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Use of native species to improve carbon sequestration and contribute towards solving the environmental problems of the timberlands in Biscay, northern Spain

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ABSTRACT

The rapid transformation of natural forest areas into fast-growing exotic species plantations, where the main objective is timber and pulp production, has led to a neglect of other services forests provide in many parts of the world. One example of such a problem is the county of Biscay, where the management of these plantations has negative impacts on the environment, creating the necessity to evaluate alternative tree species for use in forestry. The actual crisis in the forest sector of the region could be an opportunity to change to native species plantations that could help restore ecosystem structure and function. However, forest managers of the region are using the current interest on carbon sequestration by forest to persist with the “pine and eucalyptus culture”, arguing that these species provide a big C sequestration service. Moreover, they are promoting the expansion of eucalyptus plantations to obtain biomass for the pulp and paper industry and for bioenergy. The aim of this paper is to answer the following questions: Is this argument used by the foresters well-founded? or, could the use of native species in plantations improve the C sequestration service in Biscay while avoiding the environmental problems the actual plantations cause?

To answer these questions we created three alternative future scenarios: a) the Services scenario, where there is a substitution of fast-growing exotic plantations by native broadleaf species plantations; b) the Biomass scenario, where there is a bet on eucalyptus plantations; and c) the Business as usual scenario. The changes in the C stock in living biomass in these scenarios have been simulated by a hybrid approach utilising inventories and models, and the period considered was 150 years.

Our results show that the substitution of existing exotic plantations by plantations of native species has the greatest potential for increasing C sequestration. Although short- and mid-term outcomes may differ, when the long-term (more than 50 years) is considered, the C stock in the living biomass in the Services scenario is the greatest, accumulating 38% more C than the Business as usual scenario and 70% more C than the Biomass scenario at the end of the study period. Thus, changing pine and eucalyptus by native species in plantations, while solving some of the environmental problems of the actual plantations, sequesters more C in the long-term. As C sequestration initiatives only make sense if there is a good chance of long-term persistence of the C stocks created, there is no C sequestration argument for the foresters to continue with the actual policy of the use of fast-growing exotic species.

1. Introduction

In recent decades, global climate change has focused attention on the carbon (C) sequestration service of forestlands, largely due to the Kyoto Protocol stipulating that forest C changes may be used to offset carbon emissions (Finkral and Evans, 2008; Neilson et al., 2006), leading to an increasing worldwide interest in managing forests for carbon sequestration (Woodbury et al., 2007). Several studies have found that growing trees to sequester carbon could provide relatively low-cost net emission reductions for a number of countries (Keleş and Başkent, 2007; Newell and Stavins, 2000). However, many of these studies have largely neglected ecological limitations, trade-offs with other forest products and services or restrictions to implementation (Seidl et al., 2007). The C sequestration service depends on how fast carbon is captured and transformed into biomass by plants, how fast it is lost from the system, how large the stock is when at near equilibrium and for how long the C is captured. The trade-offs between C sequestration service and the provision of other ecosystem services appear when the

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emphasis is mostly on the first of these four points, that is, the speed at which carbon can be removed from the atmosphere by plants (Díaz et al., 2009). Today, there is an increasing international recognition that carbon projects should not compromise other services, such as biodiversity protection (Canadell and Raupach, 2008; Díaz et al., 2009). In fact, the paradigm of sustainable forest management outlined by the Ministerial Conference for the Protection of Forests in Europe (MCPFE, 1998, 2005, 2007) and the United Nations Forum on Forests (UNFF, 2007, 2011), whose main objective is to promote the management, conservation and sustainable development of forests, provides the framework for multipurpose forest management.

Forest ecosystems provide many goods and services such as timber production, flood control, erosion control, water quality, biodiversity, wildlife habitat, carbon sequestration and recreation (Burger, 2009; Costanza et al., 1997; Daily, 1997; Zhang et al., 2007). This recognition of the importance of ecosystem services has increased social and economic demands on both public and private forests, presenting a challenge for 21st-century foresters to manage forests simultaneously for wood, biodiversity, carbon sequestration, energy, water quality, flood control, habitat, and recreation (Burger, 2009). In this context, other objectives beyond timber production and climate protection through C sequestration may be considered important (Seidl et al., 2007). However, the rapid transformation of natural forests into tree plantations, where economic considerations have generally been used to determinate priorities (i.e., timber production), has led to a neglect of the other services forests provide.

In the county of Biscay, northern Iberian Peninsula, most of the timberlands consist of exotic *Pinus radiata* and *Eucalyptus globulus* plantations, with the main objectives of timber and pulp production. The production of timber on these plantations is primarily based on the rotational clear-cutting of even-aged stands. Forest managers have promoted these species due to their relatively simple management, high production, short rotation periods, favourable market demand, and the development of a "pine and eucalyptus culture" among forest managers. However, these monoculture plantations of fast-growing evergreen species, together with the type of management applied, give rise to environmental problems, including soil loss and compaction (Merino and Edeso, 1999; Merino et al., 2004), nutrient loss (Merino et al., 2004), surface water turbidity and supply (Garmendia et al., 2012; Leslie et al., 2012; Poore and Fries, 1985; Rodríguez-Loinaz et al., 2011), and biodiversity loss (Amezaga and Onaindia, 1997; Santos et al., 2006; Schoeneberger, 2009) that have created an increasing social and political concern. Thus, lately the administration has been promoting sustainable forest management by forest certification, and nowadays 27% of the forest plantations in Biscay Province have a PEFC (*Programme for the Endorsement of Forest Certification*) *certification*.

Due to the negative impacts that pine and eucalyptus monocultures have on the environment, there is an urgent need to evaluate alternative tree species for use in production forestry. Furthermore, for decades the success of the forest sector has been based on increasing demand for forest-based products. Today, however, pine plantations are not profitable due to globalisation and the reduction of the demand by the building sector. The prices of pine wood have fallen by around 70% in the last decade (Eustat, 2012). This drop of wood prices has given rise to a crisis in the forest sector. The value of forest production fell by 78% between 2005 and 2010 (Basque Government, 2011). Thus, nowadays these plantations persist thanks to subsidies. The County Council of Biscay subsidizes 40% of the cost of lots of the management actions in plantations, such as the application of phytosanitary products the two first years after planting, the first and second thinning, two fertilizations, biomass recollection, etc. Moreover, 75% of the costs of construction of forest tracks and 30% of the cost of machinery are also subsidized. However, these subsidies have not stopped the reduction by more than 55% of the clear-cutting of pine plantations. As for eucalyptus, despite the drop of the price by more than 25% in the last decade, the plantations are still profitable due to increasing demand from the paper and pulp industry and the clear-cuttings have increased by more than 65%.

This situation could be an opportunity to return to native broadleaf deciduous species with long rotation periods, which can help restore ecosystem structure and function, improving the ecological services provided. However, forest sector attitudes reflect a big resistance to change. In the last years, forest managers of the region have used the current interest on carbon sequestration by forest to persist with the "pine and eucalyptus culture", arguing that these species provide a big C sequestration service (see www.basoa.org). In fact, the actual intention of this sector is to expand eucalyptus plantations to all the areas suitable for this species, neglecting all the environmental problems these plantations cause, to obtain biomass for the pulp and paper industry and for bioenergy.

The aim of this paper is to answer the following questions: Is this argument used by the foresters well-founded? or, could the use of native broadleaf deciduous species in plantation improve the C sequestration service in Biscay while avoiding the environmental problems the exotic species plantations cause? To answer this question, three alternative scenarios have been established: a) the Services scenario, where there is a substitution of the existing pine and eucalyptus plantations by native broadleaf species plantations; b) the Biomass scenario, where there is a bet on *E. globulus* plantations; and c) the Business as usual scenario. The changes in the C stock in the living biomass in these scenarios have been simulated by a hybrid approach utilising inventories and models. The period considered was 150 years, as this period approaches the production turn of the native species.

2. Methods

2.1. Study area

This study was carried out in the county of Biscay (area 2213 km^2), located in the north of the Iberian Peninsula (43° 46′ to 42° 92′ N, 03° 45′ to 02° 40′ W) (Fig. 1). The region has a mountainous topography, except within the water-catchment of

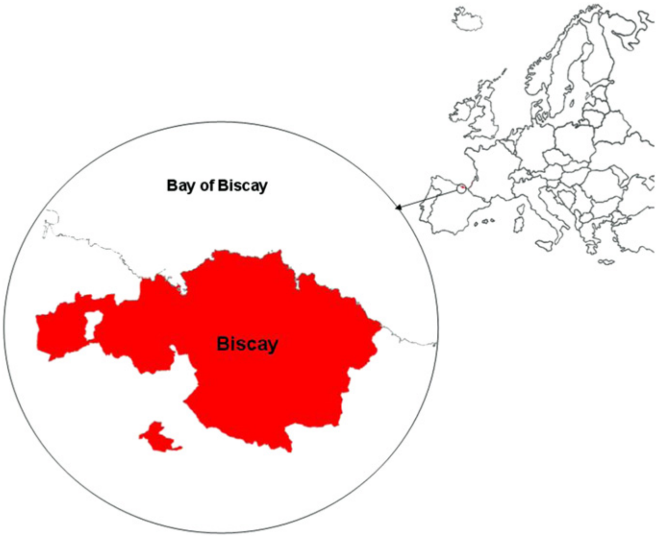

Fig. 1. Location of the study area.

the Ibaizabal River, where Bilbao and other urban nuclei are present. Approximately 50% of the region presents slopes greater than 30%, and the altitude varies from 0 to 1500 m above sea level. The climate is temperate and humid, being regulated by the Cantabrian Sea, which ensures uniformity in atmospheric variables. The principal characteristics of this climate are its slight thermal oscillations (average temperature 12.5 °C), uniform rainfall distribution throughout the year (average annual rainfall 1200 mm), and a relative lack of frost. The main primary forest types in Biscay are Cantabrian evergreen-oak forests (*Quercus ilex*), mixed-oak forests (*Quercus robur*), and beech forests (*Fagus sylvatica*). These forests are the potential vegetation of approximately 80% of the region, but today they only cover 13% of the area (NFI, 2006).

2.2. Scenarios used

Scenarios are widely used in land use planning, climate change analysis, conservation planning and, increasingly, in ecosystem service assessment (Swetnam et al., 2011) because the use of scenarios that describe realistic potential future states can assist decision-making (Peterson et al., 2003).

In this study, three alternative scenarios were defined over a time horizon of 150 years: the Services, Biomass and Business as usual scenarios.

2.2.1. Services scenario

The Services scenario is based on the Triad zoning concept. Triad zoning refers to management at the landscape level for a different set of values in each zone while producing a complete set of values at the forest or landscape level (Montigny and MacLean, 2006). In this scenario, we assume that new land use policies will limit the expansion of pine and eucalyptus plantations in areas with large slopes (>30%) or with erosion risk due to the previously mentioned problems this type of plantation of fast-growing species cause. In these areas, when the existing pine and eucalyptus plantations reach the end of their turn, the native species *Q. robur* and *F. sylvatica* are planted, depending on the altitude, with *Q. robur* plantations established below 600 m and *F. sylvatica* above 600 m. In this scenario, the existing pine and eucalyptus plantations are permitted to persist in areas of low slope and without erosion risk.

With this strategy, ecosystem services such as water flow regulation, erosion control, biodiversity conservation and scenic beauty will be improved in the region and the wood production service will be reduced.

2.2.2. Biomass scenario

The Biomass scenario was considered according to the interests of the forest sector of the province, that is, to bet on *E. globulus* to obtain biomass for the pulp and paper industry and for bioenergy. Thus, we assume that *E. globulus* plantations will be established in all the timberlands suitable for that specie when the existing pine plantations reach the end of their turn. *E. globulus*, being a frost intolerant species, is usually planted in the coastal zones and at low altitudes (Pérez et al., 2006). In the study area, these plantations can expand from the coast up to 15 km to the interior and below 600 m.

In this scenario, the wood production service will be improved in the region, but other services, such as water flow control, erosion control and biodiversity conservation, will be depleted.

2.2.3. Business as usual scenario

In addition to the two alternative scenarios presented above, a “do nothing” variant was simulated as a reference. In this scenario, we assume that when a plantation reaches the end of its turn and is harvested, the same specie is replanted, so it is assumed that the area covered by both species does not change.

In the three scenarios, some assumptions were accepted. The area covered by timberlands does not change within the studied period. Only the planted species change depending on the zone and the scenario. When a plantation is clear-cut, the area is replanted (with the same or different specie depending on the scenario) within a year. We ran all the scenarios over 150 year simulation periods.

2.3. Simulation of C stock changes in living biomass

Detecting management-induced changes in national forest ecosystem carbon balances requires a hybrid approach utilising inventories and models (Lindner et al., 2008). Changes in carbon stocks as a result of land use changes have usually been investigated by means of book-keeping models (Stevens and van Wesemael, 2008). These models construct time-dependent functions of carbon changes upon specific land use changes, which are combined with rates of land use changes. In this paper, forest inventory data supplemented with data from intensive research sites and the CO2FIX V 3.1 model (Schelhaas et al., 2004) were used to estimate carbon stock changes in living biomass in the three selected scenarios.

CO2FIX is a book-keeping model that simulates the stocks and fluxes of carbon in forest biomass, soil and wood products at the stand level. In this paper, we focus on the C stock changes in living biomass (above- and belowground). The biomass module in CO2FIX V3.1 uses empirical relationships between the size of C pools and merchantable wood volume or stand age derived from forest resource inventories and other field measurements. Carbon stored in living biomass is estimated with a forest cohort model that allows competition, natural mortality, logging and mortality due to logging damage. For each time step, living biomass is calculated as the balance between the original biomass, plus biomass growth, minus the turnover of branches, foliage and roots, minus tree mortality due to senescence, minus harvest and minus mortality due to logging. For further details on the CO2FIX model, see Masera et al. (2003) and Schelhaas et al. (2004).

2.3.1. Data and model parameters

Forest inventory data were used to determinate the age of the plantations of the different species and to obtain the area covered by the plantations of each species and each age. These data, in combination with data on slope and soil erosion, were used to obtain the transition matrixes that represent the area of land undergoing each type of transition for each forest type for each time period and for each of the three considered scenarios.

To simulate the C stock change in living biomass, the CO2FIX model uses, as its main input, data on the stem volume growth (m^3 ha^{-1} yr^{-1}); stem wood density (to convert stem volume to mass); the relative growth of the foliage, branches and roots to the growth of the stem biomass; and the intensity and time of the thinnings. In this study, yield tables and stem wood density obtained from plantations of the northern Iberian Peninsula (CPF, 2004; Madrigal et al., 1999) and relative growths of the foliage, branches and roots obtained from the study region (Montero et al., 2005) were used. We used the management regimens (the intensity and time of the thinnings and the rotation periods) commonly used for the selected species in this region (Table 1).

In this work, a constant climate and no natural disturbances were assumed. Excluding these sources of variability allowed us to isolate forest management effects on C stocks in living biomass and to explore the relative differences among the scenarios (Nunery and Keeton, 2010).

Table 1
Management regimens for the considered species used by the forest sector in Biscay.

Plantation	Initial density (trees/ha)	1st thinning		2nd thinning		3rd thinning		4th thinning		5th thinning		6th thinning		7th thinning		Rotation period
		Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	Year	Intensity (trees/ha)	
P. radiata	1600	9	600	13	400	18	200	23	140	x	x	x	x	x	x	35
P. nigra	1600	12	600	23	150	30	225	37	175	45	125	53	65	x	x	60
P. pinaster	1600	10	400	16	300	22	200	26	200	32	175	x	x	x	x	50
E. globulus	1600	x	x	x	x	x	x	x	x	x	x	x	x	x	x	13
Q. robur	1100	30	250	45	350	60	150	75	100	100	100	x	x	x	x	150
F. sylvatica	1600	12	200	25	300	40	300	55	250	70	150	85	150	100	100	120

3. Results

3.1. Land use distribution in the reference year, 2006

In 2006, the timberland cover was 103,695 ha, of which 74,714 ha (72%) comprised *P. radiata* plantations, 3125 ha (3%) comprised *Pinus nigra* plantations, 5095 ha (5%) comprised *Pinus pinaster* plantations, 12,611 ha (12%) comprised Eucalyptus (mainly *E. globulus*) plantations and 8150 ha (8%) comprised other plantations (Fig. 2a). As explained in the Methodology section, in this study, only the plantations of pine and eucalyptus, which represent 92% (95,545 ha) of the timberland, were considered. In 2006, 32% of the *P. radiata* plantations were in a young state, 22% were in the middle of the rotation period, and 46% were at the end of the rotation period. The percentages of the *P. nigra*, *P. pinaster* and *E. globulus* plantations were 52–25–23%, 24–21–55% and 29–60–11%, respectively.

3.2. Land use changes in the different scenarios

In the Business as usual scenario, the area covered by the different species plantations is assumed not to change. In the other two scenarios, the accounted changes were the following.

3.2.1. Services scenario

In the Services scenario, when all the pine and eucalyptus plantations in areas of high slope or with problems of erosion have been replaced by native species plantations, the final land uses are 52,246 ha (54% of the timberland considered) of *Q. robur* plantations, 1692 ha (1.8% of the timberland considered) of *F. sylvatica* plantations, 32,537 ha (43% of the area in 2006) of *P. radiata* plantations, 1420 ha (45% of the area in 2006) of *P. nigra* plantations, 2267 ha (45% of the area in 2006) of *P. pinaster* plantations and 5407 ha (43% of the area in 2006) of *E. globulus* plantations. Most of the new *Q. robur* plantations came from previous *P. radiata* (78%) and *E. globulus* (14%) plantations, while most of the new *F. sylvatica* plantations came from previous *P. radiata* (67%) and *P. nigra* (29%) plantations.

These changes are gradual, and they happen as the different plantations come to the end of their turn. The last species replacement happened in 2066, when the last plantations of *P. nigra*, located in areas of high slope or with erosion problems, came to the end of their turn (Fig. 2b).

3.2.2. Biomass scenario

In the Biomass scenario, when all the sites of the pine plantations suitable for eucalyptus are replaced by the latter, the final land uses are 50,505 ha (400% of the area in 2006) of *E. globulus* plantations, 39,900 ha (53% of the area in 2006) of *P. radiata* plantations, 2000 ha (64% of the area in 2006) of *P. nigra* plantations and 1960 ha (32% of the area in 2006) of *P. pinaster* plantations. Most (90%) of the new *E. globulus* plantations came from previous *P. radiata* plantations.

As in the Services scenario, these changes happen gradually, as the pine plantations located in areas suitable for *E. globulus* come to the end of their turn and are completed by 2066 (Fig. 2c).

3.3. C stock changes in living biomass

The total C stock in the living biomass in the plantations in the reference year is $4.1 * 10^6$ tC, with a mean stock of 45.4 tC/ha for *P. radiata*, 45.4 tC/ha for *P. nigra*, 40.1 tC/ha for *P. pinaster* and 31.4 tC/ha for *E. globulus*. In the three studied scenarios, the total amount of C in the living biomass increases in the first 10 years up to approximately $6.4 * 10^6$ tC. Then, the C stock decreases dramatically because much of the *P. radiata* plantations reach the end of their rotation period and are cut. After 2016, the evolution of the C stock in the three scenarios is quite different (Fig. 3).

In the Services scenario, the minimum C stock in the living biomass ($2.3 * 10^6$ tC) is found in 2030, when most of the *P. radiata* plantations located in areas with steep slopes or with erosion problems are replaced by *Q. robur* or *F. sylvatica* plantations. From that year, the C stock in the Services scenario increases gradually, rising to $7.5 * 10^6$ tC at the end of the study period (2156 year). In the Business as usual scenario, the C stock in the living biomass shows a large fluctuation during the period studied, with maximum and minimum C stocks of $6.6 * 10^6$–$6.3 * 10^6$ tC and $2.4 * 10^6$–$2.6 * 10^6$ tC, respectively. Finally, in the Biomass scenario, the C stock in the living biomass also shows fluctuations, but they are smaller than in the Business as usual scenario, with maximum and minimum C stocks of $5.1 * 10^6$–$4.5 * 10^6$ tC and $1.9 * 10^6$–$2.3 * 10^6$ tC, respectively.

The comparison of the three scenarios in different time periods produced interesting results. In the short- (0–25 years) and mid-term (25–50 years), the total amount of C stocked in the living biomass was lower in the Services scenario than in the other two scenarios (Table 2, Fig. 4a and b), being 4% and 7% smaller in the short-term and 21% and 7% in the mid-term than in the Business and usual and Biomass scenarios, respectively. However, in the long-term (more than 50 years), the opposite is true. In the Services scenario, the C stock in the living biomass is greater than in the other two studied scenarios, with the former accumulating 38% and 70% more C than the Business and usual and Biomass scenarios, respectively, at the end of the study period (110–150 years). When the Business and usual and Biomass scenarios were compared, the C stock in the short-term was 3% greater in the latter, and in the mid- and long-term, it was 18% greater in the former (Table 2, Fig. 4c).

4. Discussion

Forest management decisions, such as species selection, impact the C budget of forested landscapes (Neilson et al., 2006; Kurz et al., 2002; Vallet et al., 2009) in the short-, mid- and long-term as well as the provision of other services, such as water supply and soil protection (Guo et al., 2001). Although other ecosystem services

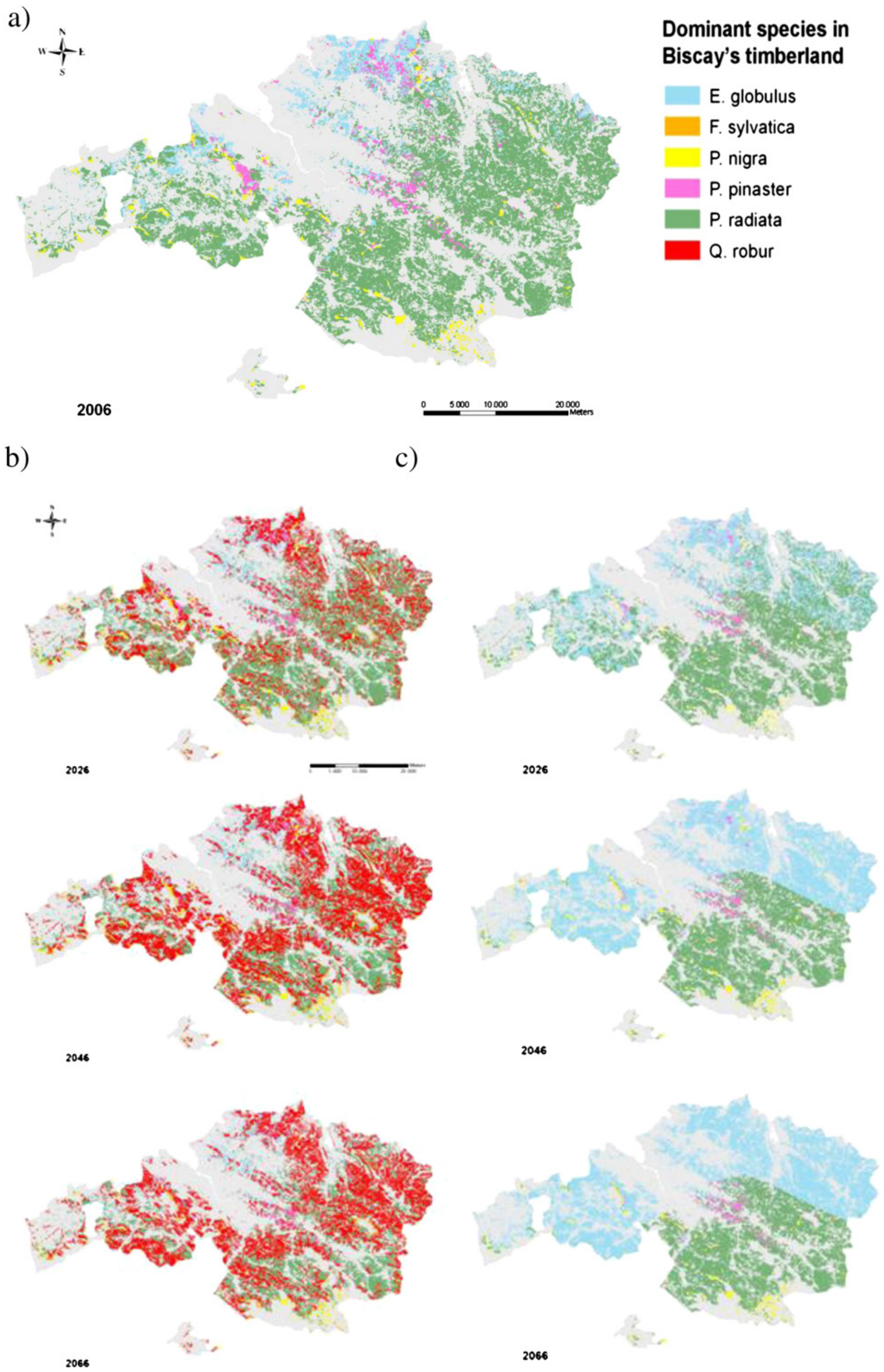

Fig. 2. Timberland distribution in the reference year (2006) (a) and its changes along the study period for the Services scenario (b) and the Biomass scenario (c).

are not analyzed in depth here, it is assumed that water flow control, erosion control, biodiversity conservation and scenic beauty will be improved in the Services scenario and depleted in the Biomass scenario. These assumptions are made based on different reasons. The main problem of the pine and eucalyptus plantations is the impacts they have on the soils during the clear-cutting operations and the soil preparation activities before planting. In these events the top layer of the soil is removed and is left without vegetation, giving rise to important losses of soil, as well as river water turbidity problems. In the years after the mechanised preparation for planting, erosion above 200 t/ha/yr has been measured (Edeso et al., 1997). In the Services scenario, although the plantations could be managed in the same way, these events would happen every 120 or 150 years and not every 13 or 35 years as it is the case for eucalyptus and pine plantations, respectively. Furthermore, planting activities, due to the machinery used, give rise to soil compaction. This fact, together with the hydrophobic characteristics of pine and eucalyptus leaves (De Blas et al.,

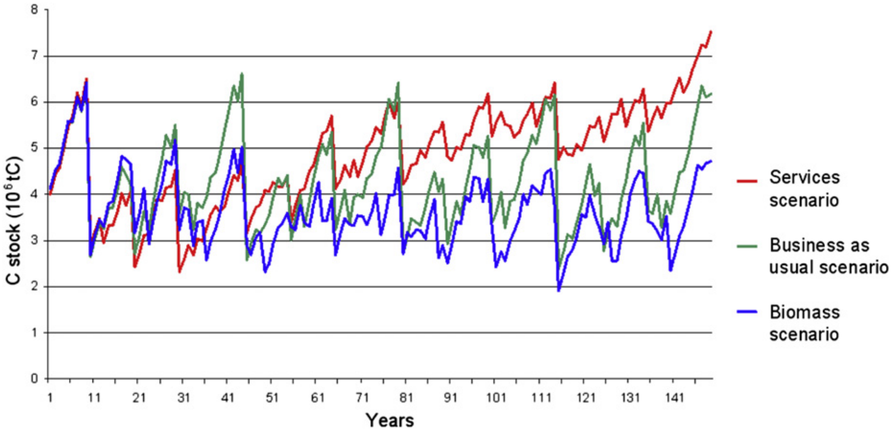

Fig. 3. Evolution of the C stock in living biomass in the three studied scenarios.

2010; Thwaites et al., 2006), reduces the water flow control capacity of these areas. As for biodiversity conservation, these periodic clear-cuttings are important recurrent perturbations that are known to increase the presence of generalist species to the detriment of specialist species (Lauga-Reyrel and Deconchat, 1999; Onaindia et al., 2004). Besides, the perennial nature of these species does not allow the presence of the native forest specialist plant species (*sensu* Rodríguez-Loinaz et al., 2012) that need the spring light to flower (Amezaga and Onaindia, 1997). Finally, the increment of the native species plantations in the Services scenario would create a landscape more diverse that would also improve the scenic beauty of the area.

In relation to C sequestration, results have shown that species selection can make a large difference not only in the previous mentioned services but also in future carbon stocks in living biomass, as has been noted in other studies (Garcia-Gonzalo et al., 2007; Seidl et al., 2007), and that the substitution of existing exotic plantations by plantations of native species in this region has the greatest potential for increasing carbon sequestration. Although the short- and mid-term outcomes may differ, when the long-term (more than 50 years) is considered in the Services scenario, the C stock in the living biomass is greater than in the other two studied scenarios, with the Services scenario accumulating 38% more C than the Business as usual scenario and 70% more C than the Biomass scenario at the end of the study period (110–150 years). Thus, our data indicate that changing pine and eucalyptus plantations to native species plantations sequesters more C in the living biomass in the long-term while improving ecosystem services such as biodiversity conservation, water flow regulation and soil protection.

Climate change mitigation depends much more strongly on the amount and permanence of carbon in the biosphere than on the velocity of its capture (Thomas et al., 2007). Some authors (Cannell, 1996; Redondo-Brenes, 2007) have noted that fast-growing plantations would accumulate carbon more rapidly than slow-growing forests up to the time of harvest, but for long-term storage, slow-growing forests would be preferable because they have higher time-averaged carbon stocks. Their results are consistent with those obtained in this study and in studies performed in other regions (Díaz et al., 2009). Our results show that a shift towards faster-growing species, such as *E. globulus*, not only does not increase C sequestration when accounting is restricted to tree living biomass, but also that the amount of C sequestered is reduced after 45 years. Thus, the argument for C sequestration cannot be used to persist with the “pine and eucalyptus culture” of the foresters in Biscay, as carbon sequestration initiatives only make sense if there is a good chance of long-term persistence of the carbon stocks being created (Díaz et al., 2009; Kirschbaum, 2006; Schulze, 2006).

Would the Services scenario be economically viable? Although in the Services scenario the main environmental problem in timberlands of Biscay would be reduced and the C sequestration service would be improved, the important provision service, i.e. wood production, would be reduced due to the slower growth of *Q. robur* and *F. sylvatica*. As nowadays the wood production is the only service that brings returns to the foresters, this reduction of timber production could be a problem for the establishment of this Service scenario. Hence, an economic viability study of the Services scenario would be necessary. Nevertheless, on one hand, we have to take into account that the production of native species could be supported by the fact that: i) the prices of oak and beech wood are higher than those of the pine and eucalyptus woods (Astrain, 2012); ii) although currently there is not a carbon market as such in Europe, it could be a source of income in a future; and finally iii) as these native broadleaf deciduous species plantations contribute to solve environmental problems that the pine and eucalyptus plantations cause, the money currently used to subsidize pine and eucalyptus plantations could be used to pay for the ecosystem services the native species plantations provide, adding another source of income to the foresters. On the other hand, we do not need to forget that the reduction of this service would happen only

Table 2
Mean difference in the C stock in living biomass among the three scenarios along the period studied.

Scenarios	Period				
	0–25 years	26–50 years	51–80 years	81–110 years	111–150 years
	Mean difference (tC)	Mean difference (tC)	Mean difference (tC)	Mean difference (tC)	Mean difference (tC)
Services vs. Business as usual	−167,606	−1,039,548	439,478	1,223,918	1,537,539
Services vs. Biomass	−315,877	−248,060	1,197,352	1,906,328	2,385,439
Biomass vs. Business as usual	148,271	−744,353	−796,474	−682,410	−847,899

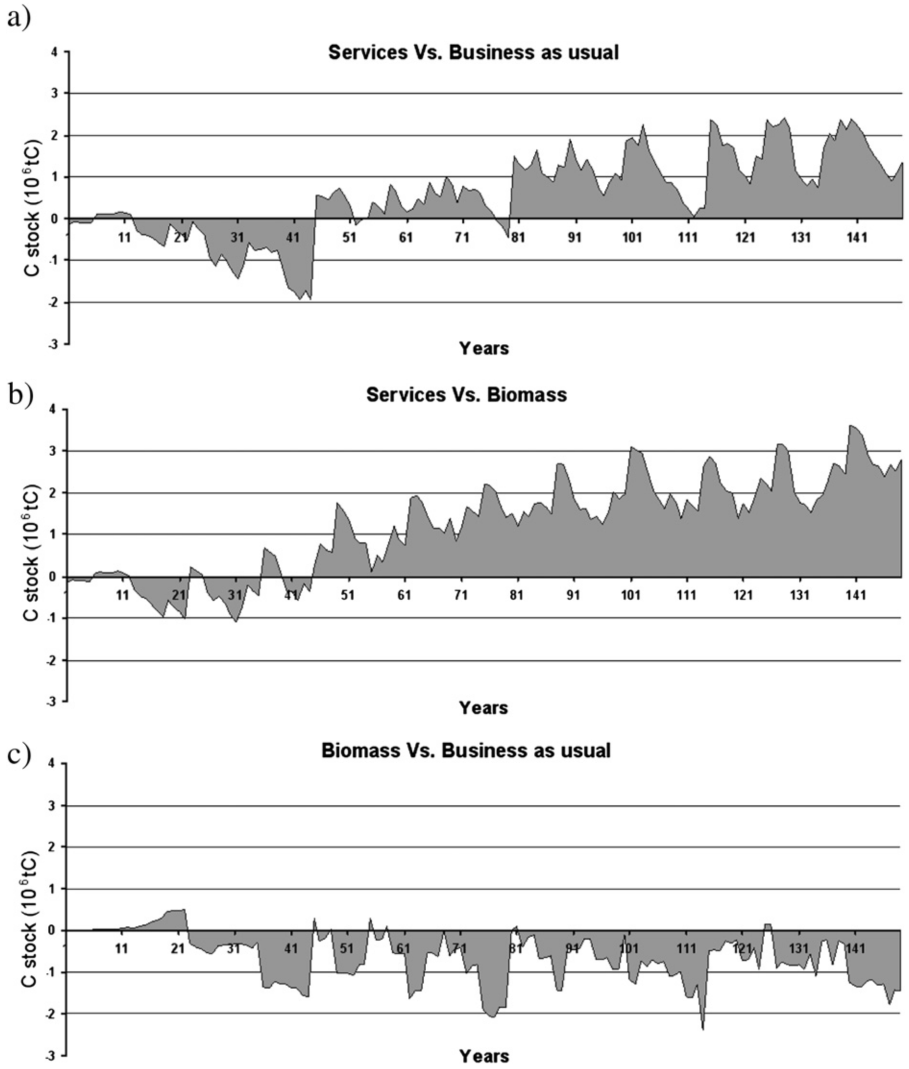

Fig. 4. Evolution of the differences in the C stock in living biomass between the studied scenarios: a) Services vs. Business as usual; b) Services vs. Biomass; c) Biomass vs. Business as usual.

in areas where the fast-growing species is replaced by a slow-growing species. In the rest of the timberland, pine and eucalyptus plantations would persist and would supply in the short- and mid-term the wood demand of the paper and pulp industry and the construction sector of the region.

4.1. Omitted deposits

When evaluating the net carbon balance of forest management activities, it is a good practice to include or to justify the exclusion of the main forest carbon stocks (IPCC, 2003), as is the case in this study. Forest ecosystems include five carbon storage pools: living trees, down dead woods, understory vegetation, forest floor, and soil (Hu and Wang, 2008; Woodbury et al., 2007). In this study, we focused on the carbon sequestration in living trees, although the C sequestered in other pools (e.g., soil) can also be high. Although the majority of carbon in the terrestrial pool is stored below ground in soils (Houghton, 2003; Janzen, 2004; Lal, 2005), the carbon flux in living trees is responsible for the largest carbon sequestration among the five forest carbon pools, which could account for 79–90% of the total carbon sequestration in forest ecosystems (Balboa-Murias et al., 2006; Hu and Wang, 2008; Liu et al., 2006). Furthermore, C storage modelling in the soil entails large uncertainties. For these two reasons, C in the soil has not been included in this study. Nevertheless, we expect the differences among scenarios to be even greater with the inclusion of the soil C because when land use changes take place, the major C stock changes in the soil occur in the top layer. Data obtained from more than 600 studies in the studied region show that the mean C stock in the first 30 cm of soil in eucalyptus plantations, *P. radiata* plantations and *Q. robur* forests were 62, 77 and 84 tC/ha, respectively (unpublished data).

In this study, understory and herbaceous layers were ignored because C estimates could not be generated for this portion of the studied forest ecosystems. In addition, the C contained in these understory components is often ignored in biomass estimates due to the low carbon content of this compartment in forests (Birdsey, 1992; Woodbury et al., 2007; Zhang et al., 2007). The same happens with the carbon stock in dead organic matter. Although this pool is subjected to change in the different scenarios, its changes were not estimated due to the unavailability of data and the lower change rate relative to living tree biomass (Chen et al., 2009).

To sum up, this work is not comprehensive in its account of all the processes in the C cycle that are at work in the forest. However, it represents a first step towards integrating C sequestration and the provision of other services in forest management plans.

4.2. Uncertainty in the projections

It is difficult to make accurate estimates of forest biomass or carbon stocks because there are many uncertainties. In this study, the CO2Fix model was used to simulate the C dynamics in the living tree biomass of timberland in Biscay. The uncertainties associated with this approach arise mainly from three sources: (i) the precision of the input data, (ii) the natural variation that exists among stands across a large area, and (iii) simplifications in the model design. With regard to (i), Nabuurs et al. (2008) showed that the parameters of the stems, as net annual increment data, have by far the highest influence on the outcome. In this study, yield tables and wood densities for the different species have been obtained from forest inventories and other field measurements of the study region, where long-term measurement series in permanent plots have been made. This method is generally considered to be highly reliable (Nabuurs et al., 2008). Nabuurs et al. also noted that generally there are fewer data for the other tree organs, creating a rather large overall uncertainty. To reduce this problem, in this study the relative growths of the foliage, branches and roots at the different ages for all the species obtained from the study region were used (Montero et al., 2005).

In regard to (ii), natural variability is not captured by CO2FIX, which can be a problem when a study is restricted to a stand at a specific place. However, in a study that takes place at the landscape scale, this factor has less relevance because spatial variability is captured in the forest inventories used to obtain the yield tables. To verify the accuracy of the results obtained with CO2FIX, we compared the modelled C stock in the living trees for the starting year with the C content in living trees obtained from the inventory data of that year (Loaiza et al., 2010). The modelled C stock was $4.1\ ^{*}\ 10^{6}$ tC and that obtained from the inventory data was $4.5\ ^{*}\ 10^{6}$ tC; thus, the difference between modelled and real stocks was less than 10%.

In relation to the simplicity of the model design, i.e., (iii), it is true that stochastic events such as C losses caused by storms and fires and the effects of climate change are not captured by the model. Warming due to climate change has been projected to have complex effects on forest growth, harvest, and disturbance (IPCC, 2007); however, due to the inability of the model to simulate these effects and the lack of data to use a process model, a constant climate and no natural disturbances were assumed in this study. Nevertheless, incorporating the effects of climate change was not within the scope of our study.

Hence, our results are to be considered as preliminary indications under stable environmental conditions and without risk. While we recognise the uncertainty inherent to this approach, it is consistent with previous modelling work that also focused on the relative differences among forest management trajectories (Eriksson et al., 2007; Nunery and Keeton, 2010; Seidl et al., 2007).

5. Conclusions

Despite the abovementioned limitations of the study, it can be concluded that considering the negative economic situation of the forest sector in Biscay, there is now an interesting opportunity for a change in forestry management. Our results have shown that the replacement of fast-growing species in unsuitable sites, i.e. erosion risk areas, by native broadleaf deciduous species such as *Q. robur* and *F. sylvatica*, would sequester more C in the living biomass, while reducing the environmental problems created by these plantations satisfying public demands. Thus, there is no C sequestration argument for the foresters to continue with the actual policy of the use of fast-growing exotic species in plantations. Nevertheless, as the use of native species would reduce the wood production, that is nowadays the only service that brings returns to the foresters, there is a need for an economic viability study of this management strategy, which may need to be supported by the administration, for example through the payment for ecosystem services.

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