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Forest Ecology and Management 202 (2004) 93–105
Forest Ecology and Management
www.elsevier.com/locate/foreco

# Growth patterns and carbon balance of *Pinus radiata* and *Pseudotsuga menziesii* plantations under climate change scenarios in Italy

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Received 20 January 2004; received in revised form 19 May 2004; accepted 4 July 2004

**Abstract**

The process-based model HYDRALL has been applied to simulate growth patterns and carbon balance of three *Pinus radiata* and one *Pseudotsuga menziesii* plantations growing in different sites in Italy, under current climate and climate change scenarios. In three out of four cases, growth patterns simulated by the model under current climatic conditions showed good convergence with measured growth patterns, as provided by stem analysis. Climatic variables for the period 1990–2100 have been obtained from the General Circulation Model (GCM) projections of the HadCM2 model. At all sites simulations predicted an increase of both temperature and precipitation. The effects of climate change on forest growth was explored by simulating 50-year stand rotations starting from different dates in the 1960–2100 period. Climate change had a positive effect on stand growth patterns, with the largest effect found for *P. menziesii* (73 and 55% increase for stand volume and height at the age of 40). Mean annual increment (MAI) was also stimulated by climate change, whereas no change in MAI temporal patterns was observed. In three out of four cases the model predicted an increase in the allocation of carbon to the foliage compartment. A positive effect of climate change on net ecosystem exchange (NEE) was observed only for the *P. menziesii* stand; in contrast, water-use efficiency, estimated as the ratio between net primary production and stand transpiration, increased in all sites.


*Keywords:* Conifer; Forest; Drought; Carbon; Model; HYDRALL

## 1. Introduction

In recent years considerable progress has been made towards process-based models that can be used to predict the impact of atmospheric $CO_2$ increase and

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0378-1127/$ – see front matter 
doi:10.1016/j.foreco.2004.07.030

climate change on forest productivity, at both local and regional scale (e.g. Kirschbaum, 1999; Waring and McDowell, 2002; see Waring and Running (1998) for general perspective).

In Mediterranean regions forest productivity is moisture-limited and climate change may enhance this limitation, resulting in a further decrease of soil water availability and prolonged drought periods (Houghton et al., 1996). In such conditions, strong interactions between $CO_2$ increase, temperature and humidity are expected to affect forest growth and its potential to store carbon. Recent field experiments provided quantitative assessments of the response of forest trees to prolonged reductions of soil moisture, stressing the need for better representation of the effects of environmental factors on carbon allocation and resulting long-term structural acclimation (Cinnirella et al., 2002).

Mukesh GautamThe role of afforestation in carbon sequestration has been acknowledged in the Kyoto protocol (Schulze et al., 2002), thus reliable tools are required for quantifying the potential of forest plantations to store carbon, both under present and future climate. Knowledge on how plant water-use efficiency could be affected by climate change is also a relevant issue at sites where the role of water as constraining factor for forest productivity is predicted to increase, so that proper management of site water balance is expected to become a crucial environmental issue.

The HYDRALL model (Magnani et al., 2000) is a physiology-based model which simulates growth patterns and canopy gas exchange of even-aged coniferous stands; in particular, it contains a new representation of the effects of hydraulic constraints on carbon allocation among tree compartments. Some components of the model have been tested so far: long-term dynamics of gas exchange have been compared with eddy-covariance data (net ecosystem exchange and transpiration at the canopy level) from pine forests across Europe (Kramer et al., 2002); the response of growth and resource allocation to the environment has also been evaluated (Magnani et al., 2002).

Requiring a rather modest level of input, HYDRALL could be managed quite easily for screening carbon balance and forest productivity, and prospect plantation sites in differing climatic situations. The objectives of this work were: (i) evaluating further the model by comparing predictions of forest growth under current climatic conditions with forest growth data provided by stem analysis; (ii) applying the model to simulate growth patterns, carbon balance and water use efficiency of tree crop plantations under climate change scenarios in Italy; to this aim, *Pinus radiata* (D.) Don and *Pseudotsuga menziesii* Mirb. plantations have been selected as case study for the Mediterranean region.

## 2. Materials and methods

### 2.1. Study sites and stand growth patterns

Three *P. radiata* stands and one *P. menziesii* stands were selected for this study (Table 1). Stands were chosen for: (i) not having undergone thinning practices; (ii) not having undergone significant mortality (current density (trees $ha^{-1}$) >90% of initial density); (iii) their proximity to meteorological stations, providing long-term climatic records. Understorey was negligible, due to initial cultural practices and dense tree canopy cover.

In each stand, stem diameter distribution was assessed and the height of 30 trees, sampled in different diameter classes, was measured. Based on

Table 1
Stands and sites with current climate (mean annual temperature and total annual precipitation)

| Stands | | Sites | | | | | |
|---|---|---|---|---|---|---|---|
| Species | Age | Location | Lat. N | Long. E | Alt. (m) | Temperature (°C) | Precipitation (mm) |
| *P. radiata* | 16 | Felitto (FEL) | 40°02′ | 15°28′ | 184 | 14.1 | 668 |
| *P. radiata* | 29 | Palata (PAL) | 41°47′ | 15°80′ | 502 | 13.7 | 658 |
| *P. radiata* | 17 | Cassino (CAS) | 41°63′ | 09°17′ | 180 | 14.5 | 748 |
| *P. menziesii* | 35 | Brasimone (BRA) | 44°08′ | 11°08′ | 860 | 10.2 | 755 |

Table 2
The HYDRALL model: functional and structural parameters and initial site conditions required in the model

| | Units according to equation/definitions | Reference |
|---|---|---|
| Functional and structural parameters | | |
| Photosynthetic quantum efficiency | mol $e^-$ quantum$^{-1}$ | Farquhar and von Caemmerer (1982) |
| Maximum carboxylation rate | mol $m^{-2}$ $s^{-1}$ | Farquhar and von Caemmerer (1982) |
| Coefficient in $g_s$ vs. $A$ equation | $Pa^{-1}$ | Leuning (1995) |
| Coefficient in $g_s$ response to vapour pressure deficit | Pa | Leuning (1995) |
| Stomatal conductance to $CO_2$ in darkness | mol $m^{-2}$ $s^{-1}$ | Leuning (1995) |
| Critical leaf water potential for xylem embolism | MPa | Magnani et al. (2000) |
| Soil water potential for maximum stomatal closure | MPa | Magnani et al. (2000) |
| Specific hydraulic conductance of fine roots | $m^3$ $s^{-1}$ $MPa^{-1}$ $kg^{-1}$ | Magnani et al. (2002) |
| Specific hydraulic conductivity of sapwood | $m^3$ $s^{-1}$ $MPa^{-1}$ $kg^{-1}$ | Magnani et al. (2002) |
| Root longevity | year | Magnani et al. (2002) |
| Sapwood longevity | year | Magnani et al. (2002) |
| Foliage density in the canopy | kg $m^{-3}$ | Persson (1980) |
| Growth respiration coefficient | – | Lloyd and Taylor (1994) |
| Nitrogen concentration in foliage | kg N $kg^{-1}$ | |
| Nitrogen concentration in fine roots | kg N $kg^{-1}$ | |
| Nitrogen concentration in sapwood | kg N $kg^{-1}$ | |
| Site initial conditions | | |
| Initial old organic matter in soil | kg DM $m^{-2}$ | Andrén and Kätterer (1997) |
| Initial young organic matter in soil | kg DM $m^{-2}$ | Andrén and Kätterer (1997) |
| Soil fraction of sand particles | $m^3$ $m^{-3}$ | |
| Soil fraction of silt particles | $m^3$ $m^{-3}$ | |
| Depth of soil explored by roots | m | |

$A$ = assimilation rate; $g_s$ = stomatal conductance.

diameter distribution and diameter–height relationship, six trees of 'average' diameter and height were felled in each stand and subjected to complete stem analysis, in order to reconstruct the past volume and height of each tree. The analysis involved the examination of growth rings of stem discs, 2–5 cm thick, taken 1 m apart along the entire stem (Hush et al., 2002). Stand volumes and heights at different ages were estimated from historical values of these 'mean' trees, assuming the social position of trees did not change, so that sampled trees could be considered as 'mean' trees also in the past. This is considered as a reasonable assumption since no sudden change in ring width was observed and given the rather short stand life period here considered (Table 1).

### 2.2. Model description

The HYDRALL model simulates the growth of a coniferous forest stand over a whole rotation. The model focuses on the key determinants of plant

Table 3
Simulation periods at different sites

| Species/site | Interval | Simulation period (years) |
|---|---|---|
| *P. menziesii*/BRA | 1 | 1962–2002 |
| | 2 | 1990–2030 |
| | 3 | 2010–2050 |
| | 4 | 2030–2070 |
| | 5 | 2050–2090 |
| *P. radiata*/PAL | 1 | 1974–2014 |
| | 2 | 1990–2030 |
| | 3 | 2010–2050 |
| | 4 | 2030–2070 |
| | 5 | 2050–2090 |
| *P. radiata*/FEL | 1 | 1981–2021 |
| | 2 | 1995–2035 |
| | 3 | 2015–2055 |
| | 4 | 2045–2085 |
| | 5 | 2055–2095 |
| *P. radiata*/CAS | 1 | 1980–2020 |
| | 2 | 1990–2030 |
| | 3 | 2010–2050 |
| | 4 | 2030–2070 |
| | 5 | 2050–2090 |

growth: light interception and gas exchange, water relations and growth allocation. In comparison with other existing forest growth models, growth allocation among tree organs is not fixed, but responds dynamically to internal and external conditions. A description of key model features follows.

### 2.2.1. Light absorption and vertical profiles

The absorption of global radiation by the sunlit and the shaded portion of a coniferous canopy, the computation of foliage isothermal net radiation and vertical integration of leaf photosynthetic parameters are based on the two-leaf model of De Pury and Farquhar (1997).

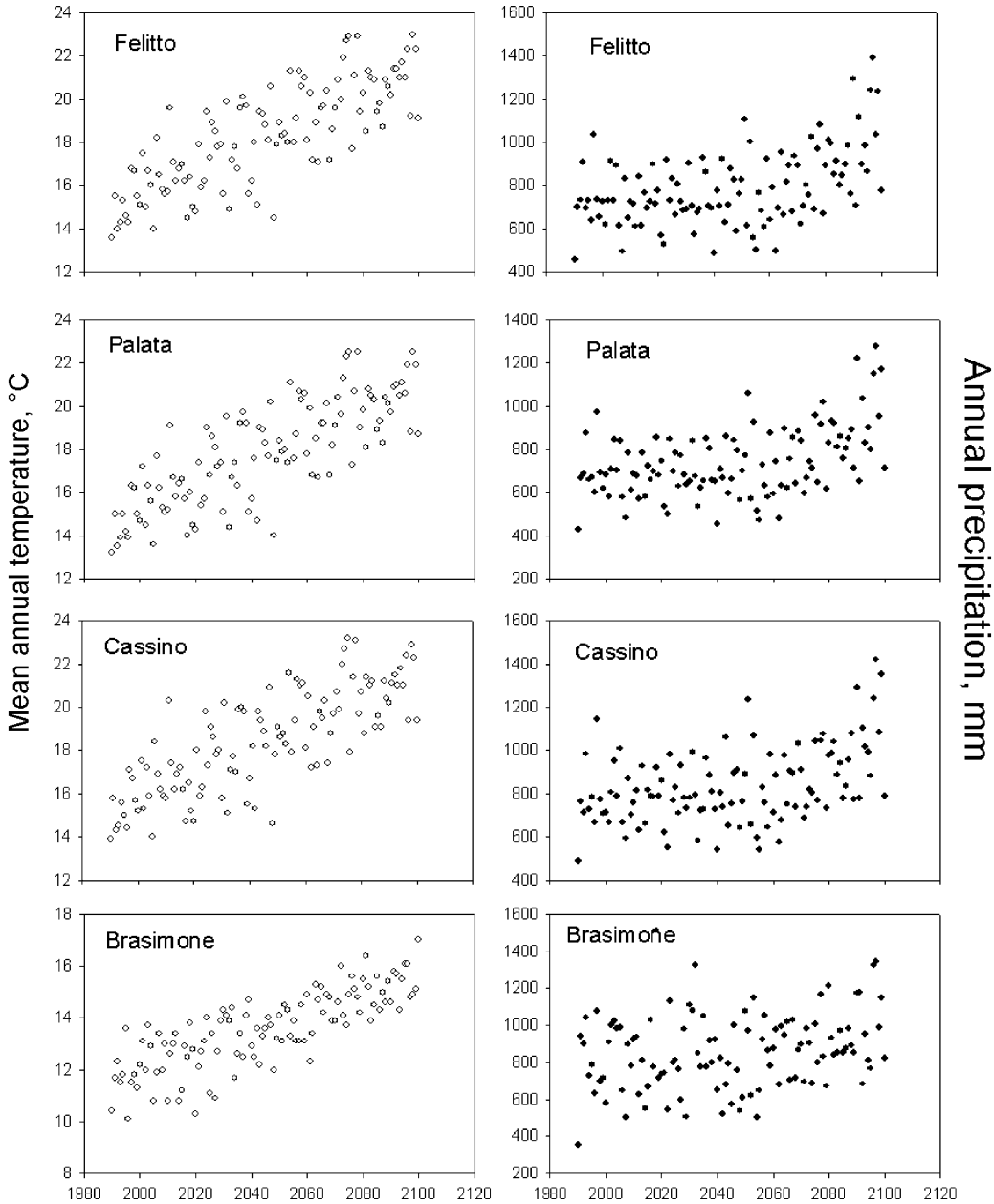


Fig. 1. Mean annual temperatures (left panels) and annual precipitation (right panels) predicted by the HadCM2 model at the study sites.

A vertical exponential profile of leaf nitrogen content over the canopy is assumed, parallel to the reduction in diffuse photosynthetic photon flux density (PPFD), and both dark respiration and maximum carboxylation rates are assumed to be proportional to leaf nitrogen (Leuning, 1997). Stand aerodynamic conductance is computed iteratively as a function of wind speed and sensible heat flux from the canopy (Garratt, 1992).

### 2.2.2. Assimilation and respiration

The representation of leaf assimilation is based on the Farquhar model (Farquhar and Von Caemmerer, 1982) and the response of leaf assimilation to PPFD follows Farquhar and Wong (1984). The dependence of stomatal conductance upon assimilation and air vapour pressure deficit is captured by the Leuning (1995) model, whilst a simple linear dependence of stomatal conductance upon soil water potential is assumed. Following Landsberg and Waring (1997), it is assumed that no gas exchange takes place whenever minimum daily temperature falls below zero. Sapwood and fine root respiration are computed as a function of average daily temperature, tissue biomass and nitrogen content (Ryan, 1991). The empirical model presented by Lloyd and Taylor (1994) is used to represent the dependence of tissue (and soil) respiration upon temperature. Growth respiration is assumed to be a constant fraction of available carbon (Thornley and Johnson, 1990).

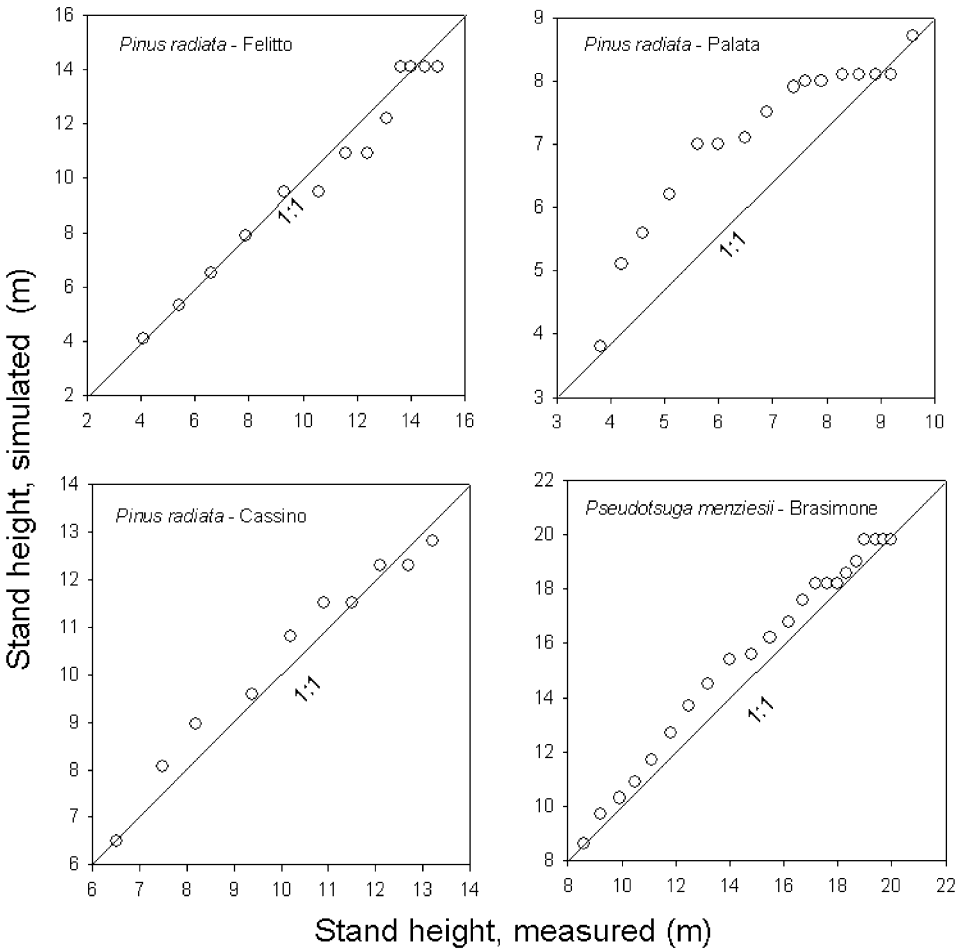


Fig. 2. Comparison between measured and simulated stand height at the study sites; the 1:1 line is reported.

*2.2.3. Water transport, growth and carbon allocation*

The transport of water through the soil–plant continuum has been modelled as described in Magnani et al. (2002). Soil water potential and hydraulic resistance are a function of soil water content, soil texture and fine root density (Campbell, 1985). Root resistance is assumed to be inversely related to fine root biomass (Magnani et al., 1996), whilst aboveground resistance is a simple function of sapwood basal area and tree height (Whitehead et al., 1984). Growth allocation among foliage, sapwood and fine roots is driven by the assumption of optimal plant growth under hydraulic constraints; a single wood compartment, comprising both stem and branches, is represented (Magnani et al., 2000, 2002). In particular, growth partitioning among tree organs is not fixed, but responds to the environment according to the hypothesis of functional homeostasis in water transport, resulting in the acclimation of plant's structure to climatic conditions. The basic assumption is that there must be a balance in the hydraulic architecture of trees, in order to prevent xylem water potential from decreasing to values that would trigger runaway embolism and foliage dieback (Magnani et al., 2000).

*2.2.4. Soil carbon dynamics*

The two-compartment model of Andrén and Kätterer (1997) has been chosen to represent soil respiration and the transition from young to old soil carbon pools. A constant humification coefficient is assumed. Decomposition of young and old organic matter and humification are affected to the same extent

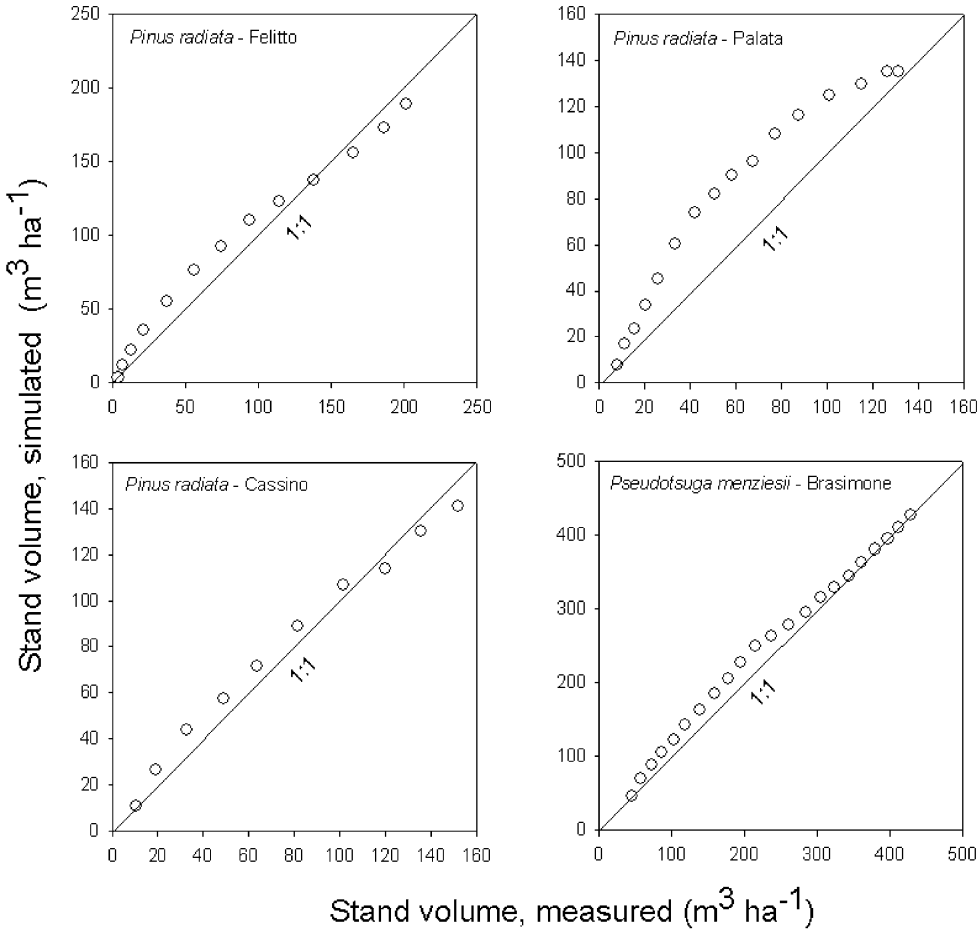


Fig. 3. Comparison between measured and simulated stand volume at the study sites; the 1:1 line is reported.

by soil temperature and soil water potential, as captured by the multiplicative model of Andrén and Paustian (1987).

The representation of both tree mortality and understorey processes was swiched off in current model simulations, given the stand characteristics described in the previous paragraph.

### 2.3. Simulation procedures and climate change scenarios

Climatic variables required as input in the model are: monthly averages of minimum and maximum daily temperatures, relative humidity, wind speed, monthly totals of global radiation and precipitation. Functional parameters and initial conditions are listed in Table 2.

As for the comparison with stand growth data, model underwent an initial calibration; indeed, modelled stand characteristics were adjusted to approximately fit 'real' stand characteristics in correspondence with the 'first' stand age reconstructed from stem analysis. No further adjustments were performed.

The following outputs are produced by the model on a yearly time step: stand density and height, gross and net primary production (GPP and NPP), net ecosystem exchange (NEE), transpiration ($E$), total tree biomass and its distribution among plant organs: leaves, stem (including branches and coarse roots) and fine roots.

For modelling stand growth under current climate, input variables were obtained from climatic records at nearby meteorological stations. For modelling 'future' stand growth, climate scenarios were produced using the General Circulation Model (GCM) projections of the HadCM2 model (Mitchell et al., 1995). The scenario data provides monthly values of climate data in $3.75^\circ \times 2.5^\circ$ spatial resolution based on the emission scenario IS92a ('business as usual'; Houghton et al., 1996), which assumes an exponential increase of carbon dioxide concentration, from 350 $\mu$mol mol$^{-1}$ in 1990 to 700 $\mu$mol mol$^{-1}$ in 2100. Downscaling of the GCM grid cell data to local sites was performed using a thin plate interpolator, taking account of elevation dependencies of climatic variables (Hutchinson, 1995). Comparison of GCM outputs for historic climate with concurrent

Table 4
Characteristics of stands simulated over different time intervals (see Table 3)

| Species/site | Simulation interval | $V_{40}$ (m$^3$) | $H_{40}$ (m) | MAI$_{40}$ (m$^3$ ha$^{-1}$ year$^{-1}$) |
|---|---|---|---|---|
| *P. radiata*/FEL | 1 | 490 (–) | 23.7 (–) | 12.3 (–) |
| | 2 | 496 (+1) | 22.5 (−5) | 12.4 (+1) |
| | 3 | 511 (+4) | 24.6 (+3) | 12.8 (+4) |
| | 4 | 521 (+6) | 25.7 (+8) | 13.0 (+6) |
| | 5 | 544 (+11) | 24.9 (+5) | 13.6 (+11) |
| *P. radiata*/CAS | 1 | 405 (–) | 20.1 (–) | 10.1 (–) |
| | 2 | 415 (+2) | 20.4 (+1) | 10.4 (+2) |
| | 3 | 440 (+9) | 23.1 (+15) | 11.0 (+9) |
| | 4 | 484 (+19) | 26.2 (+30) | 12.1 (+19) |
| | 5 | 484 (+19) | 22.7 (+13) | 12.1 (+19) |
| *P. radiata*/PAL | 1 | 203 (–) | 12.5 (–) | 5.1 (–) |
| | 2 | 199 (−1) | 11.6 (−7) | 5.0 (−2) |
| | 3 | 212 (+4) | 12.0 (−4) | 5.3 (+4) |
| | 4 | 207 (+2) | 10.6 (−15) | 5.2 (+2) |
| | 5 | 225 (+11) | 9.5 (−24) | 5.6 (+11) |
| *P. menziesii*/BRA | 1 | 566 (–) | 22.5 (–) | 14.1 (–) |
| | 2 | 711 (+26) | 29.2 (+29) | 17.8 (+26) |
| | 3 | 773 (+37) | 29.4 (+30) | 19.3 (+37) |
| | 4 | 883 (+56) | 33.2 (+47) | 22.1 (+56) |
| | 5 | 976 (+73) | 34.8 (+55) | 24.4 (+73) |

$V_{40}$, $H_{40}$ and MAI$_{40}$ are stand volume, stand height and mean annual increment at 40 years (average for the 38–42 age interval); in brackets, percent change of variables with respect to simulated values at interval 1.

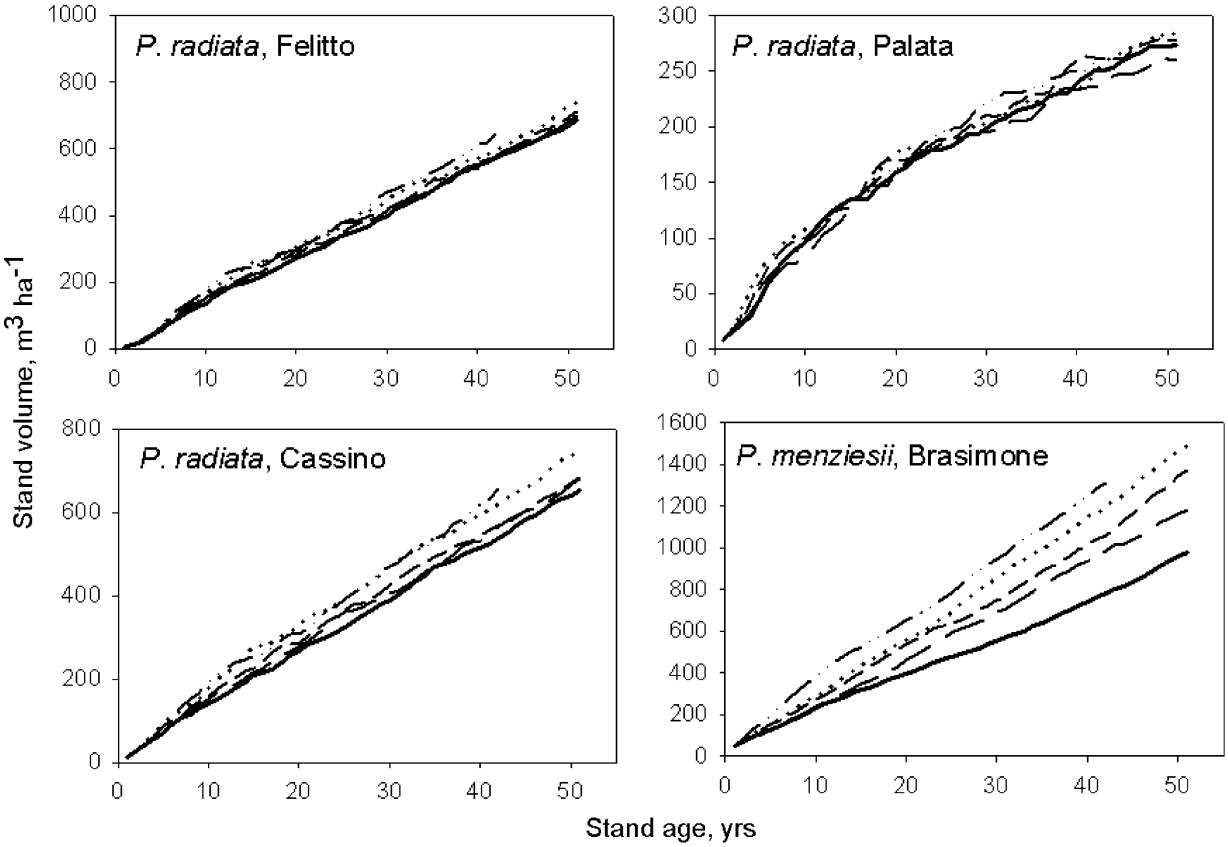


Fig. 4. Effects of climate change on stand volume; continuous line, long-dashed, short-dashed, dotted and dashed-dotted lines refer to 50 years rotation periods for stands simulated over time intervals 1, 2, 3, 4, 5, as specified in Table 3.

meteorological records was used for a better tuning of climate projections, using differences between calculated and measured monthly data for corrections.

Stands were simulated over different time intervals in the period 1960–2090, as shown in Table 3.

## 3. Results and discussion

### 3.1. Climate change scenarios

According to general expectations for the Mediterranean area (Houghton et al., 1996), the applied GCM predicted a linear increase of temperature during the period 1990–2100 (Fig. 1). Predicted temperature increase was about 0.06 and 0.04 °C year$^{-1}$ at sites where *P. radiata* and *P. menziesii* plantations have been simulated, respectively. In contrast to most GCM results for the Mediterranean area, where a slow decrease in precipitation is normally predicted (Christensen et al., 1997), GCM simulations showed a moderate increase in total annual precipitation until 2050; later on, a higher increase in precipitation can be found with a peak value around 2090 (Fig. 1). The use of the 1931–1960 time interval as reference period for calculating climatic anomalies (instead of 1961–1990, as in most other cases) may account for this discrepancy. In general, projections of precipitation are affected by large uncertainties in areas with high convective rainfall (Houghton et al., 1996). Changes in annual precipitation were found to be mainly determined by an increase in winter rainfall (October to February); in summer (June to August) rainfall is predicted to be

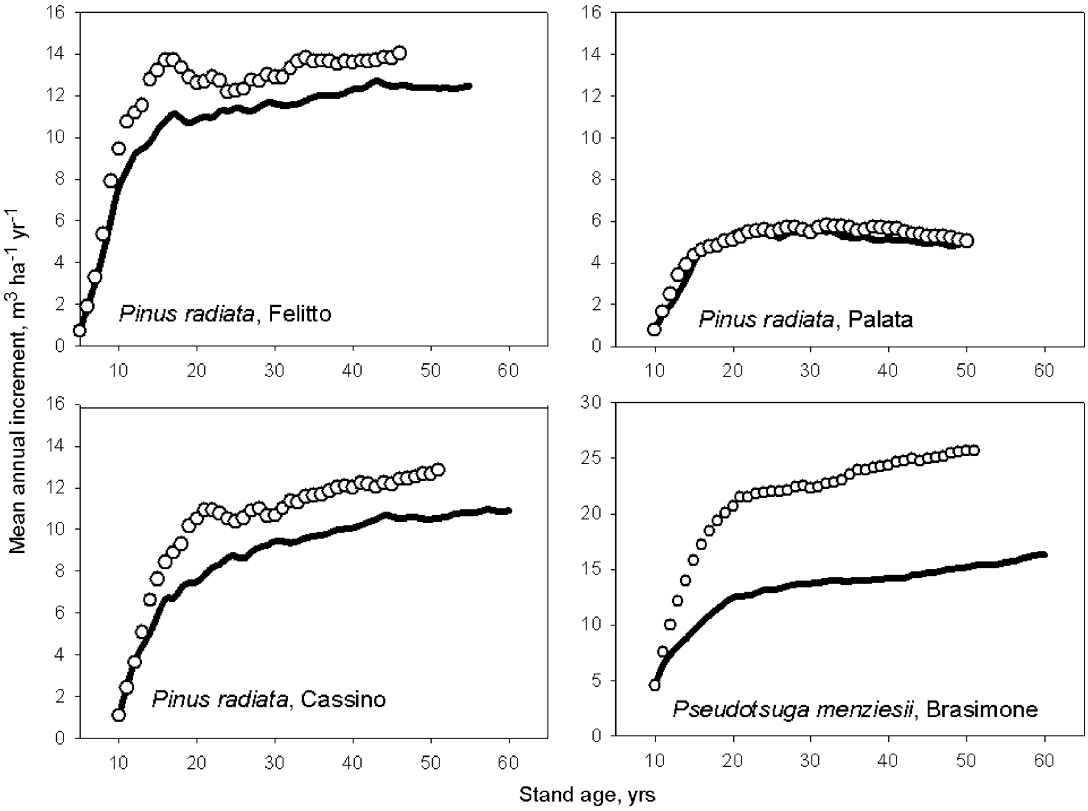


Fig. 5. Effects of climate change on mean annual increment (MAI); bold continuous line and open circles refer to stands simulated over time intervals 1 and 5, as specified in Table 3.

slightly lower than under present climate. Overall, the enhanced evaporative demand driven by increased temperatures may not be compensated by the increase of rainfall. Indeed, a more intense and prolonged summer drought period was estimated in most sites by comparing Walter-Lieth climate diagrams for the 1961–1990 and 2071–2100 periods (data not show). For both temperature and precipitation a high interannual variability was predicted, stressing the need for careful consideration of the effects of extreme climatic events.

### 3.2. Measured and simulated growth patterns

Modelled stand growth has been compared with growth patterns reconstructed by stem analysis, with appreciable results (Figs. 2 and 3). Final stand volume predicted by the model was −6.1, −7.3 and +2.4% with respect to measured final stand volume, respectively, for *P. radiata* in Felitto, Cassino and Palata; −0.05% for *P. menziesii* in Brasimone. Overall, an appreciable convergence between simulated and measured stand growth patterns was observed in three out of four cases. The only case of discrepancy between measured and simulated growth patterns was *P. radiata* in Palata, where both stand height and volume are overestimated over a substantial part of the rotation period, possibly as an effect of rather strong soil limitations in this site (more than 60% of clay), which the model does not seem able to capture properly (Figs. 2 and 3).

### 3.3. Climate change effects

The effects of climate change on forest growth were explored by simulating 50-year growth periods (a whole stand rotation, approximately, starting from the plantation each time) over different time intervals

Table 5
Distribution of tree biomass among foliage ($W_f$), stem ($W_s$) and fine roots ($W_r$) at the age of 40 (average for the 38–42 age interval) for stands simulated over different time interval (see Table 3)

| Species/site | Simulation interval | $W_f$ | | $W_s$ | | $W_r$ | |
|---|---|---|---|---|---|---|---|
| | | kg m$^{-2}$ | % | kg m$^{-2}$ | % | kg m$^{-2}$ | % |
| *P. radiata*/FEL | 1 | 0.66 | 6.8 | 8.6 | 89.8 | 0.33 | 3.4 |
| | 2 | 0.65 | 7.4 | 7.9 | 89.2 | 0.30 | 3.4 |
| | 3 | 0.69 | 7.7 | 8.0 | 89.3 | 0.27 | 3.0 |
| | 4 | 0.63 | 7.1 | 7.9 | 89.9 | 0.27 | 3.0 |
| | 5 | 1.00 | 9.8 | 8.9 | 87.2 | 0.30 | 2.9 |
| *P. radiata*/CAS | 1 | 0.61 | 7.4 | 7.3 | 88.6 | 0.33 | 4.0 |
| | 2 | 0.76 | 9.5 | 6.9 | 86.7 | 0.30 | 3.8 |
| | 3 | 0.48 | 5.7 | 7.6 | 90.8 | 0.29 | 3.5 |
| | 4 | 0.57 | 6.4 | 8.1 | 90.8 | 0.25 | 2.8 |
| | 5 | 0.76 | 8.3 | 8.1 | 88.3 | 0.31 | 3.4 |
| *P. radiata*/PAL | 1 | 0.24 | 4.6 | 4.8 | 89.7 | 0.31 | 5.8 |
| | 2 | 0.22 | 4.5 | 4.3 | 89.3 | 0.30 | 6.2 |
| | 3 | 0.21 | 3.9 | 5.0 | 90.5 | 0.31 | 5.6 |
| | 4 | 0.23 | 4.4 | 4.6 | 88.9 | 0.35 | 6.6 |
| | 5 | 0.28 | 4.4 | 5.6 | 88.7 | 0.43 | 6.8 |
| *P. menziesii*/BRA | 1 | 0.95 | 8.8 | 9.5 | 88.3 | 0.30 | 2.8 |
| | 2 | 1.34 | 9.0 | 13.2 | 88.6 | 0.36 | 2.4 |
| | 3 | 2.17 | 13.2 | 13.9 | 84.5 | 0.37 | 2.3 |
| | 4 | 2.44 | 12.6 | 16.5 | 85.4 | 0.39 | 2.0 |
| | 5 | 2.48 | 12.3 | 17.2 | 85.7 | 0.40 | 2.0 |

between 1960 and 2090 (see Table 3). According to models results, climate change had a positive effect on stand growth patterns; the largest effect was found for *Pseudotsuga menziesii* (73 and 55% increase for stand volume and height at the age of 40). The exception is *P. radiata* in Palata, where changes in volume growth are small and height growth is reduced over the considered period (Fig. 4 and Table 4). Mean annual increment (MAI) was also stimulated by climate change, with the exception of *P. radiata* in Palata. On the other hand, no change in MAI temporal patterns has been observed at any site (Fig. 5). Thus, the hydraulic constraint accounted for in the model (Magnani et al., 2000), whose effect might have been anticipated by enhanced height increments, did not translate in an earlier decline of above ground productivity.

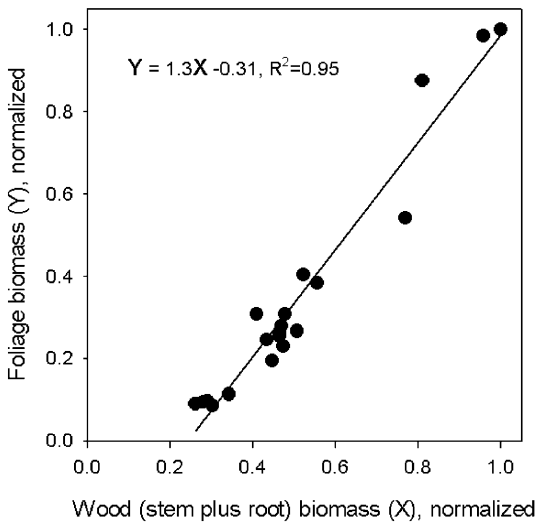


Fig. 6. Foliage biomass versus wood (stem and root) biomass, for stands simulated over different time intervals, at the age of 40; from values reported in Table 5 for all sites and species.

As far as biomass distribution between tree organs is compared between the first and the fifth simulation interval (Table 5), at all sites but *P. radiata* in Palata the model predicts an increase in foliage allocation fraction (44, 12 and 40% increase, respectively, for *P. radiata* in Felitto and Cassino and for *P. menziesii* in Brasimone). In general, total biomass increased over successive simulation intervals, with foliage biomass increasing at a faster rate than wood (stem plus roots) biomass (Fig. 6). Thus, the assumptions of functional homeostasis in water transport and optimal plant acclimation implemented in the model tend to

translate in some adjustment of tree structure to the environment. Allocation to fine roots was also predicted to change; in particular, with the exception of *P. radiata* in Palata, where the proportion of biomass allocated to fine roots compartment increased by 17%, a decrease of 30% in fine root allocation fraction was predicted for *P. menziesii* in Brasimone and a 15% decrease was predicted for *P. radiata* in Cassino and Felitto (Table 5).

Combined effects of soil properties (soil texture and depth) and summer drought may likely account for greater allocation to fine roots and decreased allocation to foliage predicted for pine in Palata. In a recent simulation study on the variability of *Pinus sylvestris* growth across Europe, the HYDRALL model predicted a substantial increase in the amounts of resources allocated to fine roots under dry conditions (Magnani et al., unpublished data).

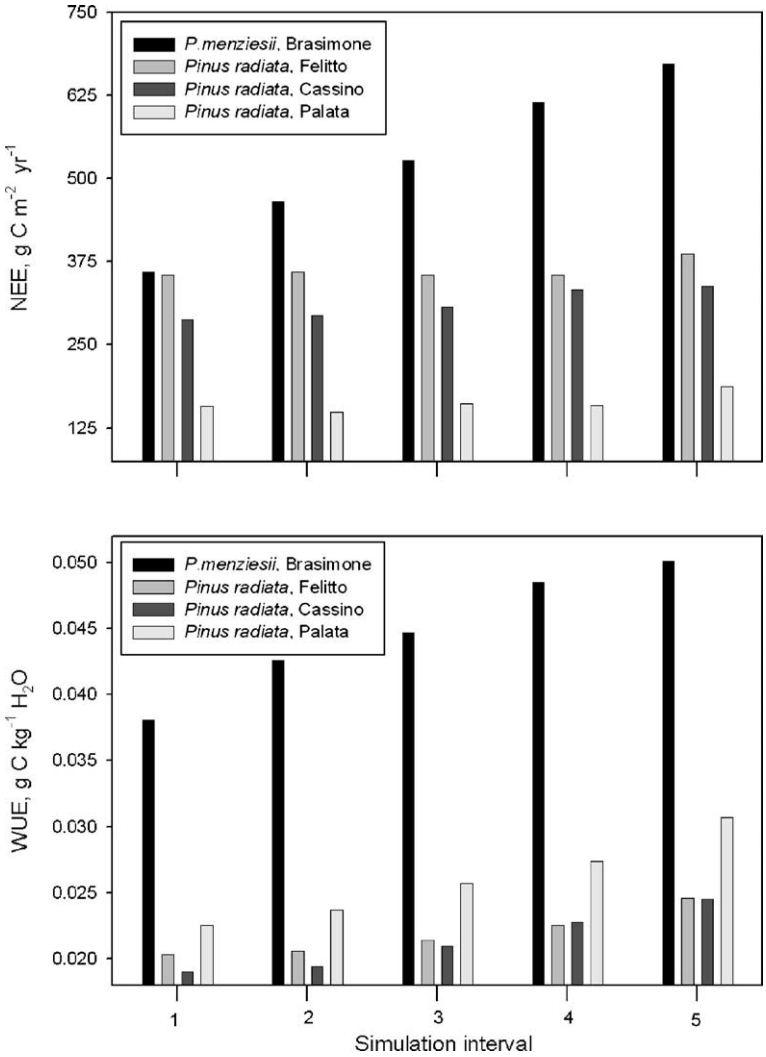


Fig. 7. Effects of climate change on net ecosystem exchange (NEE, upper panel) and water-use efficiency (WUE, lower panel); NEE and WUE values at the age of 40 (average for the 38–42 age interval) are shown for stands simulated over different time intervals in the period, as specified in Table 3; WUE at a given age has been calculated as the ratio between cumulated values of net primary production (NPP) and evapotranspiration (*E*).

As far as empirical evidence is considered, no structural acclimation in response to changes in soil water availability was observed in a 3-year study on *P. radiata* (McMurtrie and Landsberg, 1992), while an irrigation treatment was found to affect the accumulation of biomass by different aboveground plant components in a *Eucalyptus globulus* plantation (Reed and Tomé, 1998).

A clear positive effect of climate change on net ecosystem exchange (NEE) can be stated only for *P. menziesii* in Brasimone, where NEE increased more than 80% over the considered period. In contrast, no effect was observed in the case of *P. radiata* plantations. Water-use efficiency has been estimated as the ratio between net primary production (NPP) and stand evapotranspiration (*E*); in this case a positive effect has been found not only for *P. menziesii* (more than 30% increase), but also for *P. radiata* (29% increase as average for different sites) (Fig. 7).

Reaction of forest growth to climate change is a complex response, strongly dependent on combinations of climatic and site conditions (see Kirschbaum (1999) for a discussion based on both experimental and modelling results). In the above-cited study on *Pinus sylvestris*, the HYDRALL model allowed to dissect the effects of climatic factors on tree growth (Magnani et al., unpublished data). However, analysing quantitatively the effect of single factors of climate change was beyond the aims of present paper. It seems reasonable, nevertheless, to attribute the positive effect of climate change on stand growth mainly to the $CO_2$ fertilisation effect; such an effect could be larger at sites where no condition of heavy drought occurred, as in the case of *P. menziesii* at the northernmost site. In general, a strong effect of climate change on growth is predicted in regions where soil water is not a strong limiting factor (Cannell et al., 1989). Even in the case of NEE patterns, results suggest that only under the more favourable conditions experienced by *P. menziesii*, the enhancement of gross primary production by $CO_2$ and temperature increase was not compensated by stimulation of respiratory processes. In any case, no negative effects of climate change on NEE have been observed also under more critical conditions in terms of summer drought. This seems in agreement with the evidence that under Mediterranean conditions temperature effects on respiratory processes and soil organic matter dynamics could be effectively counteracted by higher soil water deficit (Reichstein et al., 2002).

In contrast, water-use efficiency increased in all sites. Both WUE components (net primary production and transpiration) were affected by climate change, but NPP stimulation was not compensated by the increase of transpiration rate. Water-use efficiency is considered a key functional trait under conditions of high light availability and low soil water content (Dewar, 1997); thus, such predictions may be viewed as of special interest for areas where enhanced evaporative demand determined by the increase of temperature may not be offset by the increase of rainfall.

## 4. Concluding remarks

The main evidence from this modelling exercise are: (i) at all the considered sites in Italy an increase of both temperature and precipitation is predicted by the HadCM2 General Circulation Model over next century; (ii) the HYDRALL model predicts a positive effect of climate change on stand growth patterns, where no soil limitations occur, and an increase in foliage allocation fraction; (iii) water-use efficiency is also predicted to increase.

## Acknowledgments

Research work jointly supported by grants from the European Union (Project: Long-term effects of climate change on European forests: impact assessment and consequences for carbon budgets, LTEEF-II, ENV4-CT97-0577) and from Italian M.I.U.R. (Project COFIN 2000—Carbon balance and stocks in forest ecosystems: physiological determinants, age-related effects and environmental constraints). We thank Antonio Lapolla and Nicola Moretti for assistance in field work and stem growth analysis. Thanks are also due to two anonymous referees for useful comments on the earlier version of the manuscript.

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