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Climate change may cause severe loss in the economic value of European forest land

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European forests, covering more than 2 million km^2 or 32% of the land surface[1], are to a large extent intensively managed and support an important timber industry. Climate change is expected to strongly affect tree species distribution within these forests[2,3]. Climate and land use are undergoing rapid changes at present[4], with initial range shifts already visible[5]. However, discussions on the consequences of biome shifts have concentrated on ecological issues[6]. Here we show that forecasted changes in temperature and precipitation may have severe economic consequences. On the basis of our model results, the expected value of European forest land will decrease owing to the decline of economically valuable species in the absence of effective countermeasures. We found that by 2100—depending on the interest rate and climate scenario applied—this loss varies between 14 and 50% (mean: 28% for an interest rate of 2%) of the present value of forest land in Europe, excluding Russia, and may total several hundred billion Euros. Our model shows that—depending on different realizations of three climate scenarios—by 2100, between 21 and 60% (mean: 34%) of European forest lands will be suitable only for a Mediterranean oak forest type with low economic returns for forest owners and the timber industry and reduced carbon sequestration.

The distribution of tree species in forests is a function of climatic (temperature, precipitation) and topographic (slope, aspect) parameters, among others. A change in climate parameters will influence the range of most species. Forests are under strong pressure from global change[7] and from the ensuing increases in abiotic and biotic hazards[8]. With an expected change of temperature and precipitation, cold-adapted and mesic species such as Norway spruce (*Picea abies* Karst), one of the major commercial tree species in Europe, will over the long term lose larger fractions of their ranges at the cost of more drought-adapted species such as oaks (*Quercus* spp.). So far, the discussion of anticipated large-scale biome shifts under climate change has focused on ecological issues[6]. However, these shifts may also have severe economic consequences, including income losses to forest owners, and reductions in raw material for the wood products industry, if measures to compensate for them are not taken.

Here we estimate the economic impact of projected climate change for a wide range of temperature increases (between 1.4 and 5.8 °C until 2100), using a high-resolution model that predicts presence or absence for 32 tree species under different climate projections in Europe (Supplementary Information S1).

The projections were conducted for the Intergovernmental Panel on Climate Change (IPCC) climate scenarios B2 and A1FI (ref. 9) by downscaling the output (temperature and precipitation) of four general circulation models and for A1B by downscaling the same variables of four regional circulation models (RCM) in combination with WorldClim[10] present climate data from a coarse (10′) to a fine (1 km) resolution (Supplementary Table S1). We expressed future climate as anomalies of three time periods (2011–2040, 2041–2070, 2071–2100) relative to a climate normal period (1950–2000). The projections reveal a temperature increase in northern Europe in winter and in the Mediterranean and eastern Europe in summer. Precipitation is expected to increase in central and northern Europe in winter and to decrease in central and (south-) western Europe in summer. Trends are similar for all scenarios, but larger and more distinct, with more extreme values, in the A1FI scenario.

To provide a comprehensive overview of potential range shifts and their economic impact, we grouped and ordered major tree species according to their economic importance based on an estimate of their output and value of produced timber. We fitted species distribution models[3] under present climate conditions for the whole area of Europe (excluding Russia) on a 750 × 750 m spatial resolution and projected the species range shifts for three future periods and for the scenarios B2, A1B and A1FI using four different climate model outputs per scenario. For each pixel we chose the tree species group with the highest economic performance that was still projected to occur under the given climatic conditions, to model the best-case economic scenario for managed forests.

Our models reveal that the projected changes in climate will lead to distinct changes in the potential ranges of European tree species and thus their suitable area of growth (Figs 1 and 2). We show that under all three scenarios the major commercial tree species in Europe, Norway spruce, shifts northward and probably loses large parts of its present range in central, eastern and western Europe (Fig. 1). By 2100, according to our projections, suitable Norway spruce habitats will be restricted to the higher elevations in central Europe and to areas in northern Sweden, Finland and Norway. For broadleaves such as oak and beech the model projects a range shift from today's ranges in western Europe (France, Netherlands, Germany) and the lower elevations in central and eastern Europe more to central, northern and northeastern Europe (see Fig. 2 for a moderate realization (CLM/ECHAM5) of the A1B scenario and Supplementary Figs S3–S6).

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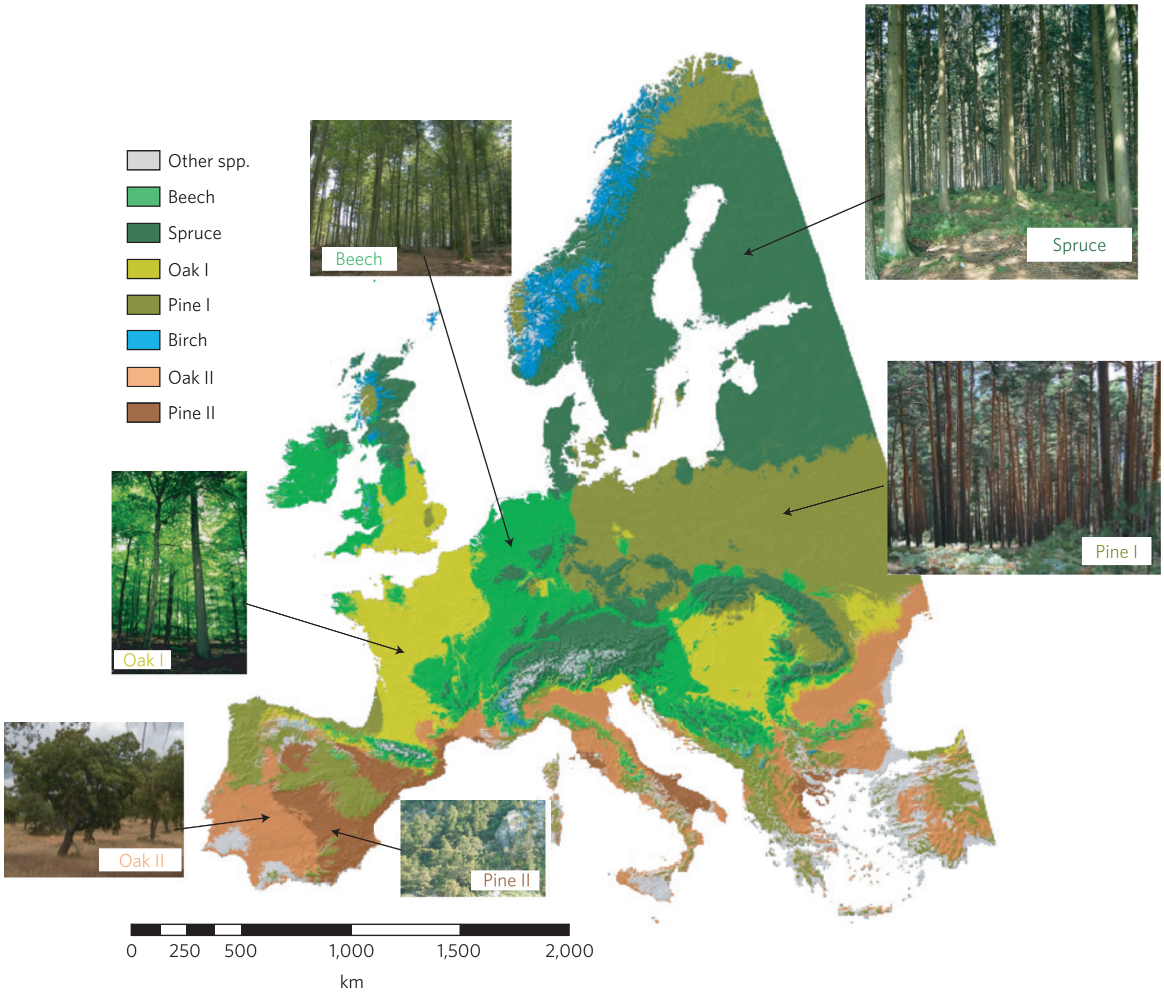

Figure 1 | Potential range of major tree species in Europe for the climate normal period (1950–2000). The size (area) of the pictures, showing typical aspects of forests dominated by the modelled species, approximately corresponds to the share of the total area in the climate normal period (birch <3% not depicted). For an explanation of the tree species groups, see Methods.

Figure 3 gives a summary of the projected species ranges as calculated for scenario A1B including uncertainties expressed as standard deviation due to the different climate models used. The oak II species group is the 'winner' of global warming with an increase to more than 32% on average of the total area under the A1B from its present range of 11%, to more than 28% under the B2 and to more than 40% under the A1FI scenario. The oak I group is expected to almost double its area under all three scenarios (Supplementary Table S5). The productive coniferous species group spruce is the 'loser', with a decrease of almost 50% of its present area under the A1B (43% for B2 and 60% for A1FI) scenario. Similarly, the pine I group loses close to 60% of its present range. The standard deviation (Fig. 3) due to different global/RCMs within one scenario reveals high uncertainty especially for the species groups pine I and oak II.

The economic value of a tree species is a function of the amount, the dimensions and the quality of timber that can be produced, as well as timber prices taking into account the costs of harvesting and regeneration. We used the large-scale simulation model EFISCEN (ref. 11), a forest projection model, to estimate timber production for the seven tree species groups divided into six diameter classes, with calculated thinning, final harvest and remaining standing volume in 5-year steps. We simulated the development of these tree species for the period from 2010 until 2100 and, using present prices and costs (Supplementary Information S3 and Fig. S7), we generated a series of cash flows and we transformed these into land expectation values (LEV), a proxy for willingness to pay and thus for the value of forest land[12–14]. The mean values for the LEV per hectare of forest land vary between €515 ha^{-1} (A1FI scenario; 2071–2100 period; 3% interest rate) and €11,612 ha^{-1} (B2; 2010; 1%) (Supplementary Fig. S8 and Tables S9 and S10).

Figure 4 illustrates the development of LEV for European forest land for an interest rate of 2% for all three scenarios. For the A1B scenario, the LEV decreases by almost 30% from over €3,280 ha^{-1} in the year 2010 to around €2,350 ha^{-1} by the year 2100. For scenario B2 the decrease is lower and changes only marginally after the year 2070, whereas A1FI reaches the lowest of all values. The decrease is due to the loss of suitable area of productive species, mainly Norway spruce and Scots pine. Mediterranean oaks that occupy more than 30% of the total area by 2100 (scenario A1B) account for only 4% of the LEV. Norway spruce makes up for more than 45% of the economic value while occupying about 15% of the total area. Applying the difference in LEV (2010–2100) of around €930 ha^{-1} (Fig. 4) to the 206 million hectare forest area in Europe outside Russia[1] (for which our model is parameterized) results in an overall forest-land value loss of more than €190 billion under the A1B scenario by the year 2100. As LEV is sensitive towards a change of the interest rate (i), the loss of land value ranges greatly, from over 80 billion for $i = 3\%$ (2100) to almost 530 billion for $i = 1\%$ (2100) for scenario A1B. For B2 the values for 2100 range from 60 ($i = 3\%$)

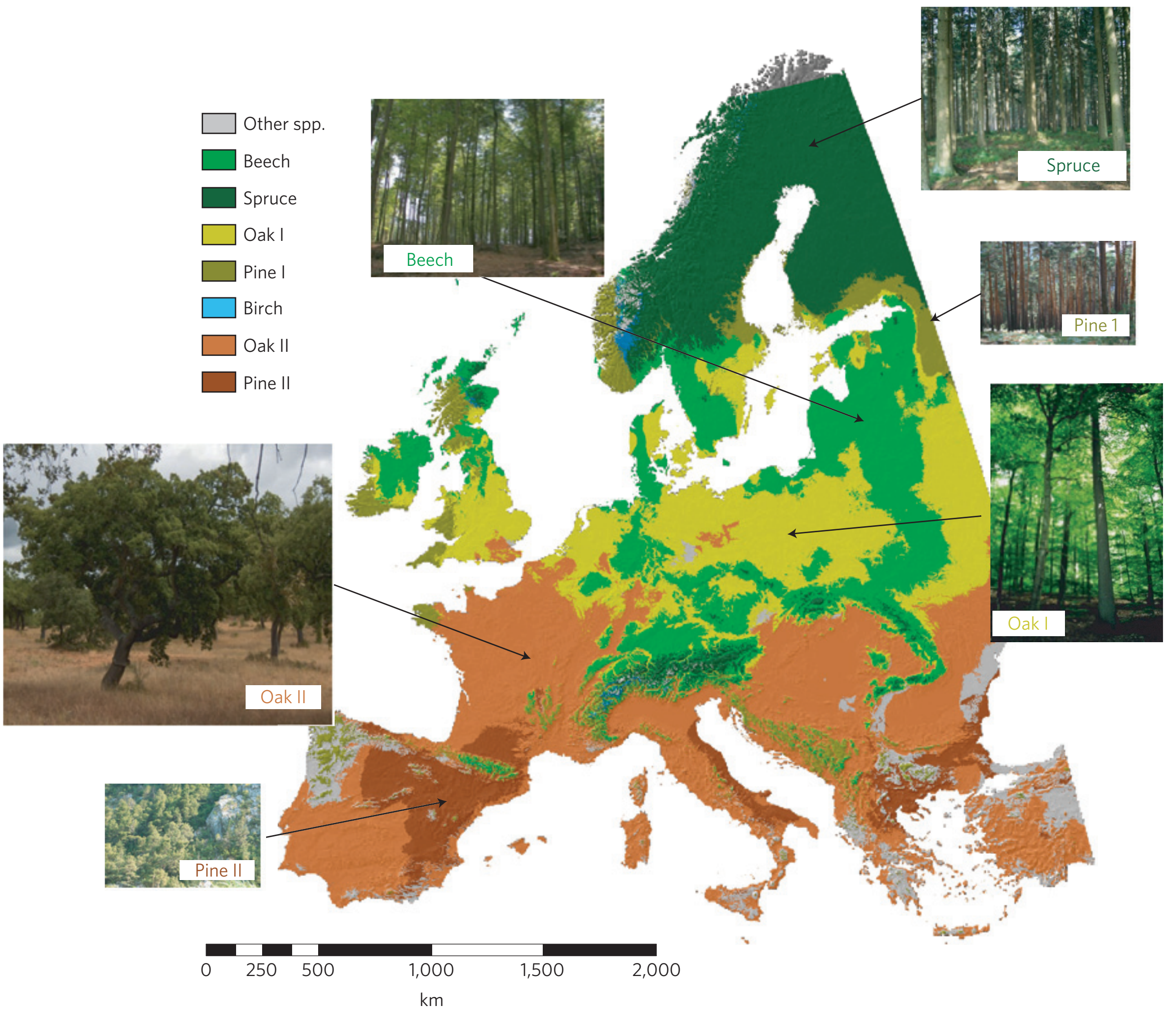

Figure 2 | Potential range of major tree species in Europe for scenario A1B, CLM/ECHAM5—moderate warming (2070–2100). The size (area) of the pictures, showing typical aspects of forests dominated by the modelled species, approximately corresponds to the share of the total area in A1B (2071–2100; birch ~0.3%, not depicted).

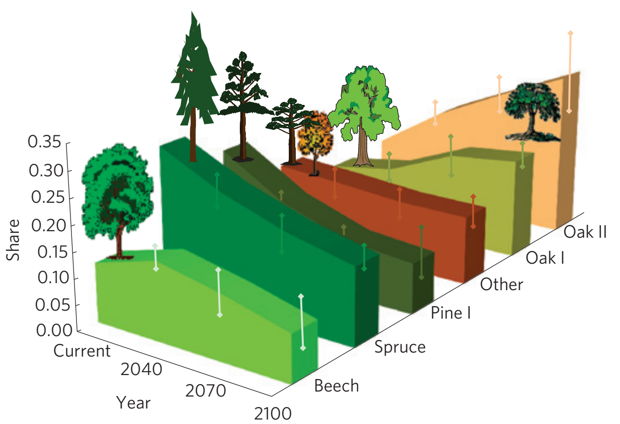

Figure 3 | Development of the share of the area of major tree species in Europe under scenario A1B until 2100. The relative size of the icons approximately corresponds to the relative height of mature trees of the species groups. The tree species group labelled 'Other' includes Pine II, Birch and Other spp. from Figs 1 and 2. The bars reflect the standard deviation resulting from four different model realizations of scenario A1B (see Supplementary Tables S5 and S6).

to 340 billion ($i = 1\%$) and for A1FI from €100 to 680 billion (see Supplementary Tables S9 and S10). The standard deviation due to different climate models depicted in Fig. 4 increases over time and is particularly high for scenario A1FI.

Uncertainties associated with the results of our study originate from different sources, including, for example, plant physiological responses to global wood market responses. Here, we address four major uncertainties associated with our results.

In general, an increase in tree growth due to CO_2-fertilization effects and a longer vegetation period is expected[15], namely for boreal forests. Yet, this is not probably true for all of Europe and for all tree species considered. Some species and regions are probably negatively affected by the expected increase in climatic extremes and associated disturbances[16] in addition to direct changes in habitat quality. Increasing storm, drought, fire and insect risks may cause further adverse effects. The positive trends we observe in some areas in Europe at present will most probably be outweighed by such negative disturbances, especially in southern and eastern Europe[15]. The results of a sensitivity analysis (Supplementary Information) show that the growth increase projected for individual regions is swamped by species range shifts, particularly by the marked contraction in the ranges of highly productive and valuable species.

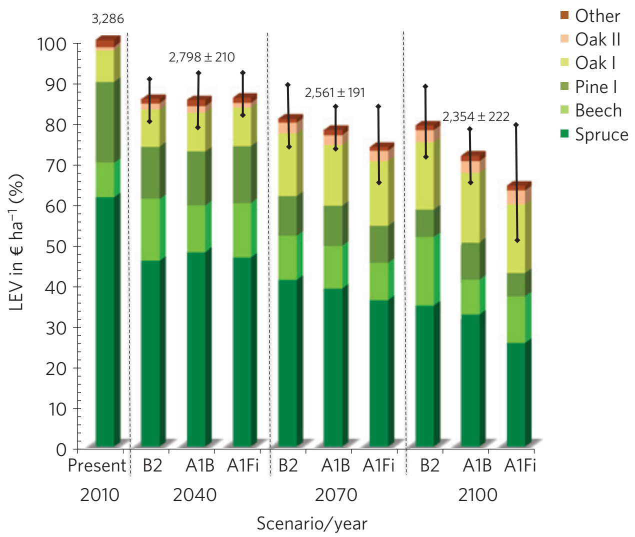

Figure 4 | Development of the relative values (2010 = 100%) of the LEV 2010–2100 for three scenarios with an interest rate of 2%. Absolute values in Euros for price–cost relations of the year 2010. The tree species group labelled 'Other' includes Pine II, Birch and Other spp. from Figs 1 and 2. The bars reflect the standard deviation resulting from four different model realizations of all scenarios (see Supplementary Tables S9 and S10).

Species range shifts have been subject to several modelling efforts[3] and often underestimate the adaptive capacity of tree species. Instead of vegetation maps, we use a presence/absence approach based on pan-European data[17] independent of expert knowledge. Such models contain uncertainty[18], for example concerning the velocity of expected changes from species migration. Namely, forest tree species show a range of options to cope with environmental changes including their extremes. Furthermore, in the past they had to deal with changing growth conditions that had affected their distribution and vitality.

With declining availability of productive timber species we have to expect dynamic market responses. The processes that affect our modelled LEV output are only partly driven by biophysical processes, but also include complex socio-economic drivers. Differences in the market value of tree species may in the future become more strongly influenced by prices and preferences as the wood of conifers such as Norway spruce becomes less available than the wood of other species. Specifically, the rapid decline of the productive species, and the associated expected rise in their wood price, may result in incentives to adapt by planting new non-European species. Many forest owners have already started to replace Norway spruce with Douglas fir (*Pseudotsuga menziesii*), a productive, non-native and more drought-adapted species that has already been planted in Europe. In the Mediterranean areas of Europe, *Cedrus atlantica* may play an increasingly important role as well as *Eucalyptus* spp. that grow already in larger areas where severe winter frosts are absent. Our model does not assume a strong influence of changing prices and preferences on the relation of the market value of different species in the future (which is a valid assumption at present owing to the relatively slow changing ranges of tree species). However, this may change rapidly when biome shifts become more pronounced. Earlier model studies[19] show that producers will adapt to large-scale extreme disturbances if they can identify suitable management options. The potential of markets to react to climate change depends on their (socio-economic) adaptive capacity[15]. In the US a large stock of forests and a dynamic forest sector can help to adapt to changing conditions by introducing new products and technologies[20]. The European forest sector is assumed to have a relatively large adaptive capacity in the boreal and temperate-oceanic regions, but may be strongly limited in its adaptive capacity in both Mediterranean and continental regions owing to low productivity and restrictions from socio-economic constraints[15]. A range of potential market reactions[19] and management strategies[21] in response to the projected climate changes including forest conversion, changing rotation times or thinning regimes are possible to alleviate climate change impacts on the forestry sector (see Supplementary Information S4 for an extended discussion of these two issues).

Predicting economic effects of climate change over longer periods[22] involves considerable uncertainty due to, for example, volatile timber prices and uncertain consumer demand. This uncertainty is the central subject of an ongoing discussion on the economics of climate change[22–24]. Major factors that are discussed are the time discount rate (time preference), the aversion to generational inequality, the growth of consumption and the interest rate to discount future economic effects of climate change. The Stern Review[22] has been criticized for adopting a very low time discount rate[23,24], which results in a very low interest rate to discount future economic effects of climate change. The interest rate is indeed the most important factor when analysing economic effects over long time periods. Therefore, we covered a range of 1–3% for the interest rate in our investigation, which seems to be adequate for European forestry[25] (see Supplementary Information S4). Our calculations of the change in LEV depend primarily on productivity differences between tree species groups, a factor that we assume might be independent of price levels and relative changes in demand[26]. However, we admit that changes in prices, interest rates and the value of different products under climate change[27] may significantly alter the results of our study.

Under the increasing pressure of biotic and abiotic disturbances that are attributed to climate change[16], some European countries are replacing climate-sensitive tree species such as Norway spruce with more drought-tolerant species mainly owing to ecological reasoning[21]. The economic effects of these forest conversion processes have only partly been evaluated[28]. To account for potential losses in productivity, not only ecological but also economic aspects should be considered when choosing species for conversion. Our results show that, if the economic assumptions behind our model apply, climate-induced biome shifts of major tree species in Europe may reduce the local productivity of European forests, with consequences for the income to forest owners and the delivery of raw material to the downstream timber industry. If this potential reduction is not compensated by appropriate adaptive management actions or by the introduction of new, more productive species mainly from outside Europe, then this could also imply reduced rates of carbon sequestration[29] and a reduced potential for climate change mitigation[30].

Methods

The species range models used to project possible range shifts of European trees are calibrated on the basis of the international monitoring network (ICP Forest)[17] database of 6,129 forest plots, regularly distributed across Europe on a 16×16 km grid covering $\sim$2.06 million km^2 of forest[1] (Supplementary Fig. S2). We calibrated present climate envelopes for major tree species on the basis of ICP Forest plots using variables derived from the WorldClim climate database[10], the digital elevation model provided by WorldClim, and augmented by our own geographic information system modelling to express the major climatic gradients in Europe at a 1 km spatial resolution. Supplementary Fig. S1 and Materials give details of the climate anomalies of the used RCMs and general circulation models and the downscaling. Generalized linear models were used to calibrate and map species distributions, stepwise optimized for variable selection and evaluated using a tenfold cross-validation. The tested models were applied to the entire European territory as maps of the present tree species ranges. The models were evaluated on the basis of the area under the receiver operating characteristic curve (area under the curve) and Cohen's Kappa (Supplementary Tables S2 and S3). To assess possible future range shifts, climate maps originating from a total of 12 climate model–scenario combinations were scaled to the same spatial resolution so that they express future climatic conditions following three IPCC scenarios: a strong A1FI, a moderate A1B and a mild B2 scenario[9]. We generated sets of climate maps for each model–scenario combination for three future time steps, namely: 2011–2040, 2041–2070 and 2071–2100. The calibrated generalized linear models were then translated into geographic information system maps using the future climates representing potential range shifts for each modelled tree species. The resulting shifts were analysed for range reduction/expansion and for overlap with present ranges. The economic evaluation was based on the output of the large-scale scenario model EFISCEN using National Forest Inventory data for major European tree species that were grouped according to economic performance[11]. We formed seven groups of tree species (in decreasing order of economic importance): spruce (highly productive conifers), beech (medium productivity—*Fagus sylvatica* L.), pine I (pines of medium productivity—for example *Pinus sylvestris* L.), oak I (oaks of medium productivity—for example *Quercus petraea* (Matt.) Liebl.), pine II (Mediterranean pine of low productivity—*Pinus halepensis* Mill.), oak II (Mediterranean oaks of low to very low productivity—for example *Quercus cerris* L.) and birch (low productivity—*Betula* spp.). Supplementary Table S2 shows the group details. The output of EFISCEN in terms of timber production for different species, together with actual prices and costs for timber, was used to derive the LEV (ref. 14) as a proxy for the willingness to pay for European forest land. Supplementary Information gives details on the workflow within EFISCEN (Supplementary Fig. S6), the output of the simulations, the economic evaluation approach and background information for the calculation of the LEV (Supplementary Fig. S8), including the detailed model that was used (Supplementary Table S7), the LEV of the different tree species groups for three different interest rates, and for three climate scenarios. We discuss the effect of climate change on tree growth, effects of a change in relative value of different forest resources, potential land-use change, and management effects, as well as the influence of emerging technologies and new species on the economic output of forests in Supplementary Information S4. We included a sensitivity analysis concerning the influence of an assumed productivity increase on the loss of LEV (see Supplementary Information for more details).

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References

1. FOREST EUROPE, UNECE & FAO *State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe* (FOREST EUROPE, 2011); available via http://go.nature.com/QgoqFD.
2. Thuiller, W. *et al.* Consequences of climate change on the tree of life in Europe. *Nature* **470,** 531–534 (2011).
3. Thuiller, W. *et al.* Predicting global change impacts on plant species' Distributions: Future challenges. *Perspect. Plant Ecol. Evol. Syst.* **9,** 137–152 (2008).
4. Pielke, R. A. Land use and climate change. *Science* **310,** 1625–1626 (2005).
5. Heikkinen, R. *et al.* Methods and uncertainties in bioclimatic envelope modelling under climate change. *Prog. Phys. Geogr.* **30,** 751–777 (2006).
6. Walther, G-R. *et al.* Ecological responses to recent climate change. *Nature* **416,** 389–395 (2002).
7. Bonan, G. B. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* **320,** 1444–1449 (2008).
8. Kurz, W. A. *et al.* Mountain pine beetle and forest carbon feedback to climate change. *Nature* **452,** 987–990 (2008).
9. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
10. Hijmans, R., Cameron, S. E., Parra, J., Jones, P. & Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25,** 1965–1978 (2005).
11. Schelhaas, M-J. *et al. Model Documentation for the European Forest Information Scenario model (EFISCEN 3.1.3)* Alterra Report 1559/EFI Technical Report 26 (2007).
12. Faustmann, M. Calculation of the value which forest land and immature stands possess for forestry. *Allg. Forst Jagdztg.* **25,** 441–445 (1849).
13. Samuelson, P. A. Economics of forestry in an evolving society. *Econom. Inq.* **14,** 466–492 (1976).
14. Gaffney, M. Keeping land in capital theory: Ricardo, Faustmann, Wicksell, and George. *Am. J. Econom. Sociol.* **67,** 119–141 (2008).
15. Lindner, M. *et al.* Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *For. Ecol. Manage.* **259,** 698–709 (2010).
16. IUFRO *Adaptation of Forests and People to Climate Change—A Global Assessment Report* Vol. 22 (eds Seppälä, R., Buck, A. & Katila, P.) (IUFRO World Series, 2009).
17. Fischer, R. *et al. The Condition of Forests in Europe. 2010 Executive Report* (ICP Forests and European Commission, 2010).
18. Purves, D. & Pacala, S. Predictive models of forest dynamics. *Science* **320,** 1452–1453 (2008).
19. Sohngen, B. & Mendelsohn, R. Valuing the market impact of large-scale ecological change: The effect of climate change on U.S. timber. *Am. Econom. Rev.* **88,** 689–710 (1998).
20. Shugart, H., Sedjo, R. A. & Sohngen, B. *Forests and Global climate change: Potential Impacts on U.S. Forest Resources* (Pew Center on Global Climate Change, 2003).
21. Bolte, A. *et al.* Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. *Scand. J. For. Res.* **24,** 473–482 (2009).
22. Stern, N. *The Economics of Climate Change—The Stern Review* (Cambridge Univ. Press, 2007).
23. Nordhaus, W. D. A review of the stern review on the economics of climate change. *J. Econom. Lit.* **45,** 686–702 (2007).
24. Weitzman, M. L. A review of the stern review on the economics of climate change. *J. Econom. Lit.* **45,** 703–724 (2007).
25. Benitez, P. C., McCallum, I., Obersteiner, M. & Yamagata, Y. Global potential for carbon sequestration: Geographical distribution, country risk and policy implications. *Ecol. Econom.* **60,** 572–583 (2007).
26. Knoke, T., Ammer, C., Stimm, B. & Mosandl, R. Admixing broadleaved to coniferous tree species: A review on yield, ecological stability and economics. *Eur. J. For. Res.* **127,** 89–101 (2008).
27. Raunikar, R., Buongiorno, J., Turner, J. & Zhu, S. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. *For. Policy Econom.* **12,** 48–56 (2010).
28. Hanewinkel, M., Hummel, S. & Cullmann, D. Modelling and economic evaluation of forest biome shifts under climate change in Southwest Germany. *For. Ecol. Manage.* **259,** 710–719 (2009).
29. Fischlin, A. *et al.* in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L. *et al.*) Ch. 4 (Cambridge Univ. Press, 2007).
30. Canadell, J. & Raupach, M. Managing forests for climate change mitigation. *Science* **320,** 1456–1457 (2008).

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Author contributions

M.H. initiated the research, performed the economic evaluation and wrote the body of the paper. N.E.Z. and D.A.C. performed the statistical modelling of species range shifts; M-J.S. and G-J.N. provided the EFISCEN simulations. All authors were involved in revising and finalizing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.H.

Competing financial interests

The authors declare no competing financial interests.