# Modeling climate change effects on the potential production of French plains forests at the sub-regional level

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**Summary** We modeled the effects of climate change and two forest management scenarios on wood production and forest carbon balance in French forests using process-based models of forest growth. We combined data from the national forest inventory and soil network survey, which were aggregated over a  $50 \times 50$ -km grid, i.e., the spatial resolution of the climate scenario data.

We predicted and analyzed the climate impact on potential forest production over the period 1960–2100. All models predicted a slight increase in potential forest yield until 2030–2050, followed by a plateau or a decline around 2070–2100, with overall, a greater increase in yield in northern France than in the south. Gross and net primary productivities were more negatively affected by soil water and atmospheric water vapor saturation deficits in western France because of a more pronounced shift in seasonal rainfall from summer to winter.

The rotation-averaged values of carbon flux and production for different forest management options were estimated during four years (1980, 2015, 2045 and 2080). Predictions were made using a two-dimensional matrix covering the range of local soil and climate conditions. The changes in ecosystem fluxes and forest production were explained by the counterbalancing effect of rising CO<sub>2</sub> concentration and increasing water deficit. The effect of climate change decreased with rotation length from short rotations with high production rates and low standing biomasses to long rotations with low productivities and greater standing biomasses. Climate effects on productivity, both negative and positive, were greatest on high fertility sites. Forest productivity in northern France was enhanced by climate change, increasingly from west to east, whereas in the southwestern Atlantic region, productivity was reduced by climate change to an increasing degree from west to east.

*Keywords: carbon balance, climate scenario, forest management, temperate forest.* 

# Introduction

Global change includes both rapid changes in climate variables such as temperature, radiation and precipitation, as well as changes in the atmospheric concentration of greenhouse gases, soil water and nutrient cycling. Thus, from the point of view of tree physiology and ecosystem functioning, global change affects both climate variables and plant resources.

Some changes, such as the increase in atmospheric  $CO_2$  concentration ([ $CO_2$ ]), uniformly affect large areas; others, such as nitrogen deposition or soil water availability, show great variation both locally and regionally. These changes may interact with tree species and local site characteristics that control forest productivity (Medlyn 1996, Medlyn and Dewar 1996). Therefore, to predict the effect of global change on tree functioning and forest production, a sub-regional analysis is needed. So far, only global or regional long-term trends of forest production in Europe have been assessed, based on a limited number of representative sites (Karjalainen et al. 2002,

Nabuurs et al. 2002); sub-regional variations in climate and site conditions have not yet been investigated.

Forest aging is a major factor controlling forest productivity and hydrology (Spiecker 1999, Nabuurs et al. 2002). One may suppose, therefore, that climate change affects forest production and function differently at different stages during the life cycle of a forest. Because management is the major factor affecting the age distribution of European forests, the interactions between climate change and management must be carefully analyzed.

In this study, we combined a sub-regional climate scenario, plot fertility data and forest management scenarios and used three process-based forest growth models to quantify the effects of climate change, plot fertility and management on forest growth, carbon balance and hydrology. We focused our analysis on France, which is characterized by a high diversity in biogeographic zones, silvicultural practices and tree species.

## Materials and methods

## Models

The process-based models used in this study are CASTANEA (Dufrêne et al. 2005), GRAECO (Porté 1999) and OR-CHIDEE (Krinner et al. 2005). CASTANEA and GRAECO are forest growth models (GRAECO for pine forests only), whereas ORCHIDEE is a dynamic global vegetation model, not specific to site or species. The forest growth models (CAST-ANEA and GRAECO) include the ecophysiological knowledge obtained locally for the forest species (Granier and Loustau 1994, Porté and Loustau 1998, Porté 1999, Berbigier et al. 2001, Medlyn et al. 2002, Porté et al. 2002) and were evaluated against long term CO<sub>2</sub> and H<sub>2</sub>O flux data (Granier et al. 2000a, 2000b, Berbigier et al. 2001), as well as growth data from long-term plots (Davi 2004, Le Maire et al. 2005). In contrast, ORCHIDEE has been designed to simulate the global carbon cycle and thus distinguishes only 12 plant functional types (PFT), three of them for temperate forests: temperate needle-leaf, temperate winter-deciduous broadleaf and temperate evergreen broadleaf.

All three models include a description of the carbon and water cycles in the soil–vegetation–atmosphere system and of the related processes (air-to-leaf  $CO_2$  diffusion, photosynthesis, evapotranspiration, respiration, allocation, growth, phenology, mortality and mineralization), together with their sensitivity to climate variables and air [CO<sub>2</sub>]. ORCHIDEE also includes the complete SVAT model (Soil–Vegetation–Atmosphere Transfer model) SECHIBA (Ducoudrée et al. 1993) to calculate the hydrologic and energetic budget.

Tree structure is described by a combination of five functionally different parts: foliage, stems, branches, coarse roots and fine roots. In addition, a carbohydrate storage compartment is considered for broadleaf trees (i.e., in ORCHIDEE and CASTANEA).

The allocation scheme in the pine forest model (GRAECO) is like 3-PG (Physiological Principles Predicting Growth; Landsberg and Waring 1997); but unlike 3-PG, it distinguishes two canopy layers and allocates NPP first among individual

trees according to their contribution to stand leaf area index (LAI) and second to tree parts. The allocation scheme in ORCHIDEE dynamically calculates the fraction of assimilates to be allocated to the different plant parts taking into account environmental influences (light availability, temperature and soil water; see Friedlingstein et al. 1998). Phenology is fully prognostic, based on growing degree days, chilling or soil water content indexes specific to each PFT and calibrated with remote-sensing data (Botta et al. 2000). The allocation scheme in CASTANEA differs mainly in its fixed priority scheme that can be implemented seasonally (Dufrêne et al. 2005).

For the soil organic carbon cycle, the CENTURY model was implemented in CASTANEA and ORCHIDEE. In the pine forest model GRAECO, heterotrophic respiration is dependent on soil temperature and water and constrained by the mean litter input without controlling the closure of the soil carbon mass balance.

## Climate scenario

Version 3.0 of ARPEGE/Climate, the Météo-France atmospheric model, has been used to simulate present and 21st century climate through a 140-year numerical experiment (Gibelin and Déqué 2003). The greenhouse gas and aerosol concentrations were based on the IPCC-B2 scenario, which prescribes a continuous increase in [CO<sub>2</sub>] from 375 ppm in 2000 to 600 ppm in 2100 and a corresponding increase in global surface temperature of +2.8 °C (IPCC 2001). This is a global model with variable spatial resolution with a value of 50 km over France (n = 360 grid points). Ocean surface temperatures are provided by an atmospheric model with a coarser resolution, which is coupled to an oceanic water circulation scheme (Royer et al. 2002). The radiative forcing scheme includes four greenhouse gases (CO2, CH4, N2O and CFC) in addition to water vapor and ozone, and five aerosol classes (land, marine, urban, desert and sulphate) (Morcrette 1990). Cloudiness, precipitation and vertical diffusion are implemented according to the statistical approach described in Ricard and Royer (1993). The hydrology-soil-vegetation surface scheme is modeled with the ISBA model (Douville et al. 2000). Maps showing the seasonal anomaly predicted by the scenario in the mean daily precipitation are provided (see Figure 3).

## Modeling experiments

Two modeling experiments were performed: (1) a simulation of the annual energy, carbon and water exchanges over 140 continuous years; and (2) a simulation of complete forest rotations during the four years 1980, 2015, 2045 and 2070.

*Experiment 1* Canopy fluxes from a fixed forest canopy were modeled over an entire annual cycle using predicted meteorological data at each year of the climate scenario.

Site-based predictions were performed for different species at five locations using CASTANEA and GRAECO, the latter for maritime pine only. Forest canopy structure was characterized according to observations at three forested sites (Le Bray, Fontainebleau and Hesse). These are mature stands with LAIs close to the maximum value for the rotation (Table 1). Leaf area index was kept unchanged throughout the 140-year exTable 1. Site and stand characteristics for the forests modeled in Experiment 1. All species except *Pinus pinaster* were modeled with CASTANEA and ORCHIDEE; *Pinus pinaster* was modeled with GRAECO and ORCHIDEE. In Figure 1, the Fontainebleau site corresponds to Area 1; the Hesse site corresponds to Area 2; the Puechabon site corresponds to Area 5; and the Bray site corresponds to Area 3. Abbreviation: LAI = leaf area index.

Parameter	Site and species							
	Fontainebleau (NW)			Hesse (NE)	Puechabon (SE)	Bray (SW)		
	Quercus petraea	Pinus sylvestris	Fagus sylvatica	Fagus sylvatica	Quercus ilex	Pinus pinaster		
Elevation (m)	120	120	120	300	270	60		
Soil water holding capacity (kg $H_2O m^{-2}$ )	90	115	136	180	127	110		
Mean annual temperature 1950–1990 (°C)	10.2	10.2	10.2	9.2	13.6	12.9		
Stand age (years)	136	100	135	30	58	29		
Standing stock (trees $ha^{-1}$ )	1025	530	622	3840	8500	533		
Upper canopy LAI	7.1	5.0	4.5	7	2.3	3		
Understory LAI	0	0	0	0	0	1.5		
Mean height (m)	32	24	33	15	6	19		
Basal area $(m^2 ha^{-1})$	31.3	33.9	32.8	22.5	n/a	35.8		
Mean circumference (m)	1.57	1.08	1.07	0.23	0.07	0.92		

periment. We obtained time series of 140 annual energy,  $H_2O$  and  $CO_2$  fluxes that reflect changes in forcing variables (temperature, radiation, precipitation, air–water vapor saturation deficit or  $[CO_2]$ ). Results must therefore be interpreted as changes in the potential values of fluxes exchanged from a mature forest, analogous to the notion of potential evaporation used in meteorology.

Grid-based predictions were made by the model OR-CHIDEE and maps of annual NPP averaged at four periods centered in 1968, 2008, 2048 and 2078 were produced.

*Experiment 2* The second experiment was aimed at describing the effects of climate on the entire life cycle of the forest according to two or three optional management scenarios. The 1960-2100 climate scenario was split into four periods averaged around the years 1980, 2015, 2045 and 2070. Management scenarios were run from plantation to the final cut for three species: beech (Fagus sylvatica L.), sessile oak (Quercus petraea (Matt.) Liebl.) and maritime pine (Pinus pinaster Ait.). This experiment was carried out at several grid points located at the center of the geographical area covered by each species in France and for different site conditions depending on foliar nitrogen content (N) (g N  $g_{DM}^{-1}$ ) and soil water-holding capacity  $(W_c)$  (kg H<sub>2</sub>O m<sup>-2</sup> or mm), as explained in the following section. For clarity, only the four extreme conditions are illustrated below (low N and low  $W_c$  (LN-L $W_c$ ); low N and high  $W_c$  $(LN-HW_c)$ ; high N and low  $W_c$   $(HN-LW_c)$ ; and high N and high  $W_c$  (HN–HW<sub>c</sub>)), and two locations for beech (NW (1) and NE (2)) and for maritime pine (SW (3) and S (4)) are used (Figure 1).

#### Soil conditions

As explained above, site conditions were described in terms of two parameters: N and  $W_c$ . In the first experiment, site conditions were those measured at each site, whereas in the second

experiment, two or three nitrogen availabilities were specified according to the observed range found in the literature and two or three soil water availabilities,  $W_c$ , were determined relative to each species and each grid point, according to the French soil inventory data (Table 2).

#### Management scenarios

Only even-aged monospecific tree rotations were modeled. Forest management scenarios were defined for each modeled species in terms of tree age at the final cut and thinning regime (Table 3). The scenarios are standard sylviculture scenarios widely applied in the different geographic zones covered by this study.

## Results

## Experiment 1

Over the period 1960–2100, air temperature and vapor pressure deficit systematically increases (+3 °C and +150-200 Pa at some sites), whereas annual precipitation either decreases or remains stable depending on location (Figure 2). The change in climate is not steady, but alternates between periods of rapid increase, e.g., 2010-2030 and 2050-2070, and more stable periods like 2030-2050 and 2070-2090. This pattern shows significant geographical variation: changes in temperature and atmospheric water vapor saturation deficit are generally more pronounced in southwestern France than in northern France. The change in the annual sum of precipitation is weak, but there is a shift in the seasonal distribution from spring and summer to winter, which is more pronounced in southwestern France (Figure 3). The area of Mediterranean climate, characterized by hot and dry summers, expands from its present location westward and northward at the expense of the area of oceanic temperate climate.



Figure 1. Annual net primary productivity (NPP) of the "temperate needleleaves" functional type over France (upper left) and its anomalies in 2008, 2048 and 2088 (upper right, lower left and lower right, respectively). Numbers refer to the grid point location used for long-term predictions.

Table 2. Leaf nitrogen concentrations (N) and soil water-holding capacity  $(W_c)$  by species used in Experiment 2.

Parameter	Species					
	Quercus petraea	Fagus sylvatica	Pinus pinaster <sup>1</sup>			
Region	North	North and northeast	Southwest			
$N(g N g dm^{-1})$	0.022, 0.029	0.022, 0.029	$0.01, 0.0125, 0.015^{1}$			
$W_{\rm C} ({\rm kg}{\rm H_2O}{\rm m^{-2}})$	75, 125, 200	75, 125, 200	70, 110, 150			

<sup>1</sup> Data are from Loustau et al. 1999.

Table 3. Summary of the management scenarios implemented in Experiment 2. The short rotation scenario was applied to Pinus pinaster only.

Variable		Species			
		Quercus petraea	Fagus sylvatica	Pinus pinaster	
Region		North	North	Southwest	
Short rotation	Duration (years)	_	_	30	
	No. of thinnings	-	-	2	
Standard rotation	Duration (years)	135	99	45	
	No. of thinnings	12	7	5	
Long rotation	Duration (years)	160	150	90	
	No. of thinnings	11	9	5	





Figure 4 shows the time course of different carbon budget variables (gross primary productivity (GPP); net primary productivity (NPP); the ratio of autotrophic respiration to GPP  $(R_a/GPP)$ ; and net ecosystem exchange of CO<sub>2</sub> (NEE)) over the entire period 1960–2100. To compare species and locations, not models, only the CASTANEA results are shown.



Figure 3. Anomaly in mean daily precipitation (mm day<sup>-1</sup>) in winter (DJF = December, January, February), spring (MAM = March, April, May) summer (JJA = June, July, August) and autumn (SON = September, October, November) over France between (1960–1989) and (2070–2099).



Figure 4. Change in annual canopy fluxes from mature stands simulated by the model CASTANEA over the period 1960-2100 for five species at different geographical locations (moving averages, n =10 years). Numbers in parentheses following species' names in the legend refer to the map in Figure 1. Abbreviations: GPP = gross primary productivity;  $R_a$  = autotrophic respiration; NPP = net primary productivity; and NEE = net ecosystem exchange of CO<sub>2</sub>.

However, for maritime pine, GRAECO leads to comparable results. For all species, GPP increases throughout the 1960–2100 interval, although at a higher rate in the first half of the period (Figure 4). The autotrophic respiration  $R_a$  is almost stable until 2000 and then increases continuously. Consequently,

the  $R_a$ /GPP ratio decreases until 2000 and then increases until about 2080, which corresponds to a maximum in air temperature. This explains the NPP pattern that shows a maximum around 2030 and decreases afterwards. Also, some specific and geographic differences appear. Growth of deciduous spe-



Figure 5. Changes in rotationaveraged annual gross primary productivity (GPP) for Fagus (North, upper boxes) and Pinus (South, lower boxes) for the years 1980, 2015, 2045 and 2080 for different management scenarios and soil conditions: A and B = high foliar nitrogen concentration; C and D = low foliar nitrogen concentration; A and C = low soil water-holding capacity; B and D = high soil water-holding capacity. Symbols:  $\blacklozenge$  = short rotation scenario;  $\square$  = medium rotation scenario; and  $\bigcirc$  = long rotation scenario. Fagus rotations were simulated by the model CASTANEA and Pinus rotation by the model GRAECO. Numbers in parentheses refer to the locations mapped in Figure 1.



Figure 6. Changes in rotationaveraged annual net primary productivity (NPP) for Fagus (North, upper boxes) and Pinus (South, lower boxes) from 1980, 2015, 2045 to 2080, for different management scenarios and soil conditions: A and B = high foliar nitrogen concentration; C and D = low foliar nitrogen concentration; A and C = low soil water-holding capacity; B and D = high soil water-holding capacity. Symbols:  $\blacklozenge =$ short rotation scenario;  $\square$  = medium rotation scenario; and  $\bigcirc$  = long rotation scenario. Fagus rotations were simulated by the model CASTANEA and Pinus rotation by the model GRAECO. Numbers in parentheses refer to the locations mapped in Figure 1.

cies in the north increases in response to climate change, especially beech in the northeast. For this species, both NPP and NEE increase continuously until 2100. In contrast, the potential gross and net productions of holm oak and maritime pine stands in the south increase more slowly and sometimes decrease. Species differences are evident when comparing the *Quercus, Fagus* and *Pinus* stands simulated at the same AR-PEGE grid point (location 1 in Figures 1 and 4, the Fontainebleau site) where GPP changes were higher in *Quercus petraea* than in *Fagus*, which were higher than those of *Pinus* stands. A more detailed analysis concerning the climatic impact and its various effects on carbon and water fluxes as simulated by CASTANEA can be found in Davi (2004).

The geographical variation in the evolution of potential forest fluxes of energy, water and carbon are mapped over France using the ORCHIDEE model (Figure 1). Only potential NPP for the PFT corresponding to temperate needle-leaf forests is shown, which summarizes very well the geographical trend found in Figure 4. The climate scenario reduced potential forest production less in northeastern France than in western maritime areas where the increased water deficit was larger.

## Experiment 2

In the following, only representative results are illustrated (Figures 5-8). The simulation of complete rotations indicated interactions between forest management and climate change and its geographical variation. Whereas only slight effects of management scenario on GPP are simulated, larger impacts on

NPP, NEE and mean annual increment in stemwood (MAI) are predicted as a result of autotrophic and heterotrophic respiration responses to increasing temperature and to the differential standing biomass and litter input according to each scenario. In accordance with Experiment 1, models predict generally positive or neutral impacts of the scenario on the forest production and carbon balance in northern France. A different situation occurs in the southwest, where interactions occur between scenario effects and effects of both management regime and site conditions.

The 1960-2100 time course of broadleaf forest development in northern France shows some differences between eastern and western sites with minor interactions between management scenario and site conditions. Gross primary production averaged over the rotation increases throughout the period, although not at a constant rate. In contrast, NPP reaches a maximum early in 2000 in the western sites where soil waterholding capacity is low, and by 2040 where soil water-holding capacity is high, whereas it continues to increase until the end of the simulation at the eastern point. Net ecosystem exchange of CO<sub>2</sub> mimics the NPP pattern with marginally smaller variations between dates. The trend predicted for MAI is similar to that for NEE, although between the two periods 2045 and 2070, the MAI change varies among sites from a slight increase in the eastern grid points to a neutral trend or even a slight decrease in the western  $LW_c$  sites. We conclude that CASTANEA did not predict noticeable interactions between climate, site and the two management scenarios.



Figure 7. Changes in rotation- averaged annual net ecosystem exchange (NEE) for Fagus (North, upper boxes) and Pinus (South, lower boxes) from 1980, 2015, 2045 to 2080, for different management scenarios and soil conditions: A and B = high foliar nitrogen concentration; C and D = low foliar nitrogen concentration; A and C = low soil water-holding capacity; B and D = high soil water-holdingcapacity. Symbols:  $\blacklozenge$  = short rotation scenario; 
= medium rotation scenario; and  $\bigcirc = long$ rotation scenario. Fagus rotations were simulated by the model CASTANEA and Pinus rotation by the model GRAECO. Numbers in parentheses refer to the locations mapped in Figure 1.

In the south, both the trend predicted and the interactions between climate, site and management scenario were opposite to those in the north. Over the 1960-2100 time period, all variables representing the rotation-averaged GPP and NPP or MAI increase until 2015 to 2045, and then decline, generally to lower values than those of 1980. The western grid points show a greater increase in productivity than the eastern grid points, where the decrease in summer precipitation and associated increase in air-water vapor saturation deficit are maximal. There is an interaction between the management scenario and climate effects, the short rotation scenario being the most sensitive to climate. The effects of management and climate are enhanced under fertile conditions, corresponding to high leaf nitrogen concentrations (HN) and  $HW_c$ , so that the short rotation management at HN and HW<sub>c</sub> are most responsive to climate change. For instance, GPP, NPP and the other variables clearly exhibited the largest ranges of variation over the period 1960-2100 for the short rotation scenario. Conversely, the long rotation in LN and  $LW_c$  are less sensitive to climate. From 2000 onwards, NEE declines in every case, a consequence of the temperature-driven enhancement in the autotrophic and heterotrophic respiration.

# Discussion

Comparison of the climate scenario prediction with observed data for the period 1960–2000 leads to the conclusion that, on average, the ARPEGE model predictions provide a good reconstruction of climate and its geographical distribution, although with local discrepancies (Pluviaud 2000, Cloppet 2002).

Compared with observed data, the climate scenario smoothes the observed variability and dampens the range of most climate variables, cutting off the extreme events such as severe windstorms or extreme temperatures.

Validation of the models used here against flux and growth data issued from the CARBOEUROPE project flux sites and permanent forest inventory plots has been achieved by Davi (2004). Results show that CASTANEA reproduces correctly the diurnal fluxes ( $r^2$  from 0.62–0.90; Davi 2004) and canopy fluxes and tree growth sensitivity to climate was captured well by the three models used in the present study (J. Ogée et al., INRA-EPHYSE, France, unpublished data). Hence, our prediction of the responses of French forests to climate change is credible in terms of the processes accounted for, i.e., the energy, hydrological and carbon balances and wood production.

The interaction with nutrient cycling, e.g., the feedback effect of increased organic matter mineralization was not addressed in our experiment because of the lack of published information about the quantitative impact of site management and tree aging on the nitrogen and phosphorus cycles at the local level. Modeling and observations identified nitrogen cycling as an important environmental process interacting with climate effects and having an effect on forest productivity in Europe for the last 25 years (Medlyn et al. 2000, Nellemann and Thomsen 2001, Ollinger et al. 2002, Milne and Van Oijen 2005).

The observed changes over time in forest productivity are explained by the interaction between effects of increasing  $[CO_2]$ , temperature and soil water deficit on GPP,  $R_a$  and  $R_h$ .



Figure 8. Changes in rotation-averaged annual mean annual increment (MAI) for Fagus (north, upper boxes) and Pinus (south, lower boxes) from 1980, 2015, 2045 to 2080, for different management scenarios and soil conditions: A and B = high foliar nitrogen concentration; C and D = low foliar nitrogen concentration; A and C = low soil water-holding capacity; B and D = high soil water-holding capacity. Symbols:  $\blacklozenge$  = short rotation scenario: = medium rotation scenario; and  $\bigcirc$  = long rotation scenario. Fagus rotations were simulated by the model CAST-ANEA and *Pinus* rotation by the model GRAECO. Numbers in parentheses refer to the locations mapped in Figure 1.

First, productivity of deciduous species increased most in response to the increasing length of the growing season; this explains the more pronounced enhancement of GPP in these species compared with evergreens. Second, temperate tree species respond differently to increasing [CO<sub>2</sub>] and water deficit, with the stomatal response of *Pinus* to elevated [CO<sub>2</sub>] being neutral, whereas Quercus and most forest understory species close their stomata at elevated [CO<sub>2</sub>] at least in the short term (Medlyn et al. 2001). Fagus species seem to behave like coniferous species but this is less well documented. The difference in sensitivity explains in part the greater sensitivity of oak compared with beech and pine, as modeled in Experiment 1. The seeming difference between species is actually due in part to differences in local site conditions: the modeled oak stand tended to have a higher LAI and lower  $W_c$  than the Pinus and Fagus stands, which magnified its sensitivity to drought.

In both Experiments 1 and 2, the impact on GPP of increasing  $[CO_2]$  is negated by drought in southern France. There, NPP is enhanced less than GPP because of increased  $R_a$ . Net ecosystem exchange of  $CO_2$  is further reduced because of the increased  $R_h$ . The response of MAI is a consequence of a drough-induced decrease in carbon allocation to the stem. Gross primary productivity is relatively insensitive to the management scenario (Figure 5). Thus, NPP, MAI and NEE are differentiated according to scenario because management has a larger effect on the rotation-average standing stock and hence respiration than on mean stand LAI, which determines GPP.

Geographical variations in water deficit further explained the inversion in the west to east gradient between north and south. We think the local variations are magnified over the geographical area of France, which is characterized by steep climate variations resulting from the interaction of maritime, continental and mountain influences. Four biogeographical zones meet in France, a unique case in Europe, and their geographical distribution will be affected differently by the climate scenario-a conclusion supported by the modeling of phytogeographic zones (V. Badeau et al., INRA-Nancy, France, unpublished report, 2004) and the large-scale model ORCHIDEE (Ciais et al., unpublished results). In terms of the geographical variation of the climate change effects, our conclusion confirms preliminary investigations carried out for the southwestern region as summarized by Loustau et al. (2001). It also refines the conclusions published about the global impacts of climate change on European forests so far. Nabuurs et al. (2002) and Karjalainen et al. (2002) reported a uniform positive impact on GPP of global change in northern European and German forests, respectively, in accordance with our predictions 1 and 2 for Scots pine, oak and beech in northern France. These studies, based on the B2 scenario, consistently predict a strong positive effect on GPP of climate change for the next 30 years, followed by a plateau. This pattern was interpreted as a compound effect of climate and forest aging. More recently, using a  $0.5 \times 0.5^{\circ}$ -grid over Europe and a simple model, Milne and Van Oijen (2005) found a strong regional pattern in the 1990-2050 change in age-independent net ecosystem productivity, with a larger increase in the boreal zone and a decline in Mediterranean forests.

An original finding of our analysis is the interaction between climate and  $[CO_2]$ , nitrogen availability and  $W_c$ . This interaction is predicted because  $[CO_2]$  is more limiting under fertile conditions, i.e., for stands following their curve of maximal productivity, whereas productivity on poorer and drier sites is constrained by limiting factors that remained unchanged over the period examined. Other modeling analysis may lead to a different conclusion when considering the rising rate of nitrogen deposition, which evokes a larger response at less fertile sites (Milne and Van Oijen 2005). An emerging conclusion, consistent with the limiting factor law, is that productivity changes occur when a limiting factor is either removed by an increase in  $[CO_2]$  or nitrogen availability or made more limiting, e.g., an increase in soil water deficit.

The response of the short rotation scenarios is dominated by the sensitivity of the juvenile phase to climate: standing biomass and therefore respiration are low, whereas productivity is relatively high. During the early phase, the impacts of climate change tend to cumulate from year to year before canopy closure, as long as there is some free space to allow LAI to increase. Conversely, the relative mass of old stands is larger for long rotations. After canopy closure, stand LAI is increasingly constrained by limiting resources such as water and nitrogen (Magnani et al. 2000, Delzon et al. 2004); stand productivity decreases whereas the standing biomass stock increases continuously. Because LAI is constrained, climate changes have smaller effects on GPP and greater impacts on respiration.

The different interactions of climate change with forest management between northern and southern zones are explained mainly by the contrast between scenarios which is greater for the southern pine forests and less dramatic for the broadleaf forests in the north. The short rotation scenario in the pine forest corresponds to a highly intensive forest management regime optimized for fiber production, whereas the long rotation exceeds by 40 years the date of the final cut currently applied in this area. Difference in age at the final cut is 55 years or ~ 60% of the final age of the long rotation, and the strong interaction observed in the southwestern pine forest is due to an age effect. Conversely, the difference in age at the final cut is nol 15 (10%) and 50 (33%) years for oak and beech, respectively.

Although sustainable forest management must rely primarily on site-specific characteristics and data, we think our results provide valuable information about the regional forcing trends constraining future changes in the physical environment of the forest. Where climate change effects enhance productivity, our results suggest optimizing forest management by reducing the limiting factors, e.g., increasing rooting depth and fertilization. Conversely, where detrimental effects on productivity are expected, enhancement of drought resistance, e.g., through species substitution, LAI optimization with appropriate thinning regimes and site preparation, may limit the restriction to forest growth. The improvement of  $W_c$  and fertilization are key factors for adapting forests to the seasonal shift in precipitation predicted by the climate scenario.

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