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Climate change effects on mediterranean forests and preventive measures

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Abstract This paper synthesizes and reviews literature concerning climate change effects on Mediterranean forest ecology and management as well as the restorative techniques necessary to maintain forest health, forest yield and biodiversity. Climate change compounded with trends of rural abandonment are likely to diminish forested areas within the Mediterranean basin that will be replaced by fire prone shrub communities. This could be favoured by outbreaks of pathogens, fire and other large-scale disturbances. Landscape fragmentation is expected to impede species migration. Annual increments and subsequent income from forests are expected to decrease. Reafforestations are necessary to ensure the presence of propagules of forest species and their site-specific varieties best adapted to future climatic conditions even though they may be different from the present forest-plant community. Current challenges in biodiversity conservation can only be met by afforestations whose main objective is to maintain ecosystem functioning. A new silviculture must emerge encompassing these habitat displacement and economic concerns while maximizing carbon sequestration.

Keywords Global warming · Mitigation strategies · Forest restoration · Reforestations · Biodiversity · Carbon sequestration

Introduction

Climate change is one of the major challenges for forestry in the coming decades since it is expected to drastically modify growing conditions for trees. Observed changes in climatic trends include a decrease in precipitation in the Mediterranean

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area for the period 1961–1990 (De Luís et al. 2001; Peñuelas et al. 2002; Piñol et al. 1998). Not only has precipitation decreased, but annual rainfall patterns have changed with increasing intensity of rains (De Luís et al. 2001).

Temperature is expected to increase between 2 and 4°C over the next century in the Mediterranean basin (Palutikof and Wigley 1996; Rambal and Hoff 1998). Precipitation is expected to decrease in summer and autumn, but to increase in winter, resulting in higher intensity precipitation events, reduction of soil moisture (Déqué et al. 1998) and an overall decrease in water availability due to increased evapotranspiration. Climate models project that increasing atmospheric concentrations of greenhouse gases will result in changes in the frequency, intensity, and duration of extreme events with more hot days, heat waves, heavy precipitation events, and fewer cold days (Hulme and Sheard 1999; IPCC 2001a), although the magnitude of these changes is difficult to predict.

The changes in the pattern of rainfall distribution may have a stronger effect on forest growth than the decreased precipitation because trees are adapted to grow within the constraints of a given climate and water regime. Although forest stands show some plasticity to cope with unstable conditions, growth and vitality are expected to suffer with changes in timing and duration of water stress.

Research on global warming effects on forest ecosystems has focused on the physiological-level (e.g., Castells et al. 2002; Catovsky et al. 2002; Peñuelas and Llusià 2003) as well as on landscape-level responses (e.g., Peñuelas and Boada 2003). There is also rising interest in studying the increase of carbon sequestration through forest management (e.g., Canadell and Pataki 2002; Guo and Guifford 2002). There are only a few studies focusing on the impact that global warming is expected to have on forestry practices, which, in turn, largely determine future forest composition and structure in this changing environment (Lindner 2000). And there is a general lack of information on climate change effects for particular biomes.

In this paper we review more than 60 studies, including both modelling and empirical studies, addressing the effects of global warming on forest ecosystems. These studies were obtained from exhaustive searches on CAB Abstracts and Web of Science since the early 1980's when climate change studies began to appear. We selected two kinds of papers: (1) those which presented quantitative and empirical analyses on the observed consequences of climatic change on forests under controlled conditions or in natural forests and (2) abstraction studies that model the modifications that global warming is expected to have on Mediterranean forests and forestry. These papers were selected because they met two criteria: (1) they provided relevant and specific information on the modifications of the functioning and management of Mediterranean forests due to climate change and (2) proposed management strategies to mitigate these modifications. Our objective is to assess the current understanding of global warming on Mediterranean forests, with special emphasis on forest management so as to provide general and specific information and strategies for forestry practices in the coming decades that may be useful for foresters, forest researchers and policy makers.

Impacts of Predicted Changes

Forest health

Significant disruptions of ecosystems from disturbances such as fire, drought, pathogens, invasion of exotic species and storms are expected to increase (IPCC

2001b). Generally pathogens and trees are in a balance in which the pathogen's virulence is just enough to kill weak trees but those growing at their full potential are able to complete their life cycle without any serious interference from the pathogen. As trees are weakened by unfavourable environmental conditions an increasingly larger proportion will become susceptible to pathogens. This will have a twofold effect on the pathosystem. First, many trees will die reducing the standing biomass, and second, the pathogen population will build up to the point of threatening trees that perhaps could resist a light attack but not a heavy infestation. Losses will probably be greatest for trees on the edges of their natural distribution where a small change will make the environment unsuitable for them. Some forest diseases now considered minor may become serious.

Climate change may be implicated in the increasing incidence of oak declines such as *Quercus ilex* L., (holm oak) decline due to *Phytophtora cinnamomi* Rands (Phytophtora root rot) in the Iberian peninsula (Brasier 1996; Sánchez et al. 2000). *P. cinnamommi* requires wet soil conditions to proliferate which are not typical of the holm oak habitat. In the last few decades floods have occurred more frequently creating favourable conditions for pathogen proliferation in these forests (De Luís et al. 2001). These floods have been followed by drought events that have weakened the trees and made them more susceptible to the pathogen, resulting in higher mortality than ever before.

Olivera and Colinas (1995) found general decline for *Quercus suber* L. (Cork oak) in Northeastern Spain associated with a 30-years weather trend of increased warming and dryness. This may be a short term fluctuation or a long term trend that will increase with time. Attempts to forecast an interaction of climate change with such ecologically complex and possibly even chaotic sets of processes as oak decline phenomena or pathogen activity must be taken with caution (Brasier 1996; Sánchez et al. 2000). But given our knowledge of life cycles, habitats, and infection patterns of important pathogens we may anticipate and monitor for potential problems that may be mitigated or controlled if diagnosed early.

Ceratocysits ulmi (Buism.) Moreau (Dutch-elm disease) and *Hypoxylon mediterraneum* (De Not.) J. H. Miller (Hypoxylon canker) attacks are likely to become more active in southern Europe through global warming since these fungi are favoured by high temperatures and dry conditions (Tainter and Baker 1996). *Heterobasidion annosum* (Fr.:Fr.) Bref. (Heterobasidion root rot) is likely to cause increasing damage in northern latitudes where the present temperatures only allow infection of new wounds in the warm months, and it may cause decreasing damage in southern latitudes where it cannot infect new wounds in the hotter months because they dry too quickly (Tainter and Baker 1996). The overall effects will probably be more complex with variations corresponding to different geographical regions.

Special attention must be given to *Bursaphelenchus xylophilus* (Steiner and Buhrer) (Pine wilt nematode), which damaged about 2.3 Mm^3 of pine timber in Japan in 1979 (Sasse 1998). This pathogen was found in Portugal for the first time in 1999 (Mota et al. 1999) and the affected populations have remained stable so far. Given that this nematode is currently limited by cold temperature, strong prevention to avoid colonization of new areas is essential because, with new stress conditions and warming temperatures, forests will become more susceptible and the nematode's potential distribution in Europe will increase.

Hódar et al. (2003) showed that *Thaumetopoea pytiocampa* Denis and Schiffermüller (Pine tent caterpillar) could increase its defoliation effects on Spanish

Pinus sylvestris L. (Scots pine) populations with climatic warming, causing increased mortality. In turn, this would decrease seed production, seed mass and seedling survival. *P. sylvestris* seems to be particularly sensitive to drought suggesting that this pine species may become endangered in the Mediterranean basin especially in the relict stands of its southernmost location on isolated high mountains (Hódar et al. 2003; Martínez-Vilalta and Piñol 2002).

Species migrations and displacements

If temperatures change as rapidly as predicted, then the reassembly of ecological communities should take place within the life span of individual trees, which is much faster than occurred during the advance and retreat of the glaciers (IPCC 1990). However, natural homeostasis may slow down climate change effects (Allué-Andrade 1995). According to the Convention on Biological Diversity (CBD 2001), early models which forecasted shifts in forest biomes or ecosystems as intact entities as a response to climate change are no longer considered useful. As communities are the result of interactions among organisms as well as among organisms with their abiotic environment, we may expect that rapid climate change may alter species assemblage composition (Walther et al. 2002). However, a current biome shift has been documented recently (Peñuelas and Boada, 2003) in which *Calluna vulgaris* (L.) Hull (Heather) and *Fagus sylvatica* L. (European beech) in the higher elevations are being replaced by *Q. ilex* as it extends beyond the former upper limit of its range with onset of the milder weather conditions.

Lloret et al. (2004) present four different hypotheses to predict which populations are most likely to be affected by global warming. The first is the selection hypothesis, which predicts that the less abundant species are more likely to disappear as they are presently at the extremes of their range and will face more problems with seed dispersal. The following populations would be more prone to disappearance: (1) peripheral populations of trees in ecotones, (2) geographically localised species which have no populations in other areas of suitable habitat, (3) species with limited genetic diversity, (4) specialised species which require a narrow range of environmental conditions during some phase of their life, (5) poor seed dispersers, (6) montane and alpine species, and (7) freshwater and coastal wetland forest types (Allué-Andrade 1995; CBD 2001; Kräuchi 1993; Layser 1980; Neilsen 1993; Peters and Darling 1985). The aforementioned decrease of *P. sylvestris* stands growing at their altitudinal limit supports the selection hypothesis.

There are three additional hypotheses according to Lloret et al. (2004). The sampling hypothesis states that species loss is proportionally related to species abundance. This applies when seedling recruitment is reduced by drought but mortality is not increased once seedlings have been established (Lloret et al. 2004).

In contrast, the idiosyncratic hypothesis asserts that the loss of a species is completely unrelated to species abundance. The predictions of this hypothesis are demonstrated when species dispersal and the ability to conquer new sites are particularly important.

Finally, the shift hypothesis states that under new conditions, and in response to extreme events, some previously rare species may become dominant and vice versa. This may occur when previously dominated plants and those from the understory are more resistant to drought than the canopy species and a shift in dominance takes place.

Past records of treeline elevation suggest a 100 m shift for each 1°C change in temperature (Perry 1994) although it is highly species dependent. Modern trees are unlikely to migrate as fast as those of 10,000 years ago because freeways, cities and farms will impede seed dispersal (Perry 1994). Higgins and Richardson (1999) predicted that seed dispersal will not decrease despite habitat loss because rare events of long-distance spread would continue to occur. They consider these long-dispersal events as key for rapid-plant migration. As an illustration they report a modal spread of 160 m yr^{-1} and maximum spread of over 750 m yr^{-1} rate for *Pinus pinaster* Aiton (maritime pine) across African fynbos landscape. Nonetheless, these authors believe that habitat loss reduces the probability of successful colonization across a fragmented landscape for many plant and animal species.

Similar rates of spread are reported in other studies. Iverson et al. (2004) modelled migration rates for five North-American forest species with broad distributions and found that after a period of 100 years, species migrated to an area 10–20 km from their original point. They conclude that rare, long-distance dispersal events are not sufficient to resolve limitations of migration. These two migration models support both the selection and the sampling hypothesis, as seed dispersal and a seedling recruitment will be critical for successful migration and establishment of forest species displaced by habitat shifts.

Model simulations suggest that deciduous trees, such as *F. sylvatica* or *Quercus petraea* L. (sessile oak), would invade today's subalpine belt (Kräuchi 1993; Kräuchi and Kienast 1993; Montoya-Oliver 2001), and various conifers would be displaced and migrate into today's alpine zone which consequently would become afforested provided that soils are suitable for forest growth. These models support the shift hypothesis. Forest species presently adapted to the highest mountain altitudes may be in jeopardy given that their habitat will become more reduced and they will have no opportunity to migrate. We are already seeing what could be the early signs of this event as *Pinus uncinata* Mill. (mountain pine) undergoes a serious decline process in the Southern slopes of the Pyrenees (Casamayor and Colinas in prep.), an example of the selection hypothesis.

Field studies are also providing interesting data on the observed effects of global warming. The 1990's was a very dry decade in Europe which prompted Mediterranean foresters to launch field studies on the effects of drought on forest structure. Results indicate that present germination and growth conditions for new saplings are quite different from those existent when the trees from current stands germinated (Lloret and Siscart 1995; Montoya 1995; Montoya-Oliver 1995). These studies describe serious damages in terms of weakened trees, increased susceptibility to pathogens, increased fire hazard and finally the death of many populations. These damages were more serious in hardwood than in softwood species, except for *Quercus coccifera* (L.) (Kermes oak) and *Pinus halepensis* Mill. (Aleppo pine) where outcomes still appear uncertain (Montoya 1995). Drought sharply decreased *Q. ilex* populations, even when new ramets appeared after drought, because these stands consisted of small groups of large, mature trees which probably could not withstand subsequent episodes of drought. Acorn production also diminished with drought, therefore fauna populations, which are indispensable for seed dispersal, probably were also affected by these fluctuations. Acorns successful in germination would find less dense forests for establishment, a serious challenge for this species which requires shade in its early stages (Montoya 1995).

P. halepensis appears to be a likely substitute for *Q. ilex* in the short term because it is more resistant to drought, although its populations are also expected to diminish under long term drought conditions (Cámara-Obregón 1998; Lloret and Siscart 1995). Empirical studies show that *Q. ilex* decline more strongly affected genetically poorly-adapted stands, those from reforestations and those managed under productivity criteria (Montoya-Oliver 1995). Unfortunately the *Q. ilex* stands able to survive drought later suffered attacks by bark beetles (*Scolitidae*) leading to the conclusion that the duration of drought events is a critical factor determining *Q. ilex* survival. *Erica* spp. (Heather) and *Phyllirea latifolia* L. (Mock privet), two shrubby plants, less affected by drought, are likely to increase in the *Q. ilex* habitat with loss of oak cover (Lloret and Siscart 1995; Ogaya and Peñuelas 2003; Ogaya et al. 2003). This demonstrates how the shift hypothesis may work in response to conditions of extreme drought.

P. pinaster is deteriorating very rapidly in places where water stress is precocious and intense, even when climate change is only a weak trend (Allué-Andrade 1995). Irregular weather during spring can create dieback in some species, particularly *Pinus pinea* L. (Umbrella pine) (Allué-Andrade 1995). Presently, *Pinus nigra* Arnold (Austrian pine), *P. pinea, P. pinaster* and *P. sylvestris* are more damaged than the surrounding understory. Substitution of these species is likely and *Juniperus thurifera* L. (Spanish juniper), the conifer species least damaged by drought (Montoya 1995), may replace many conifer species.

Another factor that may drastically modify current forests are the invasions of exotic species. Plant invasions are enhanced by human activities, which contribute to the transport of propagules over a long range of distances and will become more important as new climatic conditions develop (Walther et al. 2002). Introduced exotic species will diminish resources available for native plants through competition and will affect the fundamental properties of an ecosystem (Dukes and Mooney 1999). It remains unclear to what extent these invasions will affect whole plant communities.

Fire, erosion and desertification

Total burned area in Spain has increased by 600% between 1960 and 1990 (Prieto 1993) and fire-return frequency has decreased for the same period. (De Luís et al. 2001). Although this trend is partly due to non-climatic effects (e.g.: the amount of fuel has increased at the expense of marginal agriculture), climate warming is thought to have contributed greatly, principally because of the daytime temperature increases and the relative moisture decrease which have affected vegetation growth, fuel structure and combustibility. There has been an increase in number of days per year in which low relative humidity and high temperatures create conditions necessary for large catastrophic fires (De Luís et al. 2001; Hulme and Sheard 1999; Lloret and Siscart 1995; Piñol et al. 1998; Vélez 1995).

The synergy created by increasing fire frequency and high intensity storms could, in turn, increase soil erosion. Giovannini et al. (2001) compared soil erodability after fire in pine forests, shrublands and bushlands, all of which had originated after crop abandonment. They found that soil erodability after fire was similar to that of the original crop. However, De Luís et al. (2001) showed that high intensity rainfalls after fire could adversely affect establishment of new plants, because of soil and nitrogen losses. This could promote the shift from forest cover to shrubland and bushland, especially in areas close to sub-desert zones and steppes. Xeric zones would suffer the greatest impact. Already there is empirical evidence of species migration from arid zones towards less arid areas (Allué-Andrade 1995; Montoya-Oliver 2001) which is exacerbated by socio-economic factors such as rural abandonment (Puigdefabregas and Mendizabal 1998).

Management implications

Forestry

Active forest management is absolutely necessary to curb global warming effects (Allué-Andrade 1995; Lindner 2000; Montoya-Oliver 2001). Without intervention, including transplanting propagules to new preserves, it seems unlikely that many plant species, especially those species persisting in preserves or present in small isolated populations, will survive a period of rapidly changing climate (Davis 1989). Weather in forestry management plans can no longer be a descriptive study of the past but a predictive analysis of the future. We may find that the most poorly-adapted seedling in a given area will be the best one at the end of the rotation (Montoya-Oliver 1995). Maintaining, restoring and establishing ecologically and economically viable forest communities will require multiple strategies, including efforts to maximize carbon storage in standing forests and wood products.

Management strategies are divided into three approaches (Brown 1997; Eggers 2002) (Table 1). The first is the Conservation Management Strategy which aims to prevent emissions and conserve current forest carbon pools through diminishing deforestation, increasing rotation period, reducing thinning intensity and restricting many harvesting activities. According to this strategy, fires and pathogens should be controlled to sequester the maximum amount of carbon possible.

The second approach is the Storage Management Strategy. It aims to increase the amount of carbon stored in vegetation and soil through an increase in forested areas and/or carbon stored per unit area in natural and plantation forests. This includes increasing carbon storage in wood products, thereby increasing harvest levels.

Afforestation and reforestation are important measures included in this strategy, and seedling choice appears critical for success. Montoya-Oliver (2001) found that seedlings from natural regeneration are better adapted than those from artificial reforestations. Greater damages occurred in artificially reforested *P. nigra* stands than in natural ones, but not for other Spanish *Pinus* species (Montoya 1995). Reforestations utilizing species and provenances from warmer places have been suggested (Allué-Andrade 1995; Montoya-Oliver 2001), broadening the genetic base of the stand, and increasing species diversity to diminish pathogen attacks (such as those by *T. pytiocampa* described above). Another tactic is reforestations at higher altitudes adjacent to natural stands to facilitate tree migrations (Hódar et al. 2003).

Shorter rotations have been suggested as a tool to reduce climate change impact by facilitating the match of the seed source to site conditions (Montoya-Oliver 2001) but positive results could be offset by the extra carbon from long-term soil pools that is released to the atmosphere when rotations are shortened (Harmon et al. 1990). A large percentage of this small wood would be transformed into fuel or paper, or

Table 1 Summary of forest management options to mitigate climate change

Strategy	Aim	Techniques	Costs	Benefits	References
Conservation management	Prevent emissions and conserve forest C pools	Increase rotation period, reduce thinning intensity, restricting many harvesting activities	Wood harvesting later than at optimal economic conditions	Increased control of pathogens and fires, Diminished investment in forest operations	Brown (1997), Eggers (2002)
Storage management	Increase C stocks	Afforestation and reforestation	Investment in plantations	Planting of best-adapted propagules at the end of the rotation Diminishing unemployment	Montoya-Oliver (2001)
		Shorter rotations	Release of extra carbon from long-term soil pools	Match of the seed source to site conditions	Montoya-Oliver (2001), Harmon et al. (1990)
Substitution Management	Maximize the time C is sequestered as wood	Transfer of C biomass into wood products	Investment in obtaining higher quality products	Higher income	Brown (1997)
		Improvement of industrial efficiency	R+D investment in infrastructures	Higher industrial efficiency	Brown (1997)
		Substitution of fossil fuels for firewood	Adaptation of energy systems	Fire prevention	Palosuo et al. (2000), Schlamadinger and Marland (2000)

would be left in the forest to decompose, resulting in a relatively rapid conversion to atmospheric CO_2.

The third approach is the Substitution Management Strategy. This strategy includes the transfer of carbon biomass into furnishings, construction and other wood products; the improvement of industrial efficiency to obtain maximum power at minimum biomass burning; the use of firewood instead of fossil fuels when possible, and increased recycling of forest products in order to accumulate carbon for long periods. In the near future, firewood production can be much more valuable and environmentally and economically profitable than any other alternative use of forests (Palosuo et al. 2000; Schlamadinger and Marland 2000). This firewood can come from thinning by-products, from the recovery of traditional coppice practices (*Q. ilex, Q.pyrenaica, Q. humilis* Mill.), or from intensive, short rotation forest crops for firewood with species such as *Eucaliptus* spp., *Robinia pseudoacacia* L (Black locust), *Acacia* spp., *Populus* spp., and *Salix* spp.

Forest biodiversity and ecosystem functioning

Within reforestation management strategies outlined above the promotion and conservation of biological diversity should be prioritised. The following elements are suggested for the development of guiding principles for forest adaptation to climate change (CBD 2001): (1) preservation of the pool of natural species and genetic variability of forests, (2) networking protected areas or natural ecosystems by creating ecological corridors or by maintaining appropriate ecological components in associated areas to allow natural migration of ecosystem elements, (3) reduction of forest fragmentation caused by anthropogenic activities, (4) restoration of degraded lands, (5) description of best management practices that will maintain or enhance adaptive capacity or resilience of ecosystems, e.g., establishment of wooded ecotones and buffer zones in order to allow ecosystem replacement.

Probably the first guiding principle is the easiest to accomplish with minimal costs. There are currently several programmes committed to genetic resources conservation for *Pinus pinaster, Pinus halepensis* and *Pinus brutia* Ten. (Turkish pine) (Alía and Martín 2003; Fady et al. 2003), *Castanea sativa* Mill. (European chestnut) and several Mediterranean oaks. Although these programs were not specifically undertaken in order to cope with climate change they can be strengthened and employed for this purpose.

There appears to be an agreement among researchers that new forest plantations which include a diversity of species and varieties designed to adapt to changing conditions and to increase carbon storage in forest vegetation and soil are an opportunity for innovative forest restoration (Fearnside 1999; Hódar et al. 2003; Stier and Siebert 2002), and that this challenge should be undertaken to preserve ecosystem functioning. Preserving ecosystem functioning requires ever-broadening views of above and belowground forest processes. Forest researchers and planners must take a critical look at the implications of management decisions and evaluate outcomes of innovative ideas, developing new silvicultural techniques based on feedback from rapidly changing forest conditions. The utilization of exotic species with rapid growth potential may backfire as in the *Pinus radiata* plantations introduced in páramo grasslands in Ecuador (Chapela et al. 2001) where up to 30% of the carbon stored in soil has been lost in less than 20 years following forest plantation.

The reason for this still remains uncertain but the authors suggest that in this case the ectomycorrhizal community, which was drastically simplified after the plantation, could extract previously accumulated carbon, resulting in inordinately high productions of *Suillus luteus* (L. ex Fr.) S.F.Gray (slippery jack) sporocarps.

Total and organic carbon losses have also been shown after *P. radiata* plantations on former grassland in New Zealand (Alfredsson et al. 1998; Parfitt et al. 1997; Scott et al. 1999). These newly introduced plantations also affected ecosystem functioning in terms of decreasing total nitrogen and altering acidity and concentrations of exchangeable cations. Similar studies, to our knowledge, have not been developed for exotic plantations in Mediterranean ecosystems, but they highlight the importance of monitoring the balance of system inputs and outputs for exotic plantations.

References

Alfredsson H, Condron LM, Clarholm M, Davis MR (1998) Changes in soil acidity and organic matter following the establishment of conifers on former grassland in New Zealand. For Ecol Manag 112:245–252

Alía R, Martín S (2003) EUFORGEN Technical Guidelines for genetic conservation and use for Maritime pine (*Pinus pinaster*). In: International Plant Genetic Resources Institute, Rome, Italy, pp 6

Allué-Andrade JL (1995) Naturaleza, efectos y amortiguamiento del cambio climático en los bosques españoles. Montes 40:21–28

Brasier CM (1996) *Phytophtora cinnamomi* and oak decline in southern Europe. Environmental constraints including climate change. Ann For Sci 53:347–358

Brown S (1997) Forests and climate change: role of forest lands as carbon sinks. Proceedings of the XI World Forestry Congress. Antalya, Turkey. 1:107–121

Cámara-Obregón A (1998) Comportamiento y posibles aplicaciones de *Pinus halepensis* Mill. en España, frente al cambio climático. Cuadernos de la Sociedad Española de Ciencias Forestales 7:51–60

Canadell JG, Pataki D (2002) New advances in carbon cycle research. Trends Ecol Evol 17:156–158

Castells E, Roumet C, Peñuelas J, Roy J (2002) Intraspecific variability of phenolic concentrations and their responses to elevated CO_2 in two mediterranean perennial grasses. Environ Exp Bot 47:205–216

Catovsky S, Holbrook NM, Bazzaz FA (2002) Coupling whole-tree transpiration and canopy photosynthesis in coniferous and broad-leaved tree species. Can J For Res 32:295–309

CBD (Convention on Biological Diversity) (2001) Forest biological diversity, Rep. No. UNEP/CBD/SBSTTA/7/7. UNEP, Montreal

Chapela IH, Osher LJ, Horton TR, Henn MR (2001) Ectomycorrhizal fungi introduced with exotic pine plantations induce soil carbon depletion. Soil Biol Biochem 33:1733–1740

Davis MB (1989) Lags in vegetation response to greenhouse warming. Climatic change 15:75–82

De Luís M, García-Cano MF, Cortina J, Raventós J, González-Hidalgo JC, Sánchez JR (2001) Climatic trends, disturbances and short-term vegetation dynamics in a Mediterranean shrubland. For Ecol Manag 147:25–37

Déqué M, Marquet P, Jones RG (1998) Simulation of climate change over Europe using a global variable resolution general circulation model. Clim Dynam 14:173–189

Dukes JS, Mooney HA (1999) Does global change increase the success of biological invaders? Trends Ecol Evol 14:135–139

Eggers T (2002) The Impacts of Manufacturing and Utilisation of Wood Products on the European Carbon Budget. European Forestry Institute. Joensuu, Finland. 90 p

Fady B, Semerci H, Vendramin GG (2003) EUFORGEN Technical Guidelines for genetic conservation and use for Aleppo pine (*Pinus halepensis*) and Brutia pine (*Pinus brutia*). In International Plant Genetic Resources Institute. Rome, Italy, 6 p

Fearnside PM (1999) Plantation forestry in Brazil: the potential impacts of climate change. Biomass Bioenerg 16:91–102

Giovannini G, Vallejo R, Lucchesi S, Bautista S, Ciompi S, Llovet J (2001) Effects of land use and eventual fire on soil erodibility in dry Mediterranean conditions. For Ecol Manag 147:15–23

Guo L, Guifford R (2002) Soil carbon stocks and land use change: a meta analysis. Global Change Biol 8:345–360

Harmon ME, Ferrell WK, Franklin JF (1990) Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–701

Higgins S, Richardson DM (1999) Predicting plant migration rates in a changing world: The role of long-distance dispersal. Am Nat 153:464–475

Hódar JA, Castro J, Zamora R (2003) Pine processionary caterpillar *Thaumetopoea pityocampa* as a new threat for relict Mediterranean Scots pine forests under climatic warming. Biol Conserv 110:123–129

Hulme M, Sheard N (1999) Escenarios de Cambio Climático para la Península Ibérica. Climatic Research Unit- University of East Anglia, Norwich, UK. 6 p

IPCC (Intergovernmental Panel on Cimate Change) (1990) Scientific Assessment of Climate change – Report of Working Group I Cambridge University Press, Cambridge, 365 p

IPCC (2001a) Climate Change 2001: Synthesis report. WMO/UNEP, Wembley. 397 p

IPCC (2001b) Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, 886p

Iverson LR, Schwartz MW, Prasad AM (2004) How fast and far might tree species migrate in the eastern United States due to climate change? Global Ecol Biogeogr 13:209–219

Kräuchi N (1993) Potential impacts of a climate change on forest ecosystems. Eur J For Pathol 23:28–50

Kräuchi N, Kienast F (1993) Modelling subalpine forest dynamics as influenced by a changing environment. Water Air Soil Pollut 68:185–197

Layser EF (1980) Forestry and Climatic Change. J For 78:678–682

Lindner M (2000) Developing adaptive forest management strategies to cope with climate change. Tree Physiol 20:299–307

Lloret F, Peñuelas J, Estiarte M (2004) Experimental evidence of reduced diversity of seedlings due to climate modification in a Mediterranean-type community. Global Change Biol 10:248–258

Lloret F, Siscart D (1995) Los efectos demográficos de la sequía en poblaciones de encina. Cuadernos de la Sociedad Española de Ciencias Forestales 2:77–81

Martínez-Vilalta J, Piñol J (2002) Drought-induced mortality and hydraulic architecture in pine populations of the NE Iberian Peninsula. For Ecol Manag 161:247–256

Montoya R (1995) Red de seguimiento de daños en los montes. Daños originados por la sequía en 1994. Cuadernos de la Sociedad Española de Ciencias Forestales 2:83–97

Montoya-Oliver J (1995) Efecto del cambio climático sobre los ecosistemas forestales españoles. Cuadernos de la Sociedad Española de Ciencias Forestales 2:65–76

Montoya-Oliver J (2001) Selvicultura y cambio climático. Montes 64:69–74

Mota MM, Braasch H, Bravo MA, Penas AC, Burgermeister W, Metge K, Sousa E (1999) First report of *Bursaphelenchus xylophilus* in Portugal and in Europe. Nematology 1:727–734

Neilsen RP (1993) Transient ecotone response to climatic change: some conceptual and modeling approaches. Ecol Appl 3:385–395

Ogaya R, Peñuelas J (2003) Comparative field study of *Quercus iles* and *Phillyrea latifolia*: photosynthetic response to experimental drought conditions. Environ Exp Bot 50:137–148

Ogaya R, Peñuelas J, Martínez-Vilalta J, Mangirón M (2003) Effect of drought on diameter increment of *Quercus ilex, Phillyrea latifolia*, and *Arbutus unedo* in a holm oak forest of NE Spain. For Ecol Manag 180:175–184

Olivera A, Colinas C (1995) Observaciones sobre la posible correspondencia entre la evolución climática y el decaimiento de los alcornoques en Cataluña. Proyecto Final de Carrera. University of Lleida, Lleida Spain

Palosuo T, Wihersaari M, Liski J (2000) Net greenhouse gas emissions due to energy use of forest residues—Impact of soil carbon balace. In: Pelkonen P, Hakkila P, Karjalainen T, Schlamadinger B (eds) Woody biomass as an energy source—challenges in Europe, vol. 39. EFI Proceedings, Joensuu, Finland, pp 115–122

Palutikof JP, Wigley TML (1996) Developing climate change scenarios for the Mediterranean region. In: Jeftic L, Keckes S, Pernetta JC (eds) Climate change and the mediterranean, vol. 2. Arnold, London, pp 27–56

Parfitt RL, Percival HJ, Dahlgren RA, Hill LF (1997) Soil and solution chemistry under pasture and radiata pine in New Zealand. Plant soil 191:279–290

Peñuelas J, Boada M (2003) A global change-induced biome shift in the Montseny mountains (NE Spain). Global Change Biol 9:131–140

Peñuelas J, Filella I, Comas P (2002) Changed plant and animal life cycles from 1952–2000 in the Mediterranean region. Global Change Biol 8:531–544

Peñuelas J, Llusià J (2003) BVOCs: plant defense against climate warming? Trends Plant Sci 8:105–109

Perry D (1994) Forest ecosystems. The Johns Hopkins University Press, Baltimore/London, 649 p

Peters RL, Darling JD (1985) The greenhouse effect and nature reserves. BioScience 35:707–717

Piñol J, Terradas J, Lloret F (1998) Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. Climatic change 38:345–357

Prieto F (1993) Incendios forestales en España. Ecosistemas 4:32–33

Puigdefabregas J, Mendizabal T (1998) Perspectives on desertification: western Mediterranean. J Arid Environ 39:209–224

Rambal S, Hoff C (1998) Mediterranean ecosystems and fire: the threats to global change. In: Moreno JM (eds) Large forest fires. Backuys, Leiden, The Netherlands, pp 187–213

Sánchez ME, Navarro RM, Trapero A, Fernández P (2000) La ‘‘Seca’’ de encinas y alcornoques: una visión histórica. Montes 62:29–39

Sasse J (1998) The forests of Japan. Japan Forest Technical Association

Scott NA, Tate KR, Ford-Robertson J, Giltrap DJ, Smith CT (1999) Soil carbon storage in plantation forests and pastures: land-use change implications. Tellus B 51:326–335

Schlamadinger B, Marland G (2000) The role of bioenergy and related land use in global net CO_2 Emissions. In: Pelkonen P, Hakkila P, Karjalainen T, Schlamadinger B (eds) Woody biomass as an energy source—Challenges in Europe, vol. 39. EFI Proceedings, Joensuu, Finland, pp 21–28

Stier SC, Siebert SF (2002) The Kyoto Protocol: an Opportunity for Biodiversity Restoration Forestry. Conserv Biol 16:575–576

Tainter FH, Baker FA (1996) Principles of forest pathology. John Wiley and Sons, New York, 832 p

Vélez R (1995) El peligro de los incendios forestales derivado de la sequía. Cuadernos de la Sociedad Española de Ciencias Forestales 2:99–109

Walther G-R, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J-M, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395