montreal process identified the "maintenance of forest contribution to global carbon cycles" as an essential component in sustainable management of forest ecosystems. Carbon sink evaluations provide reference information to policy-makers, stakeholders, resource managers and concerned citizens about the sustainable use of our forests for present and future generations. Two forest areas in northern and central Spain ('Páramos y Valles' and Central Mountain Range) were chosen as pilot areas to test the use of the National Forest Inventory to calculate carbon biomass forest sink at operational level.

Data from the Second and Third National Forest Inventory (2NFI and 3NFI, respectively), together with biomass equations were used. Total carbon biomass sink was calculated as a balance between carbon dioxide inputs and outputs in forest biomass. Tree growth between 2NFI and 3NFI, new plots and ingrowth (recruitment and upgrowth) biomass were considered as inputs, while forest harvesting and natural mortality were considered as outputs. In 'Páramos y Valles', 2.46 Mg CO_2 ha^{-1} year^{-1} was fixed in the tree biomass of forest ecosystems from 2NFI to 3NFI, whereas in the Central Mountain Range the fixation was 0.72 Mg CO_2 ha^{-1} year^{-1} in the period between inventories. The balance of CO_2 in the two areas was positive in 3NFI, with more than four million Mg of CO_2 accumulated in 'Páramos y Valles' and more than 72 million Mg of CO_2 fixed in the Central Mountain Range. Forest ecosystems are carbon sinks in the tree biomass in the two areas considered.

1. Introduction

The necessity of monitoring and measuring progress towards sustainable development strategies has prompted the elaboration of Criteria and Indicators. They cover a very wide range of topics, from social equity and cohesion to environmental protection. In operational forestry, FSC (Forestry Stewardship Council), PEFC (Program for the Endorsement of Forest Certifications) or TARAPOTO process (Sustainability Criteria and Indicators for the Amazon Forests) are good examples of Criteria and Indicators used around the world. Within Criteria and Indicators, those related with 'climate change' and 'conservation and management of natural resources' are crucial in sustainability assessment.

Since the Industrial Revolution (usually dated from 1750), CO_2 emissions have dramatically increased by 31%, from 280 ppm to 379 ppm (Forster et al., 2007), due to human activities such as coal heating, power generation from fossil fuels, transport, etc., causing global warming and other ecological problems. Society demands actions to mitigate the causes of climate change. In this framework, forests can play a crucial role in the climate change mitigation process, as stated in Good Practice Guidance for land use, land-use change and forestry (Arnold et al., 2005). Climate change could affect forest growth because the growth rate depends on their health as well as on the availability of nutrients, water and sunshine, factors that may all be influenced by climate change as well. In this sense, ecosystem management, that could be defined as the balance between ecosystem functions and human requirements of natural resources (Grumbine, 1994) can help foresters to cope with climate change challenges. Ecosystem management represents a shift from single-species management (that focuses primarily on economic demand for specific resources such as timber) towards a more holistic approach that recognizes the intrinsic values and services and interconnected nature of ecosystem functions and human needs (Blockstein, 1999).

By understanding the carbon cycle in forest dynamics under different management regimes, foresters can design suitable forest strategies. The carbon cycle is essential to environmental assessment because it is closely related with the different environmental and socio-economic attributes or functions, values, services and benefits that forests provide (food, fuel production, biodiversity,

* Corresponding author. Tel.: +34 979 10 84 87; fax: +34 979 10 84 40.
E-mail address: chdeaza@pvs.uva.es (C. Herrero).

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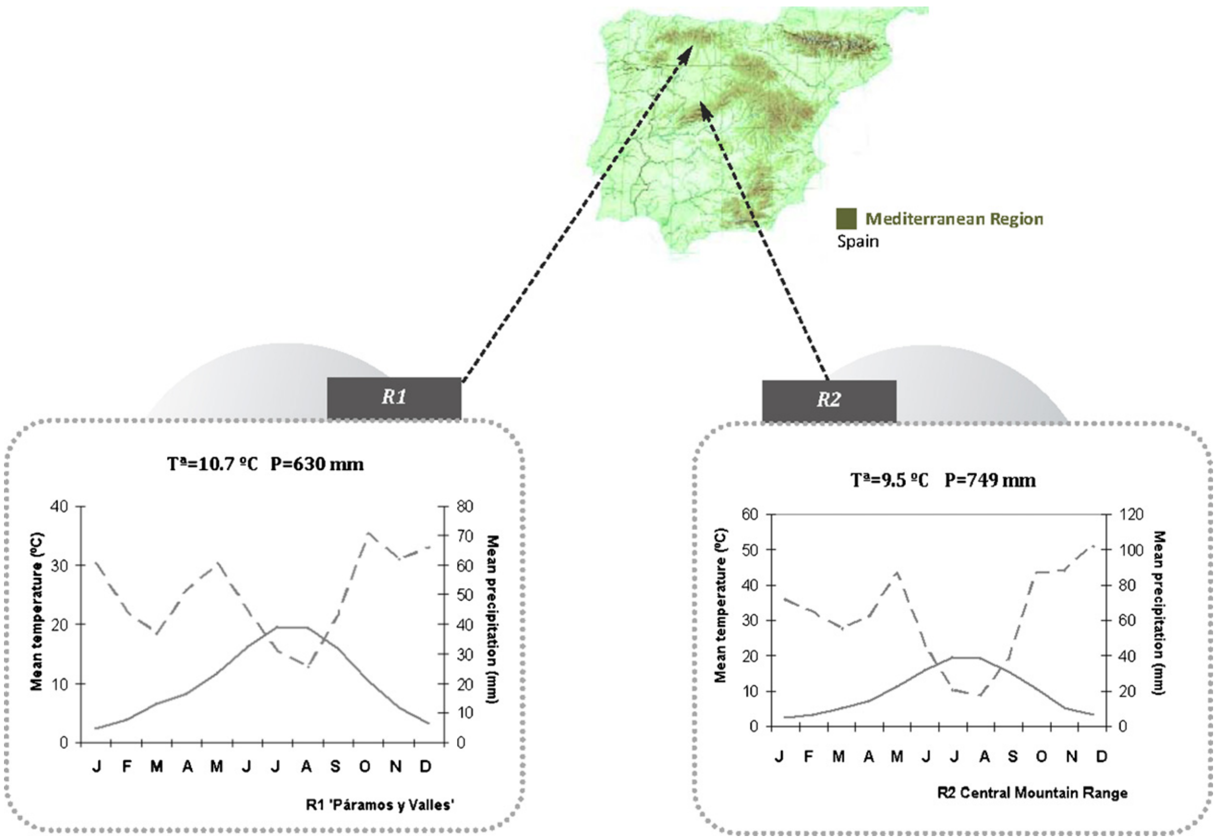

Fig. 1. Situation of the studies areas. Note: *T*ª is mean annual temperature (°C) and *P*: mean annual amount of precipitation (mm).

carbon sequestration, climate regulation, watershed protection and nonmaterial benefits such as spiritual or aesthetic benefits).

Several Ministerial Conferences have been held in Europe (Strasbourg, 1990; Helsinki, 1993; Lisbon, 1998; Vienna, 2003; Warsaw, 2007) to analyze the role of forest management under the sustainability paradigm and its potential as a carbon sink. In these conferences, it was suggested that there is a need to make an inventory of the biomass stored in wood and forest stocks and to compare carbon stored in and taken up by forests with the amount of CO_2 emitted by fossil fuel combustion. Accurate biomass and growth data are needed to calculate forest potential for CO_2 fixation. At a national level, standardized methods for calculating forest CO_2 sinks and sources are important to achieve if countries are to accomplish Kyoto emission reduction objectives.

Forest carbon stock changes can be measured by accounting net sink and sources directly. However, due to lack of data at global scale, practical application of this methodology is difficult. Additionally, this methodology does not fully cover all of the forest life cycle stages and there is no data available to consider the contribution of different disturbances (fire, pests, etc.) to carbon stock dynamics. To develop accurate and suitable methodologies to estimate the annual forest carbon sink, forest inventories provide suitable data from stand situations and can help us to monitor broad-scale forest biomass carbon budgets (national and regional levels). This is done by converting data from wood volume (m^3) or biomass (Mg) to carbon content (Mg C) and CO_2 fixation (Mg CO_2) by using appropriate equations or biomass expansion factors. National Forest Inventories (NFIs) are developed routinely in many countries around the world: USA (Brown et al., 1997; Schroeder et al., 1997), Sweden (Hägglund, 1985), Finland (Tomppo, 1996), China (Fang and Wang, 2001) and Spain (Bravo and Montero, 2003). The general methodology includes data, at both tree and stand levels, that is usually recorded every 5–10 years. These data can be used to calculate forest carbon budgets adequately to monitor Kyoto Protocol accomplishment. The Kyoto Protocol (UNFCCC, 1997) states that some of the forest carbon stock changes can be accounted to reduce greenhouse emissions budgets during the first commitment period (2008–2012).

In the current context, there is a strong impetus for developing appropriate sustainable forest management policies. However, Indicator development is a hard because different expectations (from data providers and end-users) have to be fulfilled. Different Indicators have to be developed in different objectives (policy design, management guidelines, operational forestry, monitoring, etc.) at different spatial and terrestrial scales. In some cases, raw data are used, but often composite indicators (an ecological footprint) or dimensionless indexes (such as the environmental sustainability index) accomplish end-user needs better. Additionally, to select proper indicator variables, issues such statistical methods (obtaining, managing and analyzing data sets), cost-effective procedures and variable aggregation strategies are crucial in developing indicators for assessing sustainable forest management.

Although the services provided by forests and woodlands are numerous and diverse at different spatial and temporal levels, information on forest carbon fixation could help us to provide a reference point available to decision-makers for developing policies on conservation, management, and sustainable development. Indicators related with forest carbon stocks are included in different Criterion and Indicator systems but a clear and unified methodology has not been fully stated yet.

The objective of this project was to develop a methodology to calculate carbon sequestration in natural forests and plantations based on National Forest Inventory data. Two areas in northern and central Spain, where two consecutive Spanish NFI cycles were conducted between 1990 and 2003, were chosen as test zones. Results from the two areas were analyzed to obtain relevant information about carbon stock quantification and dynamics.

2. Methods

2.1. Study areas

Two different forest areas in northern and central Spain were selected (Fig. 1). These two areas cover a wide range of Mediterranean forest types. 'Páramos y Valles' represents a homogeneous transitional sector between the Cantabrian Mountain and 'Tierra de Campos' region. Altitude ranges from 800 to 1000 m asl. The climate is Mediterranean with a slight Atlantic influence. Winters are cold and long, while summers are dry and warm. Mean temperature is 10.7 °C and mean annual rainfall is 630 mm (107 mm in summer). Total area is over 186,000 ha, with forests covering 33% of this area (61,571 ha). The forest landscape is dominated by pine plantations (41.5% of the forest area) and natural oak stands (38%). Dominant species are *Pinus sylvestris* (18.1%), *Pinus nigra* (18.2%), *Pinus pinaster* (5.2%) and *Quercus pyrenaica* (38%).

The 'Central Mountain Range', the other study area (Fig. 1), it is one of the most important Mediterranean mountain ranges in the Iberian Peninsula. Altitude ranges from 1000 to 2500 m asl. The climate is sub-Mediterranean with a pronounced summer (July and August) drought. The average rainfall is 749 mm (94 mm in summer) and the mean annual temperature is 9.5 °C. Total area is over 2.5 million ha, with forests covering 77% of this area (1.9 million ha). The forest landscape is dominated by natural and planted pine stands and natural oak stands (11.9%). Dominant species are *P. sylvestris* (6.2%), *P. pinaster* (10.5%) and *Q. pyrenaica* (11.9%).

2.2. Data

Data from two consecutive cycles of the Spanish National Forest Inventory (second and third cycles, hereinafter called 2NFI and 3NFI), have been used to calculate the tree biomass carbon stock. Spanish NFI plots (Bravo et al., 2002; Icona, 1990) are distributed systematically using a grid of 1 km^2. Each plot consists of four concentric subplots with a radius of 5, 10, 15 and 25 m. For these subplots, the minimum diameter recorded is 7.5, 12.5, 22.5 and 42.5 cm, respectively. To expand the data to hectares, the following expansion factors are used: 127.32, 31.83, 14.16 and 5.09 for each minimum diameter, respectively. At plot establishment, the following data are recorded for every tally tree: species, diameter at 1.3 m (dbh) to the nearest millimeter, total height to the nearest quarter meter, and the distance and azimuth from the plot center in meters and degrees, respectively. Diameters are measured with a caliper in two perpendicular directions. At remeasurement, dbh and total height are measured again in former tally trees, while all the variables (dbh, total height, position and species) are recorded in new tally trees.

In our study areas, 2NFI was conducted in 1991 in 'Páramos y Valles', and between 1990 and 1992 in the different provinces of the Central Mountain Range; 3NFI was conducted between 2002 and 2003 in both regions. The main NFI plot characteristics are shown in Table 1.

2.3. Carbon estimations

Biomass equations developed by Montero et al. (2005) were applied to estimate tree carbon content. After felling, sample trees were collected across diameter classes to fit the biomass models. Different sample fractions (stem, branches under 2 cm diameter, branches between 2 and 7 cm diameter, branches above 7 cm diameter, needle and root biomass) were weighed in the field to calculate the fresh weight; a subsample was dried in the laboratory at 102 ± 2 °C to constant weight to obtain dry weight conversion factors. With this database, Montero et al. (2005) fitted allometric functions with diameter at breast height as an independent variable to each fraction and to the whole biomass to calculate the dry biomass (Eq. (1)):

Table 1
Main NFI plot characteristics.

	2NFI		3NFI	
	dbh	Ht	dbh	Ht
'Páramos y Valles'	4818 trees		7251 trees	
Mean	17.01	8.79	20.23	10.78
Standard deviation	6.00	3.61	6.54	2.90
Minimum	7.50	2.30	7.50	3.00
Maximum	95.00	39.50	101.90	21.00
Central Mountain Range	55,280 trees		73,788 trees	
Mean	23.53	9.66	24.43	10.59
Standard deviation	12.60	3.98	13.10	4.57
Minimum	7.50	2.19	7.50	1.81
Maximum	128.54	28.75	137.80	32.75

dbh: diameter at breast height (cm); Ht: total height (m).

$$\ln B_i = a + b \times \ln \text{dbh} \tag{1}$$

where

$$B_i = \text{CF} \times a \times \text{dbh}^b \tag{2}$$

and

$$\text{CF} = \exp\left(\frac{\text{SEE}^2}{2}\right) \tag{3}$$

where B_i is biomass of the fraction i, dbh is the diameter at breast height, CF is the correction factor, SEE is the standard error of the estimate and a and b are parameters to be obtained.

Carbon amount in each fraction and in the whole tree were calculated by multiplying each value by 0.5 in accordance with Kollmann (1959) and IPCC recommendations (Penman et al., 2003). Mean basic density of 0.50 Mg m^{-3} was assumed in all species. Carbon dioxide amount was estimated by multiplying carbon amount times 3.67 (ratio between CO_2 molecular weight and C atomic weight). Finally, carbon storage in harvested wood products was not included in our calculations, following IPCC guidelines (Penman et al., 2003). These procedures have been used before (Bravo et al., 2008) to evaluate carbon sink in Mediterranean pine forests. On the other hand, although some shrub biomass equations are available for Mediterranean shrubs (Navarro and Blanco, 2006), the carbon pool in shrubs was not included in this paper because local equations were not available.

2.4. NFI comparisons

For comparison, different considerations were made in plots measured in both inventories (2NFI and 3NFI) and in plots measured by the 2NFI or the 3NFI. If harvest or thinning operations had not been carried out between the two inventories, the growth of all tally trees was considered as carbon input by growth in the ecosystem balance. However, if harvest or thinning operations had been carried out, the carbon in the cut trees was considered as output through harvesting, while carbon increased in living trees was considered as input. Dead trees between the two inventories were considered as carbon output through natural mortality. In accordance with IPCC guidelines (Penman et al., 2003), to compute the carbon emissions, we included the default assumptions that all carbon in harvested biomass (above- and below-ground) and in below-ground biomass of dead trees was oxidized in 2NFI. Trees that had become tallies in 3NFI (ingrowth) were considered as input. Finally, carbon in plot biomass measured only in 3NFI was considered as input by new plots. In all cases, appropriate expansion factors based upon inventory design were applied.

3. Results

A method to estimate forest carbon sequestration based upon National Forest Inventory data was developed. This method was used in two different forest areas in northern and central Spain. In addition to the NFI database, methodology was based on available biomass equations and standard assumptions on wood density and carbon content.

With respect to biomass carbon content, differences between species were found (Table 2). *P. sylvestris* always stored more carbon (158.1 and 159.1 $Mg\,CO_2\,ha^{-1}$ in 'Páramos y Valles' and the Central Mountain Range, respectively) than *P. pinaster* (148.8 and 123.4 $Mg\,CO_2\,ha^{-1}$ in the two areas, respectively). *Q. pyrenaica* stored just 19.2 $Mg\,CO_2\,ha^{-1}$ in 'Páramos y Valles' and 65.6 $Mg\,CO_2\,ha^{-1}$ in the Central Mountain Range. In general, the differences between species were due to different tree architecture and biomass allocation. However, differences between the two areas could be due to the different forest age and structure: in 'Páramos y Valles' there were mainly young stands, while a balanced age distribution was found in the Central Mountain Range. In the case of *Q. pyrenaica*, the reason could be the degradation of 'Páramos y Valles' oak stands.

In both areas and in all analyzed species, the harvest rate (harvest divided by the sum of growth and ingrowth) was lower that 100%, meaning that carbon was accumulated in all forest ecosystem types. A higher harvest rate value was found in *P. pinaster* plantations in the 'Páramos y Valles' area. This was due to a forest management strategy that replaces this species by other better-adapted ones (mainly *P. nigra*). A low harvest rate was found in *P. nigra* in both 'Páramos y Valles' (21.7%) and the Central Mountain Range (23.5%) due to different causes: first, in 'Páramos y Valles', age structure and a better adaptation caused more infrequent thinning operations in *P. nigra* stands than in other species and, second, carbon fixation by ingrowth was higher in this type of stands. On the other hand, in the Central Mountain Range, the scattered distribution of this species meant that harvesting was not frequent.

Oak (*Q. pyrenaica*) and pine (*P. sylvestris*, *P. nigra* and *P. pinaster*) represented more than 68% of total carbon present in 3NFI (97.5% in 'Páramos y Valles' and 68.9% in the Central Mountain Range). However, other important species (like *Quercus ilex*) also fixed carbon in tree biomass in both regions (Table 2). In terms of growth, pine species represented 94.4% and 59.6% in 'Páramos y Valles' and the Central Mountain Range, respectively. The higher value in pine species in 'Páramos y Valles' was because plantation range was between 30 and 60 years and they were managed for wood production. On the other hand, oak stands in this region presented a low-vigor coppice structure and showed small growth in the last 60 years. However, oak input new plots were more numerous than *Pinus* spp. plantations for two reasons: (1) the recovery of the natural forest and (2) the different spatial information used to classify 2NFI and 3NFI forest areas. A crop map of the area (MFE200) was used in 2NFI, while the National forest map (MFE50) was used in 3NFI. *Pinus* stands in the Central Mountain Range presented a greater balance between growth (59.2%) and ingrowth (56.7%) inputs by stand development. Finally, output results showed that the harvest was focused on the *Pinus* spp. species in the two regions, especially in 'Páramos y Valles' (79.4%), where the first thinning is still being carried out at the present time (Table 2).

Table 2
Carbon dioxide (Mg CO_2) balance by species in studied areas.

	Pinus sylvestris	*Pinus nigra*	*Pinus pinaster*	*Quercus pyrenaica*	*Quercus ilex*	*Pinus pinea*	*Castanea sativa*	*Fraxinus* spp.	Others	Total
"Páramos y Valles"										
3NFI	1,765,407.34	1,823,059.41	473,129.48	415,902.38	35,038.67	–	–	3419.00	77,495.00	4,593,451.28
Growth	265,886.35	201,875.61	86,559.36	31,487.42	447.40	–	–	0.00	943.00	587,199.14
Ingrowth	658,443.50	1,119,109.39	214,030.47	140,596.30	31,064.57	–	–	0.00	50,088.00	2,213,332.24
New plots	26,559.58	45,559.60	8861.68	121,434.35	0.00	–	–	3419.00	25,641.00	231,475.21
Harvest	397,082.82	287,095.10	273,849.91	58,854.98	1158.13	–	–	0.00	188,029.00	1,206,069.94
Mortality	4151.61	1845.96	0.00	1037.76	0.00	–	–	0.00	0.00	7035.33
Net Balance	549,655.00	1,077,603.54	35,601.61	233,625.33	30,353.84	–	–	3419.00	−111,357.00	1,818,901.32
Harvest rate (%)	42.96	21.73	91.10	34.20	3.68	–	–	0.00	368.46	43.07
Central Mountain Range										
3NFI	18,662,808.42	1,519,000.00	16,112,371.32	13,637,687.77	12,090,519.48	2,788,165.26	2,299,547.65	2,238,927.42	3,055,047.79	72,404,075.11
Growth	2,049,163.77	198,000.00	2,161,474.33	996,428.17	1,011,321.72	362,316.39	257,800.95	233,170.37	182,028.34	7,451,704.05
Ingrowth	5,806,077.30	547,000.00	5,136,234.16	3,161,343.79	2,939,996.17	757,338.00	633,231.88	275,932.02	998,744.84	20,255,898.16
New plots	596,675.74	61,000.00	953,834.81	1,328,222.68	2,061,514.89	192,405.15	356,333.46	418,111.94	835,221.72	6,803,320.38
Harvest	5,201,542.52	175,000.00	5,228,093.93	2,837,705.24	2,138,274.43	316,615.34	800,794.24	103,245.03	725,386.73	17,526,657.46
Mortality	344,009.09	19,000.00	551,941.40	258,968.99	119,722.10	29,885.66	289,531.20	40,473.19	90,598.54	1,744,130.18
Net Balance	2,906,365.21	612,000.00	247,1507.97	2,389,320.41	3,754,836.24	965,558.53	157,040.84	783,496.11	1,200,009.63	15,240,134.94
Harvest rate (%)	66.22	23.49	71.64	68.25	54.12	28.28	89.87	20.28	61.43	63.26

4. Discussion

A method to quantify carbon dioxide has been developed based on data from National Forest Inventories. The balance between different inputs and outputs in the tree biomass allows us to check stand productivity, the carbon situation and forest management sustainability.

The methodology developed allows us to quantify CO_2 with available data in an operational process. Carbon monitoring systems need to be simple enough to permit policy-makers and stakeholders to obtain comparable, verifiable information between different areas. Easily understood and measured, this method allows us to calculate the carbon fixation with perspective due to NFI periodicity, avoiding snapshots of current conditions or descriptions of past conditions. This characteristic lets us test the history and the future each 10 years as a dynamic system that provides insights into policy trade-offs. On the other hand, this method could help us to link with other ecological, social and economic indicators such as people working in forestry, wood product markets or ecosystem richness and biodiversity through the total carbon distribution among the different species.

The results of this methodology provide useful information and open up the possibility of estimating some of the basic practical forestry parameters related to carbon sequestration and to different parameters considered by international agencies and institutions, such as the European Environmental Agency (EEA), Eurostat (European Statistics), Environmental Protection Agency (EPA), UNSCD (United Nations Commission on Sustainable Development) or OCDE (Organization for Economic Co-operation and Development). These organisms improve the forest management monitoring and avoid overexploitation, deforestation and degradation of natural resources, suggest calculating different environmental indicators, including, among others, the relation between forest growth/felling (similar to our harvest rate) proposed by Eurostat, the proportion of land area covered by forests or the forest area under sustainable forest management, considered by UNSCD, plus other parameters that could be calculated with this methodology. Due to the increase of NFI implementation in developed countries, this methodology could even be used to calculate carbon inputs by non-deforestation or degradation in programs like UN-REDD (United Nations incentive for reducing emissions from deforestation and degradation), which is under discussion as a new climate change mitigation tool in the near future.

In this sense, it is necessary to consider that NFI plot analysis only estimates the carbon balance of the above- and below-ground tree biomass pool (Sierra et al., 2007). However, previous research shows that tree biomass plays a key role in estimating the carbon stocks in forest ecosystems because it represents between 40 and 70% for the total fixation in the ecosystems (Nihlgard, 1972; Whittaker et al., 1974; Zianis and Mencuccuni, 2003).

Forest ecosystems store more carbon than other terrestrial ecosystems. Forestation and other management measures to increase forest productivity could capture a significant part of CO_2 emissions (Dixon et al., 1994). Factors such as soil characteristics (Davis et al., 2003; Sierra et al., 2007), site productivity (Arnold et al., 2005), landscape and species composition, stage of stand development (Davis et al., 2003) or age (Lecointe et al., 2006) are important drivers of spatial variation in biomass accumulation and changes (Sierra et al., 2007). In our study, much greater fixation was produced in conifers than in deciduous species in the two regions. Previous studies also showed that, among the different terrestrial ecosystems, conifer forests were major carbon sinks (Gucinski et al., 1995).

In the two areas considered, silviculture was one of the most important factors that produce changes in carbon biomass fixation. Estimates of forest carbon stocks and stock changes are needed so as to know how sequestration might be increased through forest management activities, such as forestation, reforestation, stand management and forest protection (LeMay and Kurz, 2008). By comparing forest carbon stocks, we can obtain information about the impact of practical forestry. The effective practice of silviculture requires an understanding of the major processes in forest ecosystems, such as carbon sequestration dynamics. Through forest monitoring, resource managers can therefore evaluate and optimize different silvicultural scenarios. Harvest rate can be used to detect silvicultural shifts towards specific species and can help us to orientate adequate harvest plans under Sustainable Forest Management, ecosystem service provision and Kyoto Protocol measures (e.g., intensifying harvest in an oak forest to produce fuelwood or reducing harvest rate in other forests to maintain biomass stocks).

Mund et al. (2002) reported that a remarkable increase of forest growth over the past 50 years had been monitored. In our study, the increment produced by inputs (tree growth, ingrowth and new plots) was about 4.10 and 1.63 Mg ha^{-1} year^{-1} in the last decade in ‘Páramos y Valles’ and the Central Mountain Range, respectively. However, high spatial heterogeneity and temporal variability of carbon stocks and fluxes lead to large uncertainties in estimates in the long term. Although most forest ecosystems are currently acting as carbon sinks, Keenan et al. (2008), by using simulation techniques, indicated that European forests could shift from net carbon sinks to net carbon sources in the 21st century. This shift would be more dramatic in Mediterranean forests since the soil water content is lower than in other forest ecosystems and rain water supply dependency is higher. In addition, in the Mediterranean area, uncertainties about forest responses to climate change must be considered (Sabaté et al., 2002) and examined in the future to possibly increase carbon uptake or reduce carbon losses through management (LeMay and Kurz, 2008).

European forests were shown to be a net carbon sink of 0.06 Pg of C year^{-1} and likely to continue at this rate or more for the next century (Milne and van Oijen, 2005). Increases in carbon fixation between two consecutives inventories in different species have been found in several studies carried out in Portugal, France, Spain and Ireland in the Forsee project (Forsee, 2005). Vucetich et al. (2000) found similar results in Scot pine forest ecosystems in a northern latitudinal gradient crossing Poland, Lithuania, Latvia, Estonia and Finland.

In our study, forest ecosystems were also demonstrated to be a net carbon sink. More than three millions Mg of CO_2 were fixed in the ecosystems as inputs between 2NFI and 3NFI periods in ‘Páramos y Valles’, with more than 34 millions Mg of CO_2 in the Central Mountain Range. The fixation percentages produced by species growth between 2NFI and 3NFI periods (around 20%), by ingrowth (between 50 and 70%) in 3NFI and by new plots installed in 3NFI (<20%) were calculated. On the other hand, more than 1 million Mg of CO_2 were lost from the ecosystems by harvests and thinning in ‘Páramos y Valles’, with seventeen million Mg of CO_2 lost in the Central Mountain Range. The total amount of CO_2 lost by natural mortality was small in the two regions. The Net CO_2 balance in the forest ecosystems of the ‘Páramos y Valles’ region was more than 150,000 Mg of CO_2 year^{-1} and more than 1,385,000 Mg of CO_2 year^{-1} in the Central Mountain Range.

In Spanish forest ecosystems, studies on carbon fixation showed a total fixation of 103 Mg of CO_2 ha^{-1} in *Pinus pinea* stands in Andalusia (southern Spain) (Montero et al., 2002) and 150 Mg of CO_2 ha^{-1} and 100 Mg of CO_2 ha^{-1} in *P. pinaster* in Soria (in eastern central Spain) (Osorio, 2005). This last study reported that the fixation of CO_2 in different stands increased from 50 Mg ha^{-1} to 150 Mg ha^{-1} for the planning carried out in the forest. This last point emphasizes the importance of forestry management in the control of carbon fixation. On the other hand, Montero et al. (2004) found higher values in the most productive area of the Central Mountain

Range, 214 and 398 Mg of CO_2 ha^{-1} of fixation total in *P. sylvestris* and *Q. pyrenaica* in 'Matas de Valsain' and 'Pinar de Valsain'. In the Northern Atlantic Spanish region, *Eucalyptus globulus* and *Pinus radiata* fixed 14.8 Mg of C ha^{-1} $year^{-1}$ and 5.7 Mg of C ha^{-1} $year^{-1}$, respectively.

Comparison between two consecutive forest inventories (2NFI and 3NFI) is useful in estimating the carbon balance in different forest ecosystems (both natural and planted stands and oak and pine dominated forests). Over the past years, efforts have been made in the creation of SFM Indicators. This methodology attempts to be a useful tool in the evaluation of carbon fixation in forests. Forest management is interested in quantifying forest carbon stocks on their landscapes and in the influence of carbon sequestration management, because carbon sequestration is a factor that needs to be integrated into current management strategies. This methodology has two advantages: (1) CO_2 balance is calculated in different stand types, considering the inputs and outputs in forest ecosystems and (2) carbon fixation is calculated in a practical, simple form, enabling future projections and analysis of alternative management scenarios through silviculture and harvest rates. However, our results are strongly dependent on available biomass equations, NFI data and wood density and carbon proportion assumptions. Biomass equations will therefore have to be tested and, if applicable, new ones developed to ensure accurate carbon estimation for these species and regions.

Regardless of their geographical location, forests serve multiple environmental, socio-economic, and cultural roles in many countries. They are among the most diverse and widespread ecosystems of the world and provide many significant resources and functions including wood and non-wood products, recreational opportunities, habitat for wildlife, water and soil, support employment and traditional uses and play a crucial role in the global carbon cycle. Quantification of carbon fixation in forest ecosystems is the first step in forest management guidelines in the context of sustainability and biodiversity conservation. New, more detailed biomass and carbon studies could help us to establish baselines and guidelines in different forest types.

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