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Species substitution for carbon storage: sessile oak versus Corsican pine in France as a case study

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Abstract

Species choice is potentially an important management decision for increasing carbon stocks in forest ecosystems. The substitution of a slow-growing hardwood species (*Quercus petraea*) by a fast-growing conifer plantation (*Pinus nigra* subsp. *laricio*) was studied in central France. Simulations of carbon stocks in tree biomass were conducted using stand growth models *Fagacées* for sessile oak and *PNL* for Corsican pine. The changes in soil carbon were assessed using the *Century* model and data from two European soil monitoring networks: 16x16 km grid and RENECOFOR. Carbon in wood products was assessed with life cycle analysis and lifespans of final products. However, only carbon stocks and their variation were accounted for: effects of energy-consuming materials or fossil fuel substitution are excluded from the analysis. To compare the growth of these two types of forest stands, an important part of the study was to assess the productivity of both species at the same site, using National Forest Inventory data.

Simulations showed that (*i*) this species substitution would lead to an additional carbon storage of 1.6 tC/ha/yr with the conifer plantation during its first rotation (64 years) (*ii*) at steady state, the time-averaged carbon stock of the conifer plantation over the whole rotation would be 42 tC/ha to 47 tC/ha lower than that of the hardwood even-aged forest, depending on applied silvicultural scenarios. The time-averaged carbon stocks including vegetation, soil and wood products are 221 tC/ha for sessile oak, and around 175 tC/ha for Corsican pine. The amount of carbon stored in wood products is low compared to the total carbon stock (5% for sessile oak, 8 to 8.5% for Corsican pine), mainly due to important losses during early wood processing, and to the short lifespans of wood products compared to the rotation length of forest stands.

Keywords

Carbon stock, species substitution, Quercus petraea, Pinus nigra subsp. laricio, biomass, soil, wood product

Introduction

Forest ecosystems can play a role in carbon storage to reduce atmospheric carbon dioxide in several ways. It is possible *(i)* to increase the areas covered by forests in order to increase the carbon stocks in terrestrial biomes, *(ii)* to change forest management options to store more carbon in already forested areas, and, *(iii)* to substitute fossil fuel by biomass or energy-intensive materials by construction timber (Cannell, 1995; Lindner, 1998). Species selection is one of the forest management options for increasing carbon stocks. Cannell (1996) pointed out that on the one hand fast-growing plantations would accumulate carbon more rapidly than slow-growing forest up to the time of harvest. On the other hand, for long time storage, slow-growing forests would be preferable as they have a higher time-averaged carbon stocks. Several studies have shown that species substitution induced by replacing primary or old-growth forests by plantations leads to a loss of carbon (Cropper and Ewel, 1987; Fleming and Freedman, 1998; Schroth et al., 2002; Erb, 2004), even when wood used in building structures is included in the models (Harmon et al., 1990). Beyond these general results, there is a lack of information about the carbon storage impact of species substitution in a large range of realistic situations of site productivities and silvicultural options.

Substituting species will imply changes in carbon stocks in both belowground and aboveground vegetation, but also in soil organic matter and in wood products. Carbon in wood products is complicated to assess (Karjalainen et al., 1994; Liski et al., 2001). Nevertheless, it has to be to taken into account since products from two different species have specific market destinations and lifespans (Dewar and Cannell, 1992; Karjalainen et al., 2002; Marland and Marland, 2003). The soil carbon content and changes with silviculture are also difficult to estimate as show *e.g.* the review of Yanai et al. (2003). But the changes in soil carbon could be high (Liski et al., 2002; Peltoniemi et al., 2004) and also should be assessed.

The objective of this article is to assess the impact on carbon stocks due to species substitution. We studied the replacement of sessile oak (*Quercus petraea* Liebl.) high forests issued from natural regeneration by Corsican pine plantations (*Pinus nigra* subsp. *laricio*) in central France (*Centre* and *Pay*s *de la Loire* regions). Within this area, according to the *Inventaire Forestier National* (National Forest Inventory, NFI), sessile oak is the main species, and occupies 327 000 ha, which represents

18% of the national resource for this species (Belouard, *pers. comm.*). This substitution is already practiced for production purposes. Corsican pine is appreciated by forest owners for several reasons. It is well adapted even on poor sites and yield can reach up to 20 m^3/ha/year, with stems of remarkable straightness and good wood quality (Riou Nivert et al., 2001). If proven and substantial, carbon sequestration could be an additional benefit of this species substitution.

This article illustrates the utility of coupling models to address issues for which field measurements cover much too long a time interval to be useful for decision-making needed in the short-term. The study was carried out by coupling models that allowed estimating the changes in carbon of the four compartments for both species (below- and above-ground vegetation, soil organic matter and wood products). We focussed on the carbon stocks and their variations, and did not take into account the effects of energy-consuming building materials and fossil fuel substitution by wood, which would be a valuable continuation of our study. In order to help decision-making at the stand level, we needed to estimate the productivity of both species at the same site, and to consider silvicultural scenarios that are prescribed for either species. Productivity assessment has been carried out by using NFI data to estimate site index in relation to environmental factors and the indicator value of understorey vegetation as did Seynave et al. (2005) for Norway spruce. Silvicultural scenarios were chosen as recommended in guides.

Material and methods

Model chains were built for both sessile oak and Corsican pine to assess the changes in carbon stocks in the four following compartments: below- and above-ground vegetation, soil organic matter and wood products. Stand biomass is controlled by silviculture and predicted by stand growth models. At each growth cycle, models update the diameter distribution (through tree diameter growth and mortality) and individual heights. All tree and stand characteristics, including carbon stock in biomass, can be computed. Stand dynamics is guided by a dominant height curve (dominant height: mean height of the 100 largest trees per hectare). Site productivity for each species is expressed by site index, which is the dominant height at a reference age (West, 2004). One of the most difficult parts of this work was to assess site index of the alternative species (Corsican pine) knowing the characteristics of the previously settled sessile oak stand. The solution to this problem is discussed in the "compared site indices" section. To simplify the study, simulations were carried out under stationary environmental conditions. Therefore, long-term growth changes documented for other species in France (Bontemps et al., 2005) were not taken into account. The differential responses of both species to hazards (windfalls, droughts, fires, insects…) were ignored due to a lack of similar quality response functions. Hence, our results are to be considered as preliminary indications, under stable environmental conditions and without risks.

1 – Compared site indices and site type selection

The site index definition used in this article for sessile oak even-aged forests is dominant height at the age of 100 years (Duplat and Tran-Ha, 1997). It will be referred as H_{100}. As the rotation for Corsican pine is shorter, here site index is the dominant height at the age of 30 years (Lebourgeois et al., 2000) and will be noted H_{30}.

The assessment of the site index of both species at the same site was made possible by combining previous studies on Corsican pine productivity in Central France (Gilbert et al., 1996) and NFI data. On one hand, Gilbert et al. (1996) established a determination key to assess H_{30} for Corsican pine, depending on environmental factors and ground vegetation. This determination key splits the geographical area into 35 site types. Among them, the installation of Corsican pine stand is possible for 15 types, but is not recommended for the other ones. The environmental factors needed are available in the NFI data (ground flora composition, soil profile description and annual rainfall). Thus, with this determination key, it is possible to assess the expected value of Corsican pine H_{30} for all plots inventoried by NFI, in particular those occupied by sessile oak high forests. On the other hand, for inventoried sessile oak stands, the NFI measures all tree circumferences and heights in the plot as well as the age of one or two trees by diameter class (small, medium and large trees). Hence, it was possible to select plots only in even-aged forest, to calculate stand age and to estimate dominant height based on the population of the 100 thickest trees per hectare. Finally, stand age and dominant height were used to estimate H_{100} for each sessile oak stand using the growth curve cluster of Duplat and Tran-Ha (1997).

The selected NFI plots matched the following criteria: *i)* Geographical area: *Cher*, *Loir-et-Cher*, *Maine-et-Loire*, *Mayenne* and *Sarthe* administrative district (south west of Paris), that represents almost 6000 km^2 of forested land, *ii)* sessile oak stands (sessile oak as predominant species), *iii)* all stands reported as even-aged forests, and, *iv)* having data on ground flora composition, soil profile description and annual rainfall. 440 stands corresponded to the above criteria.

The dominant height × age couples for sessile oak stands are shown on Figure 1. Using the growth curve for sessile oak dominant height given by Duplat and Tran-Ha (1997), the site index H_{100} was calculated. The stand condition, climatic factors and the ground flora composition of all the 440 sessile oak stands were used to assess the relevant site type according to the Gilbert et al. (1996) determination key. Finally, for each site type, we produced an estimation of the mean site index for both Corsican pine and sessile oak (Table 1).

The more relevant site type to study the species substitution was chosen to fulfill the following conditions : *(i)* installing Corsican pine is possible according to environmental factors *(ii)* the site productive capacity for Corsican pine is high compared to that for sessile oak stand, and, *(iii)* there are lot of sessile oak stands that could be replaced by Corsican pine. Given these criteria, the site type chosen for this study is *L7a* (Table 1). This corresponds to a site with a silty soil, without limestone, without strong presence of acidophilous vegetation, and with high precipitation (>780mm/yr) or adequate soil water conditions. The mean site indices for this site type are H_{30} = 15.7 m for Corsican pine and H_{100} = 24.2 m for sessile oak.

2 – Trees

The vegetation modeled in this study was that of the stand's main species. Understorey and the herbaceous layer were ignored. This simplification is justified by the low carbon content of this compartment in the French forests, estimated at 4% by Dupouey et al. (1999).

2.1 - Stand growth simulation

Sessile oak growth was simulated using the *Fagacées* growth model (Dhôte and de Hercé, 1994; Dhôte, 1996, 1997), and the *PNL* model for Corsican pine (Meredieu, 1998). Both models are implemented in the *CAPSIS* software (version 4.1) (de Coligny et al., 2003). *Fagacées* and *PNL* are distance independent models designed to simulate thinnings of different intensity and type (low or crown thinnings).

The forest management options chosen for both species corresponded to the silvicultural regimes advised by the *Office National des Forêts* (ONF, French Forest National Office). For sessile oak, this silvicultural scenario (Jarret, 1996) leads to a 204-year rotation to obtain a dominant diameter of 70 cm. For Corsican pine, two silvicultural scenarios (Riou Nivert, 1996) were simulated. The first one, noted as "intensive", aims at producing good quality wood (without nodes) in a short time (mean diameter = 50 cm, 200 stems/ha) with 3 prunings when dominant heights are 6, 9 and 12 meters. The second one, noted as "structure", aims at producing wood for building structures. The silvicultural objective is to obtain a mean diameter of 40 cm for 300 stems/ha. Rotation lengths for both Corsican pine silvicultural systems are 64 years (intensive) and 61 years (structure). The number of stems vs. dominant height curves are shown in Figure 2, and the main stand characteristics at the time of final harvest are given in Table 2.

2.2 – Carbon calculations

The carbon content of the ligneous part of the vegetation is assessed using volume equations, basic density at the ring level equations, and the carbon concentration in dry matter.

The volume equations used estimate the total aboveground volume over bark (Vallet et al., 2006). For sessile oak, equation [1] was calibrated with a 1222-trees database, with a 4 cm to 89 cm diameter range.

$$v_{tot} = \left(\frac{1}{40000\pi} . c_{130}^{2} . h_{tot} \right) \times \left(0.471 - 0.000345 \times c_{130} + 0.377 \times \frac{c_{130}^{\frac{1}{2}}}{h_{tot}} \right) \qquad [1]$$

where c_{130} is circumference in cm, h_{tot} total height in m, and v_{tot} total aboveground volume in m^3.

For Corsican pine, Vallet et al. (2006) showed that the same volume equation could be used for pines of different species, even if their diameter and height ranges are different. We checked their pine volume equation (equation [2]), fitted with a 389 Scots pine and 297 maritime pine database, on an independent 77 Corsican pine total volume database (Figure 3a and 3b).

$$v_{tot} = \left(\frac{1}{40000\pi} . c_{130}^{2} . h_{tot} \right) \times \left(0.311 - 0.000405 \times c_{130} + 0.340 \times \frac{c_{130}^{\frac{1}{2}}}{h_{tot}} \right) \times \left(1 + \frac{191.0}{c_{130}^{2}} \right) \qquad [2]$$

The *Fagacées* and *PNL* growth models provide mensurational values of all trees (circumference and height) at each simulation step (3 years for *Fagacées*, 1 year for *PNL*). This allows using ring-level basic density models, applied to the volume of the considered ring. The ring characteristics vary with silviculture. Thus, a ring-level model for basic density is more interesting than a general, species-specific coefficient as it allows taking the influence of the silviculture into account. The ring volume was assessed by difference of total aboveground volume estimations (equations [1] and [2]) between two successive steps.

The basic density model for Sessile oak (equation [3] and [4]) is a simplification of a previous work by Le Moguédec (2000), and was fitted with a database of 7 483 measurements. For sessile oak, basic density is bounded by 355 and 859 kg/m^3. If the predicted value falls outside the [355 - 859] kg/m^3 interval, the value is fixed at the lower or upper margin. For Corsican pine, basic density equation is given by equation [5]. This model (Leban et al., 1998) is the fixed part of a model with fixed and random variables developed on a database of 13 104 measurements.

$$bd = 574.63 - 0.676 \times age_c + \frac{22.61}{rw} \quad \text{(for heartwood)} \qquad [3]$$

$$bd = 533.29 - 0.676 \times age_c + \frac{22.61}{rw} \quad \text{(for sapwood)} \qquad [4]$$

$$bd = 352.3 + 3.42 \times age_c + 92.09 \times \frac{age_c}{age_t} - 5.27 \times rw \qquad [5]$$

where *bd* is the basic density (kg/m^3), age_c is the cambial age (ring age counted from the pith), age_t is the age of the tree and *rw* is the ring width (mm).

Root biomass is often assessed using biomass expansion factors (Schroeder et al., 1997; Dupouey et al., 1999; Lehtonen et al., 2004; Van Camp et al., 2004). We preferred using allometric relations with diameter as the independent variable, in order to avoid compounding errors and to take into account differences between silvicultural scenarios. An allometric relationship for the estimation of sessile oak coarse root biomass was developed by Drexhage et al. (1999). This equation [6] was fitted on 55 sessile oak root systems of trees from 7 to 17 cm diameter at breast height. No data from larger sessile oak trees where found in literature. Before using this relation in extrapolation for larger trees, we checked with 8 measurements of beech root systems up to 47 cm diameter at breast height

(Pellinen, 1986) that the model by Drexhage provided biomass of an appropriate order of magnitude. Of course, this is a rough indication of correctness, rather than a rigorous evaluation, due to the different root system morphologies of these hardwood tree species (taproot for Oak, heart-shaped system for Beech, Köstler et al. 1968).

$$\log_{10}(biomass) = -1.56 + 2.44 \times \log_{10}(dbh) \qquad [6]$$

where *biomass* is dry matter root biomass in kg, and *dbh* is diameter at breast height in cm.

For Corsican pine, no allometric relation was available to estimate root biomass. Zianis et al. (2005) reviewed many equations to estimate trees or part of trees biomass: seven relations developed for Scots pine roots might have been applied to Corsican pine. Laiho and Finer (1996) developed allometric relations for trees from 4 cm up to 24 cm diameter at breast height in Finland, but their model predicted an unreasonable large root biomass for larger trees. Other relations (Santantonio et al., 1977) had been fitted on a too narrow size range to be applied over a whole rotation. The equation by Mälkönen (1974) predicted a biomass much lower than all other ones. Because these results were not convincing, the Drexhage model for Oak was tested. It gave results inside the cluster of Scots pine root biomass curves in the Zianis review (Figure 4). As a consequence, the Drexhage et al. (1999) model [6] was preferred for both species. The consequence of using such a model was checked *a posteriori* by calculating the time-averaged, stand level root expansion factor (root biomass / aboveground biomass = 0.26). This root expansion factors is close to the value given by Dupouey et al. (1999). Moreover, a sensitivity analysis (see below, in the results and discussion section) showed that the use of the various Zianis review equations instead of the Drexhage equation would not change our main conclusions.

Löwe et al. (2000) reviewed the carbon content of dry matter estimations used by European countries for their national forest carbon reporting. The values range from 0.43 (conifers in Portugal) to 0.519 (pine and spruce in Finland). They are generally the same for different species within a country, and do not differ between conifers and hardwoods. The figure used in this article is 0.475, corresponding to the value used in Loustau (2004) for the French national carbon reporting.

Leaf carbon is counted using the mean values of dry matter for deciduous species (3.1 tDM/ha) and for coniferous species (7.3 tDM/ha), also taken from Loustau (2004), which were multiplied by the carbon content of leaves and needles calculated using the RENECOFOR data (Ulrich et al., 1994). Those percentages are 52.9% for coniferous and 50.8% for broadleaved species (Vallet, 2005), and the resulting values are 4.13 tC/ha for coniferous and 1.57 tC/ha for broadleaved species.

In the simulation, all the trees are either thinned or harvested, and we did not take into account decaying trees on ground. Deadwood not included in litter is not taken into account either.

3 – Soil carbon

Soil carbon was estimated using a soil carbon dynamics model and large database to estimate the inputs needed to the soil model. The selected model was *Century* (Parton et al., 1987; Parton et al., 1994). The database used were obtained from the French part of the European soil monitoring network with a 16x16 km grid (Vanmechelen et al., 1997; Badeau, 1998), and from the RENECOFOR network (Brêthes and Ulrich, 1997; Ponette et al., 1997). Altogether these two networks have 701 plots.

The inputs and parameters needed for the *Century* model are *(i)* average climatic data (rainfall, temperature, evapotranspiration), *(ii)* soil silt + clay fraction, *(iii)* amount of carbon input (leaves, twigs, root turnover…), and, *(iv)* lignin / nitrogen ratio of input.

The climatic data were obtained using the *Aurelhy* model of *Météo France* (Bénichou and le Breton, 1987). This model gives monthly, normal values of climatic variables at each location of a systematic grid (1 km). The normal values refer to the 1961 – 1990 period.

The silt + clay fraction had to correspond to the conditions of the study. The value used is the mean value of all soil observations of the systematic 16x16 network where species is oak and location is within the studied area (*Centre* and *Pays de la Loire* regions). This value is 55.5%.

It is especially difficult to assess the root turnover and the root system decomposition which both are large carbon inputs to the soil. To solve this problem, the *Century* model was numerically reversed to calculate the carbon inputs for each species (belowground and aboveground together) which lead at steady state to the mean soil carbon value of the 16x16 and RENECOFOR database, using all the values corresponding to the considered species, and calculated from humus layers down to 60 cm depth. The carbon input values obtained are 3.900 tC/ha/yr for sessile oak and 3.456 tC/ha/yr for Corsican pine. This method allows the calculation of input values that are reliable for several decades in simulations; however, intra-rotation variations are suppressed.

The lignin / nitrogen ratio is often given in literature as it is an indicator of decomposition rate. However, decomposition of sessile oak and Corsican pine elements have hardly been studied. The values used in this article are the mean value of all the values found in literature, grouping sessile oak and pedunculate oak together (Table 3).

Knowing the parameters and inputs for both species, a first run of the *Century* model was conducted with sessile oak values until steady state. The resulting values for soil carbon are then used as the initial state for a second run to assess the dynamics of soil carbon after species substitution.

4 – Wood products

The harvested trees are supposed to be used as wood products, except branches and twigs under 7 cm diameter, which are supposed left on the stand. Wood products were classified in five groups: 1) paper and cardboard, 2) energy wood, 3) construction (building structures, scaffolding, formwork…), 4) furniture, 5) handling (wooden pallets, wooden cases, crates…). The product life cycles of each group were described in Paquet and Deroubaix (2003). The times spent in the first and second industrial processes (from log to board, then from board to final product) as well as in the final utilization are mentioned. The efficiency of these processes for each group are from Selmani (1992) (about 50% for the first and 80% for the second, depending on the product group). Analysing the whole product life cycles (Vallet, 2005) allows to calculate the lifespan expectancy of a log assigned to one kind of product, including all losses during the processes, and considering recycling in paper or cardboard or energy use (Table 4). These lifespans are different from the lifespan of a final product. The survival function for the carbon stored in wood products is of the Weibull type (Saporta, 1990), which is often used in material reliability. The Weibull law expectancy corresponds to the lifespan of the wood product group.

It was assumed that the allocation of wood into the five product groups is different between sessile oak and Corsican pine, but that lifespan is the same for both species once a log is assigned to a group.

For sessile oak, the allocation depends of the mean diameter of the log according to the rule of Flammarion (1986) given in Table 5. Then, slicing, cabinet working, fine joinery and ordinary joinery were assigned to furniture, and framework, flooring and sleepers were assigned to construction. To take into account the carbon stocks in wood products for sessile oak, a stem taper for this species (Dhôte et al., 2000) was used on each harvested tree. Stem taper allows making logs 2 meters long with each harvested tree and to assess their mean diameters in order to divide them following the rule of Flammarion described above.

For Corsican pine, the allocation of harvested trees between different products (Meredieu et al., 1999) was done using the *WinEpiFn* software (Houllier et al., 1995). This software allows assessing the logs and then cutting them into boards (dimensions and quality) that could be obtained from a Corsican pine tree knowing its characteristics (stem taper, branch characteristics). These boards are then assigned to the five different product groups according to the wood uses for this species reported in (CTBA, 1994; ARBOCENTRE, 2005). The uses of Corsican pine wood are joinery, construction and handling with the percentages described in Table 6.

Results and discussion

The impact of species substitution on carbon stocks in the abovementioned conditions can be analysed for the steady state and transient state. The steady state is obtained when the same silviculture is repeated many times. The transient state is the dynamic that will occur after species substitution and that will lead to the steady state. We recall that for these two types of simulations the environmental conditions were regarded as stable.

1 – Steady state

For the steady state analysis, the more relevant figure to make a species comparison is the time-averaged carbon stock for all the compartments over the whole rotation (Figure 5). The average carbon stock was estimated at 221 tC/ha for sessile oak and 179 tC/ha or 174 tC/ha for Corsican pine with intensive or structure scenarios. The amount of soil carbon was almost the same in the three cases: 93tC/ha. Litter production was higher for sessile oak than for Corsican pine (3.900 tC/ha/yr and 3.456 tC/ha/yr). However, the lignin / nitrogen ratio was higher for Corsican pine (Table 3). Litter production and lignin / nitrogen ratio effects compensate, leading to the same value of soil carbon. It represents 42% of total carbon in sessile oak, 52% and 53% in Corsican pine. One would think that under a pine system, with higher growth rates and less decomposable needle, carbon stocks in soils would be higher. However, the database we used to calculate these stocks contain 172 oak sites and 135 pine sites, which give confidence in the result. If soil carbon stocks are usually higher under pines or spruces or firs than under oaks, it could also be partially due other factors, such as climate or pedologic conditions. As we considered species substitution on the same site, the other factors are kept the same here. Moreover, soil carbon variability is very high, and we can find opposite results in literature. For example, Nabuurs and Schelhass (2002) compared 16 forests systems across Europe, and had four pine systems (Scots pine and Maritime pine) and one sessile oak system. The soil carbon content under oak was higher than all the four pine systems.

The percentage of carbon in wood products was low: 5% in sessile oak, 8.5% and 8% in Corsican pine. The higher percentage in Corsican pine is due to a shorter rotation, and to a higher proportion of construction wood. The total carbon stock differences between both species are mainly in the aerial and root biomass (117 tC/ha for sessile oak vs. 71 tC/ha and 67 tC/ha for Corsican pine).

The replacement of sessile oak even-aged forest by Corsican pine plantation would lead to a 42 tC/ha to 47 tC/ha lower mean carbon stock at steady state depending on the silvicultural hypothesis for Corsican pine (figure 5).

2 – Transient state

The dynamics of carbon stock for both Corsican pine silvicultural regimes were similar to each other. As a consequence, only the results for the intensive silviculture are shown for transient state analysis (Figure 6). The Corsican pine rotation is about three times shorter than the sessile oak one (64 years vs. 204 years). Yet, the productivity of Corsican pine is higher than that of sessile oak. This leads to a same maximum value of carbon stock at the end of rotation for both species (about 290 tC/ha).

After the first rotation of Corsican pine, the short time the carbon is stored in wood products implies that carbon rapidly returns to the atmosphere and the total carbon stock falls down to about 110 tC/ha, 80 years after the species substitution. The changes in carbon stock in the case of sessile oak is marked by a longer rotation, slower dynamics and a much longer proportion of time spent at adult stages with high levels of carbon stock. These differences in stand management explain the ranking of the time-averaged mean stocks exposed beforehand.

Thus, at the end of the first rotation of the Corsican pine, its carbon stock is 102 tC/ha higher than in the case of sessile oak, which corresponds to a mean additional uptake of 1.6 tC/ha/yr during 64 years.

Pine plantation forestry in France benefits from progress in silviculture and genetic improvement, in particular for Maritime pine in the *Landes* region. The highly appreciated Corsican pine could follow the same trend. The likely impact for this study would be a shorter rotation length, which would still accentuate the difference between sessile oak and Corsican pine at the end of the first rotation, but should not change the result obtained for the steady state.

3 – Reliability of the carbon estimations

The method used in this article was to combine different equations to create model chains, one for sessile oak and one for Corsican pine, to estimate the dynamics of carbon stocks. Both *PNL* and *Fagacées* growth models have been validated in previous works with independent data. *PNL* was validated in a work of Belingard et al. (2002), and *Fagacées* was validated in a work of Nepveu and Dhôte (1998) for various silvicultural conditions.

The sessile oak volume equation was fitted to a large data set (1222 trees) containing a wide range of diameters and heights ; the quality of predictions was evaluated for national-scale carbon reporting in (Vallet et al., 2006). For pine, the volume equation used was fitted to 389 Scots pine and 297 maritime pine, and we checked that this equation was also well adapted for Corsican pine (Figure 3a and 3b). The double entry type (circumference and height), as well as the presence of a variable representing tree hardiness (variable $c_{130}{}^{0.5}/h_{tot}$) in both volume equations [1] and [2], give a good robustness to the method for addressing various silvicultural conditions. For volume as for basic density models, the fitting material were large databases covering the region under study. However, the recent reviews of Zianis et al. (2005) and the addendum of Muukkonen and Mäkipää (2006), compiling 607 biomass equations and 230 volume equations from the literature, illustrate the lack of information concerning sessile oak and Corsican pine. A more in-depth evaluation of our procedure would be interesting, for example using stand-level volume measurements by laser-scanning.

The root compartment is certainly the less reliable part of our study. For root biomass, the comparison of the Drexhage et al. model (1999) to Pellinen data (1986) and to the models given in the

Zianis et al. review (2005) for Scots pine (Figure 4) shows that the Drexhage equation is within the range of existing references. Nevertheless, accuracy remains questionable. We performed a sensitivity analysis to assess the impact of using the Drexhage model instead of alternative Scots pine equations from the Zianis review (table 7). We found out that the belowground/aboveground biomass ratio derived from the Drexhage model is close to the commonly accepted values for conifers (Dupouey et al., 1999), whereas the extreme ratios obtained for alternative models are not. Furthermore, even with models exhibiting extreme behaviours, the mean total carbon stock would be respectively 187 tC/ha and 169 tC/ha: this would not change our conclusion on the ranking of sessile oak and Corsican pine.

For soil carbon, the method we used is constrained, by construction, to provide stock values close to the observed values in European soil monitoring networks. However, we estimated the carbon input to the soil by reversing model *Century*: provided that the model parameters are correct, this procedure is valid only if soil carbon is in equilibrium with vegetation. This hypothesis probably holds for oak on State Forests, since land use changes were very limited here over centuries. On private lands and/or in Corsican pine plantations, the equilibrium conditions may not be verified. However, testing the impact of these restrictions was far beyond our possibilities, and this contributes to an uncertainty that is common to soil carbon studies (see review from Yanai et al., 2003). Direct measurements of carbon inputs to the soil would be very valuable, particularly to test the compensation between carbon inputs and lignin/nitrogen ratios for the compared species.

The estimation of carbon in wood products is based upon life cycle analysis and on estimated lifespans of final products. Several parameters are poorly known, e.g. the proportion of final products that are recycled or the lifespans of products. However, the relative contribution of products to the whole carbon stock is small (5 to 8%). This implies that the inaccuracy on products has little influence on the main result. As an example, if two years were added to all wood products lifespans, which implies a 100% increase for the life spans of energy wood, 22% for construction wood and 24% for furniture (Table 4), the part of carbon stored in wood products at steady state would increase from 11 tC/ha to 14.4 tC/ha, and the contribution of products to the total stored carbon would increase from 5 to 6.4%. This increase is negligible compared to the 42 tC/ha to 47 tC/ha difference between the time-averaged carbon stock of Corsican pine and sessile oak.

4 – Why is there such a small time-averaged proportion of carbon in wood products?

The proportion of carbon in wood products at steady state is only 5% for sessile oak and 8% and 8.5% depending on silviculture for Corsican pine. This proportion seems small, but is in accordance with other work in literature: Liski et al. (2001) studied the most favourable rotation length for carbon storage for Scots pine in Finland. Their time-averaged carbon stock estimation in vegetation is 38 tC/ha and 7.4 tC/ha in wood products. Our figures for a Corsican pine intensive silviculture are 71 tC/ha in biomass and 15 tC/ha in wood products. The higher values for Corsican are probably due to stand productivity and rotation length differences. The ratio between stocks in product and vegetation is 19.4% in Liski et al. (2001), 21% in our simulations.

This small contribution of wood products is due to three factors. First, wood losses during wood processing depends on the kind of products, and is generally about 50% during the first process (from log to board) and between 20% and 30% during the second process (from board to final product) (Selmani, 1992). Hence, only 35% to 40% of the harvested volume will become final products. Losses will become products of shorter life spans (energy, paper wood…). Secondly, all the products do not have long lifespans. For example, wood in building structures has a long life span (40 years), but represents only 23% of the construction final products. Moreover, construction final products are the product with the longest lifespan. Energy and paper wood have only a 2 years lifespan, and represent a large amount of harvested wood. Third, product lifespans are compared to rotation lengths that are much longer: 61 and 64 years for Corsican pine stands, and 204 years for sessile oak stands. One of the hypotheses for wood product is that all the wood is used for final products and recycled, or for energy; wood that could decay in landfills is not evaluated and could slightly increase the proportion of this compartment.

Conclusion

The substitution of a slow-growing sessile oak even-aged forest by a fast-growing Corsican pine plantation would have effects on carbon storage depending on the time considered. As Cannell (1996) assumed in a previous work, we show here that during the first rotation, the Corsican pine plantation would have a higher carbon uptake, but that the time-averaged carbon stocks would be lower at steady state, in comparison with slow-growing oak stands spending decades at adult stages.

The additional carbon storage of the Corsican pine plantation with the intensive silviculture compared to sessile oak could be 102 tC/ha after 64 years (Figure 6), which implies an additional storage of about 1.6 tC/ha/yr during 64 years. However, after the first rotation, harvesting of the plantation would imply a high and rapid return of carbon to the atmosphere. At steady state, the time averaged carbon stock is 42 tC/ha to 47 tC/ha lower for the Corsican pine plantation. These results were obtained by simulating forest management guidelines advised by the National Forest Office, in a situation favourable for species substitution (site type with a high productivity for Corsican pine and moderate productivity for sessile oak).

Further studies could improve and complement our results. First, new data on belowground compartments (root systems and soil carbon dynamics) would provide accuracy on the estimations. Second, carbon stocks variations in all the forests ecosystems compartments are accounted for, but the difference of wood harvesting and process between species could imply differences in carbon energy use, as well as differences of fossil fuel savings by energy or construction wood. Even if this is probably not enough to reverse conclusions, this might modify the results. Other changes, such as socio-economics, biodiversity or level of risks modifications could arise if this substitution was applied and could be studied as well. Finally, productivity changes in the last century were reported (Spiecker et al., 1996; Bontemps et al., 2005). Similar studies could be conducted with projections for the next century.

Beyond the results given in the particular case of substituting sessile oak by Corsican pine, this study shows the contribution that assembling models could bring to address complex systems evolution issues. Other carbon balance systems such as CO2FIX (Masera et al., 2003) or GORCAM (Marland and Schlamadinger, 1997) exist and can provide information on changing carbon stocks with species substitutions. The type of tools constructed in those studies is needed to provide scientific data for forest managers and policymakers.

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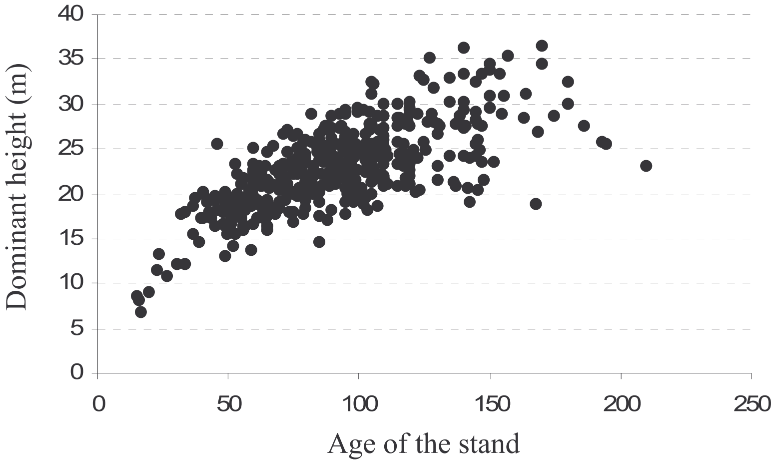

Figure 1: Dominant height vs. age of the stand for the 440 sessile oak stands selected in NFI data

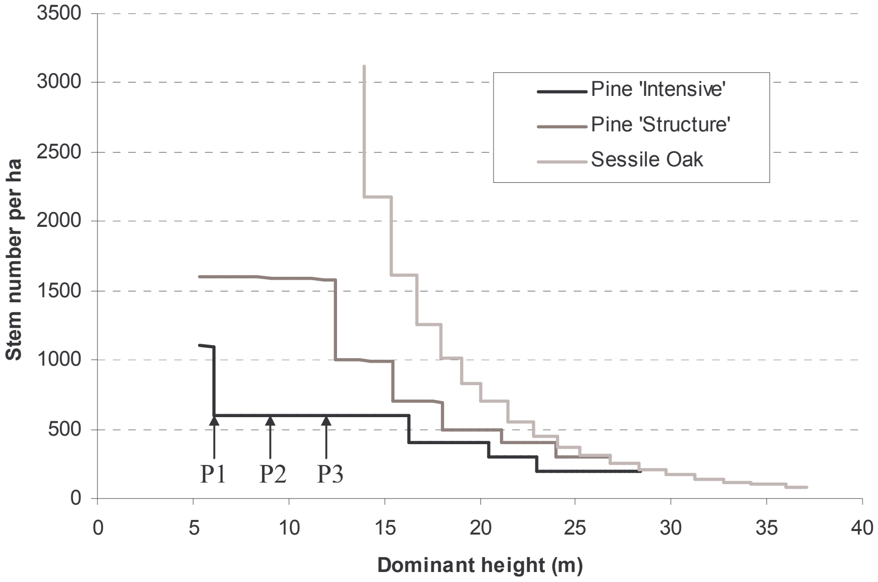

Figure 2: Number of stems vs. dominant height for the sessile oak and pine silviculture
P1: pruning when dominant height is 6 m, of 2.5 m, on 400 stems
P2: pruning when dominant height is 9 m, of 4 m, on 300 stems
P3: pruning when dominant height is 12 m, of 6 m, on 200 stems

3a)

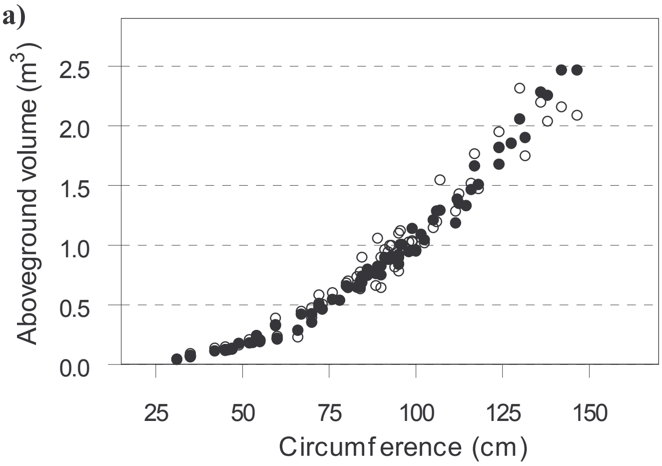

Figure 3a: Total aboveground volume vs. circumference for 77 Corsican pines
Empty circles are measured volumes, solid circles are estimated volumes

3b)

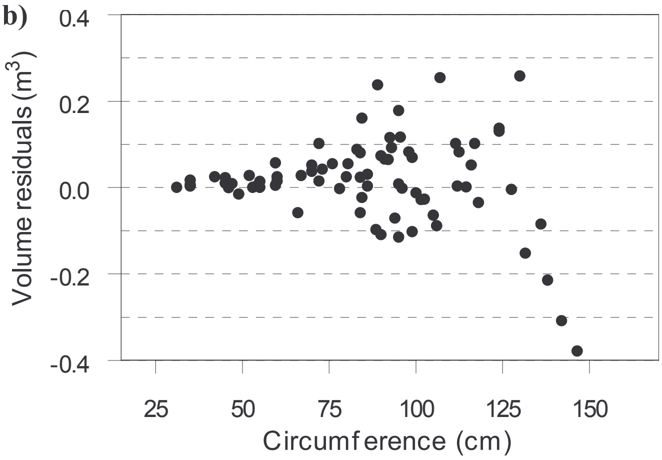

Figure 3b: Total aboveground volume residuals for the 77 Corsican pines

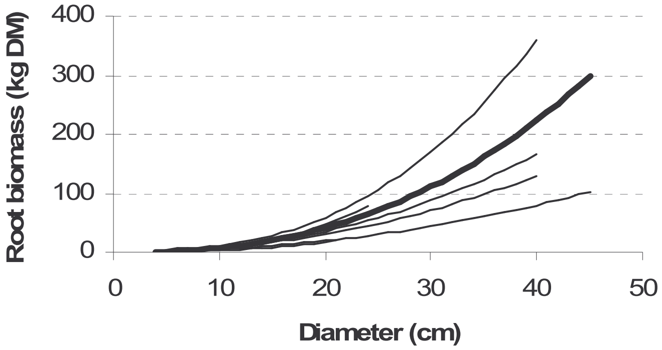

Figure 4: Drexhage model (1999) for root biomass (bold line)
and models given in the Zianis review (2005) for Scots pine root biomass (thin lines)

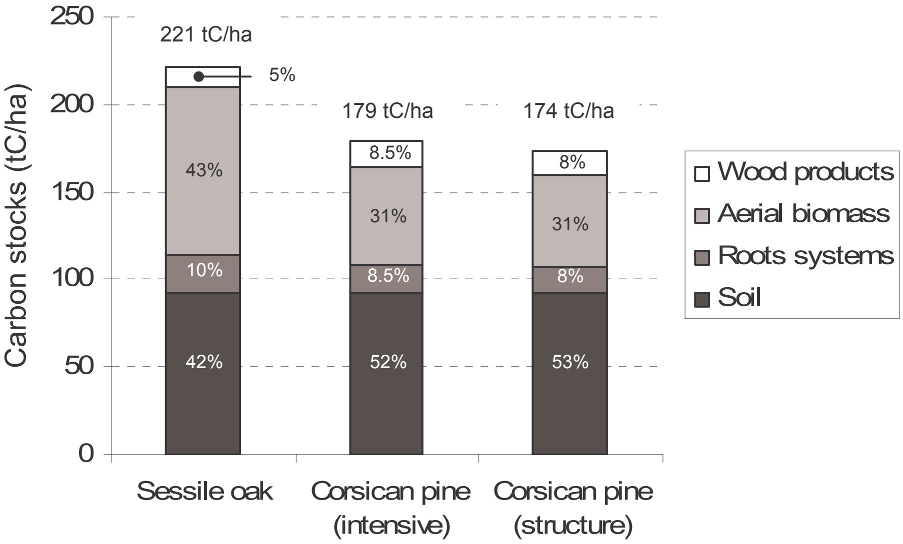

Figure 5: Time-averaged carbon stocks for the 3 silviculture types

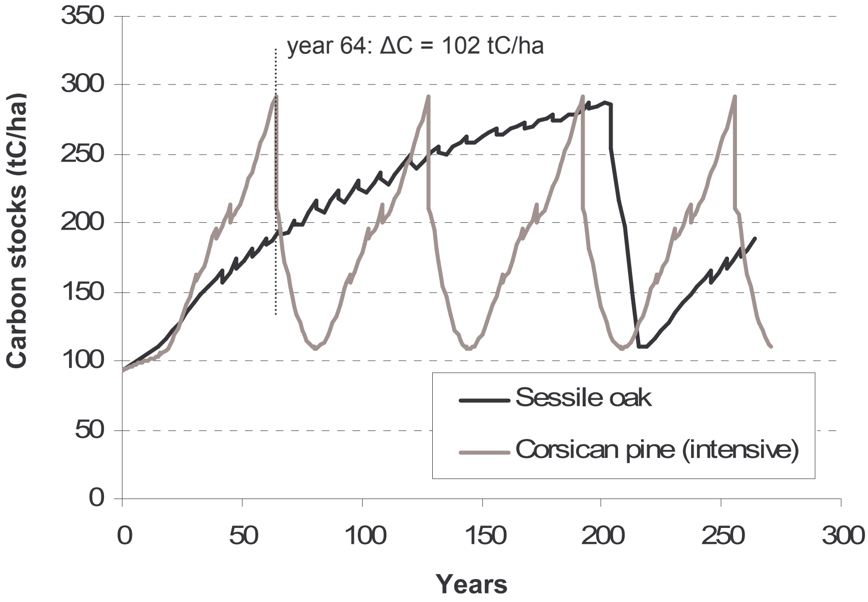

Figure 6: Evolution of carbon stocks for sessile oak
and for Corsican pine after sessile oak substitution.
For Corsican pine, only the silviculture “intensive” is plotted.
The differential carbon stock at the end of the Corsican pine first rotation (64 years) is plotted.

Site type (1)	*Number of sessile oak stands clustered by site type* (2)	*Sessile oak mean site index* (H_{100}) (2)	*Corsican pine site index* (H_{30}) (1)	*Possibility to install a Corsican pine stand* (1)
A2	1	26.7	12.8	Avoid
A4	8	21.7	15.3	Possible
A8	6	22.0	16.2	Possible
C4	2	24.4	13.1	Avoid
L1	1	22.3	13.5	Avoid
L2	37	25.2	14.5	Possible
L3	64	25.9	14.6	Possible
L4-L5	16	22.7	14.6	Avoid
L6	58	24.7	14.3	Possible
L7a	67	24.2	15.7	Possible
L7b	95	25.2	14.8	Not possible
S1	1	23.8	11.8	Not possible
S13	12	25.8	15.1	Possible
S15	36	25.2	15.5	Possible
S5	10	24.6	15	Possible
S7	25	25.2	15.5	Avoid
S9-S11	1	12.4	14	Possible

Table 1: comparison of site indices for Corsican pine and sessile oak stands in *Centre* and *Pays de la Loire* regions in France
The sessile oak stands are clustered by station type of Gilbert et al. 1996 determination key
The highlighted line is the chosen site index couple for the study
(1) Information from Gilbert et al. 1996 determination key, (2) Calculations from NFI data and Duplat and Tran Ha model (1997)

	Age	*Number of stems*	*Dominant height (m)*	*Mean diameter (cm)*	*Dominant diameter (cm)*	*Basal area (m^2)*
Sessile oak silviculture	204	82	37.1	70.7	70.7	32.2
Cors. pine intensive silv.	64	199	28.4	50.4	52.7	39.8
Cors. pine structure silv.	61	299	26.8	40.1	43.2	37.8

Table 2: Main characteristics (per ha) of the stands at the time of final harvest estimated by growth models (*Fagacées* and *PNL*)

Species	*Lignin / nitrogen*	*Compartment*	*Source*
Pedonculate oak	23.6	Litter shadow leaves	Sariyildiz and Anderson, 2003
Pedonculate oak	32.4	Litter sun leaves	Sariyildiz and Anderson, 2003
Sessile oak	32.9	Litter leaves	Cortez et al., 1996
Oak mean value	**29.6**		
Cors. pine	46.3	Litter needles	Fioretto et al., 1998
Cors. pine	58.7	Litter needles	de Santo et al., 2002
Cors. pine mean value	**52.5**		

Table 3: Values of lignin / nitrogen ratio found in a bibliography survey

Kind of product	*Lifespan of a log (yr)*
Paper and board	2
Energy wood	2
Construction	9.1
Furniture	8.5
Handling	3.9

Table 4: Lifespan expectancy of a log assigned to one of a group of products, including the losses during first and second process, and including recycling. These are not the lifespans of final products.
Construction includes wood for building structures, scaffolding, formwork…
Handling includes wooden pallets, wooden case, crates…
From Paquet and Deroubaix (2003), Selmani (1992) and Vallet (2005)

		Mean diameter of the log (cm)						
	%	*70 - 79*	*60 - 69*	*50 - 59*	*40 - 49*	*30 - 39*	*20 - 29*	*10 - 19*
A : Slicing	1	X	X	X				
B1 : Cabinet working	4		X	X	X			
B2 : Fine joinery	10			X	X	X		
C1 : Ordinary joinery	15			X	X	X		
C2 : Framework, flooring	15				X	X	X	
T : Sleepers	10				X	X		
Energy / paper wood	45						X	X

Table 5: Partition of a log between products based on mean diameter of the log for sessile oak
The crosses mean that the type of log is in the product group
The percentages indicates the distribution of the national resource for oak
From Flammarion (1986)

Quality	*Joinery*	*Construction*	*Handling*
0A and 0B	100 %	0 %	0 %
1	60 %	40 %	0 %
2	40 %	60 %	0 %
3A	0 %	0 %	100 %

Table 6: Corsican wood distribution between the different kinds of products function of the quality of the board
Notation 0A, 0B, 1, 2, 3A corresponds to the French standard NF B 52-001, 0A is the best quality wood, 3A the worst.

Model		*Mean root carbon content*	*Ratio below/above ground carbon content*	*Mean total carbon content*
Model n° in Zianis Review	*450*	11.4	0.20	175
	451	23.4	0.41	187
	453	5.6	0.10	169
	454	6.2	0.11	170
	455	20.3	0.36	184
	456	9.0	0.16	173
Drexhage 2001 (selected model)		**14.8**	**0.26**	**179**

Table 7: Results of the sensibility analysis on root biomass equation used on Corsican pine, simulations for the “intensive” silvicultural scenario. Mean carbon content values in tC/ha.