

Assisted tree migration can preserve the European forest carbon sink under climate change

Received: 30 March 2023

Accepted: 1 July 2024

Published online: 25 July 2024

 Check for updates

Debojyoti Chakraborty¹, Albert Ciceu¹, Dalibor Ballian^{2,3,4}, Marta Benito Garzón⁵, Andreas Bolte⁶, Gregor Bozic³, Rafael Buchacher¹, Jaroslav Čepl⁷, Eva Cremer⁸, Alexis Ducousso⁵, Julian Gaviria^{8,9}, Jan Peter George^{1,10}, André Hardtke¹¹, Mladen Ivankovic¹², Marcin Klisz¹³, Jan Kowalczyk¹³, Antoine Kremer⁵, Milan Lstibůrek⁷, Roman Longauer^{14,15}, Georgeta Mihai¹⁶, László Nagy¹⁷, Krasimira Petkova¹⁸, Emil Popov^{19,22}, Randolph Schirmer⁸, Tore Skrøppa²⁰, Thomas Mørtvedt Solvin²⁰, Arne Steffenrem²⁰, Jan Stejskal⁷, Srdjan Stojnic²¹, Katharina Volmer¹¹ & Silvio Schueler¹✉

Climate change threatens the role of European forests as a long-term carbon sink. Assisted migration aims to increase the resilience of forest tree populations to climate change, using species-specific climatic limits and local adaptations through transferring seed provenances. We modelled assisted migration scenarios for seven main European tree species and analysed the effects of species and seed provenance selection, accounting for environmental and genetic variations, on the annual above-ground carbon sink of regrowing juvenile forests. To increase forest resilience, coniferous trees need to be replaced by deciduous species over large parts of their distribution. If local seed provenances are used, this would result in a decrease of the current carbon sink (40 TgC yr⁻¹) by 34–41% by 2061–2080. However, if seed provenances adapted to future climates are used, current sinks could be maintained or even increased to 48–60 TgC yr⁻¹.

By removing carbon dioxide from the atmosphere, forests can play a crucial role in limiting the rise in global annual temperatures to 1.5–2 °C (refs. 1,2). European forests cover ~35% of the total land surface and store ~9.8 Tg of carbon, with an average annual sequestration of 155 TgC between 2010 and 2020³. However, climate change-induced disturbances pose a serious threat to this carbon pool^{4–6} and other forest ecosystem services. Therefore, adaptation actions are required to maintain ecosystem services and improve the resilience of forests towards further climate warming^{7–10}. To use the carbon sequestration capacity of forests, tree planting and forest restoration have been suggested as nature-based solutions to mitigate global warming^{11–14}. The selection of tree species, suitable forest reproductive material and the

promotion of mixed forests^{14,15} are expected to play important roles in forest adaptation and climate change (CC) mitigation^{16,17}.

Owing to the strong impact of CC on tree species distributions^{18–20} and the limited migration capacity of trees^{21,22}, forest restoration and adaptation will need to take the site suitability of species and populations into account. Moreover, restricted gene flow, as well as the limited capacity of trees to adapt genetically to the fast pace of CC, will result in serious maladaptations (but see ref. 23), local species extinctions and a reduction of ecosystem services within the remaining forests^{23–26}. Therefore, assisted migration (AM) of tree species and seed provenances have been proposed as measures to use species-specific climatic limits and local adaptations to improve the adaptive capacity

A full list of affiliations appears at the end of the paper. ✉e-mail: silvio.schueler@bfw.gv.at

Table 1 | Suitable cultivation areas and their variation

Species	Cultivation area (1,000 km ²)			Change in cultivation area (%)	
	Contemporary (1991–2010)	RCP4.5 (2061–2080)	RCP8.5 (2061–2080)	RCP4.5 (2061–2080)	RCP8.5 (2061–2080)
	Area	Area	Area		
<i>A. alba</i>	173.03±11.1	5.33±0.9	1.25±0.3	−97.09±0.01	−99.29±0.01
<i>P. abies</i>	647.8±25.6	349.5±49.5	219.76±47.1	−45.5±0.03	−66.00±0.02
<i>P. sylvestris</i>	528.88±26.5	610.45±71.0	630.84±90.4	17.89±0.04	27.00±0.06
<i>L. decidua</i>	21.48±2.1	4.92±0.9	3.77±0.9	−76.83±0.01	−82.45±0.01
<i>F. sylvatica</i>	48.86±4.8	89.89±15.6	84.88±20.9	85.69±0.14	77.11±0.15
<i>Q. petraea</i>	72.27±11.0	8.07±1.5	14.27±3.6	−89.17±0.00	−81.00±0.01
<i>Q. robur</i>	77.77±8.0	501.94±65.4	615.34±89.9	493.01±0.25	601.00±0.21

The potential cultivation areas, given in 1,000 km², show where each of the seven species has the highest climatic suitability in contemporary climate (1991–2010) and projected CC scenarios RCP4.5 and 8.5 for the period 2061–2080 according to the ensemble SDMs. The cultivation areas were calculated from ensemble SDMs for each species, while ‘±’ is the standard deviation of the cultivation area due to the ten SDMs in contemporary climate and the combinations of ten SDMs and five RCMs under CC scenarios RCP4.5 and 8.5. See Supplementary Table 1 for details.

and resilience of forests while maintaining the provision of ecosystem services^{27–31}. While AM can be grouped into ‘assisted gene flow’ referring to the transfer of seed provenances to new locations within the present distribution range and ‘assisted species migration’ referring to moving seed provenances beyond the present species range, we refer to AM as a more generic term including both types^{28,32}. Despite growing evidence for increasing mismatches between local adaptations and the changing climate for forest trees around the world^{33,34}, no comprehensive multispecies, continent-wide analysis of the needs and effects of AM exists to date, limiting our understanding of how local adaptations affect major ecosystem services such as the forest carbon sink (CS). On the European scale, such a study could motivate AM schemes for forest trees across the ranges of species and support policies on nature-based CC mitigation strategies.

Here we demonstrate the implementation of AM in reforestation of seven major European trees by analysing a dataset of 587 range-wide provenance trials, evaluating 2,964 provenances from their entire distribution (Supplementary Table 1 and Supplementary Figs. 1–3) and combining shifts of species distributions with population transfer models. We quantify the combined effects of adapting the selection of species and seed provenances on annual above-ground CS of European forests. Although the positive effects of species mixtures on productivity are well-documented¹⁴, our analysis is limited to single-species forests at a level of a 1 × 1 km grid cell to focus on the direct effects of seed provenance selection.

First, we selected the climatically best-suited species (species with the highest probability of occurrence) at a spatial resolution of a 1 × 1 km grid cell with multimodel ensemble species distribution models (SDMs)³⁵ (Supplementary Table 6) and used the underlying single-model SDMs for uncertainty analysis. Second, for each grid cell with the best-suited species, we identified the best-fitting seed provenances by modelling their annual CS. For a realistic estimation of CS, we restricted our predictions to those grid cells of the land surface, where at least 50% of the area is covered by forests³⁶. Thus, our models address reforestation on previous forest sites (forest regrowth), which allows us to assume constant carbon stocks in forest soils given their high variation and uncertain response to CC and forest development³⁷. To identify the best-fitting seed provenances, we developed universal response functions (URFs) for the seven tree species *Abies alba*, *Larix decidua*, *Picea abies*, *Pinus sylvestris*, *Fagus sylvatica*, *Quercus robur* and *Quercus petraea*. These models account for environmental and genetic trait variation in above-ground CS^{38,39} and allow estimates of CS to forest regrowth until stand ages of 40 years because of (1) the mitigation potential of tree planting and reforestation needs to unfold high sequestration capacity as soon as possible to limit further global

warming and (2) the limitations of the provenance dataset, which covers predominantly trials with ages up to 40 years. To use the URF for meaningful AM applications, tree species and seed source occurrences across Europe were grouped into species-specific seed provenance clusters (SPC) of climatically and geographically similar groups to correspond to range-wide local adaptation patterns (Supplementary Table 8). To quantify the effects of AM, two seed provenance sourcing scenarios were used: (1) ‘local seeds’ where the climate of the planting location and the historical climate of seed origin were identical and geographically proximate and (2) ‘adapted seeds’, where SPC producing highest CS for the climate of the planting location were selected irrespective of their climatic and geographic proximity to the planting location (Supplementary Fig. 4). These scenarios were tested for contemporary climate (1991–2010) and the period 2061–2080 under the two CC scenarios representative concentration pathways RCP 4.5 and RCP 8.5 (ref. 40). For each CC scenario, five bias-corrected regional climate models (RCMs) were applied (Supplementary Table 2) contributing to a full uncertainty analysis (Supplementary Table 9), where the variation of RCMs, the variation of SDMs and the variation of the provenance selection were used to quantify the uncertainty of future CS. The relative contributions of the sources of uncertainty⁴¹ related to the modelling frameworks and the AM scenario were mapped to quantify the geographical distribution of the sources of uncertainties across Europe (Supplementary Table 13 and Supplementary Figs. 16–22).

Large changes in forest composition required under climate change

All SDMs and climate model combinations indicate that CC is projected to cause drastic shifts in the climatic suitability of tree species, calculated as the species with the highest probability of occurrence in each forested grid cell of Europe (Table 1 and Supplementary Table 10). The suitability of conifers such as *P. abies*, *A. alba* and *L. decidua*, which have dominant shares in Central and Northern European forests as a result of their wide cultivation in past centuries⁴², declines drastically resulting in major shifts in species distributions (Table 1 and Supplementary Table 10), as reported previously^{16,19}. Under future climate, the relative share of broadleaved species such as *F. sylvatica* and *Q. robur* is expected to exceed the share of conifers (Table 1 and Supplementary Fig. 8) but all species will experience declines in suitable habitats, especially in south and southeastern Europe³⁵. Although the uncertainty in suitable cultivation areas due to different SDMs, RCMs and their combination varies between species and increases from an average of 4% under contemporary climate to 25% under RCP 8.5 (Table 1, Supplementary Table 10 and Supplementary Figs. 5 and 6), the rankings of species in suitable cultivation areas remain largely constant (Supplementary Fig. 8).

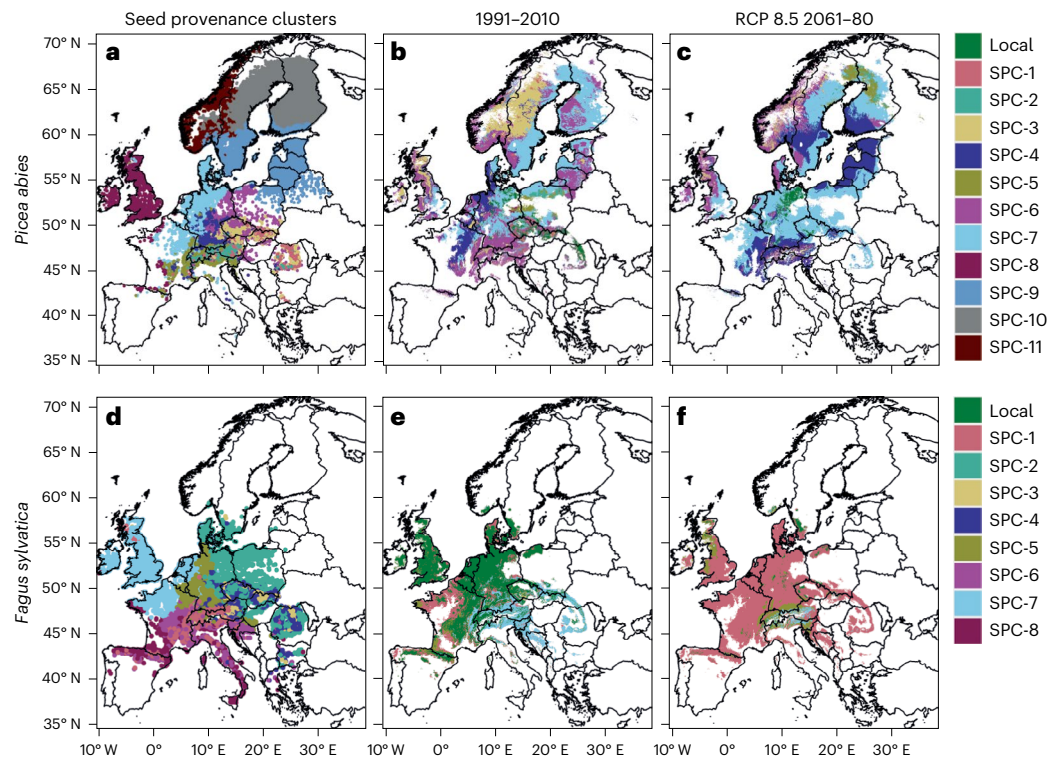


Fig. 1 | Seed provenance clusters of *P. abies* and *F. sylvatica* and their application for assisted migration. a–f, Geographic locations (a,d) of the SPC and distribution maps of *P. abies* (b,c) and *F. sylvatica* (e,f), where the SPC that are predicted to yield the highest annual CS for each 1×1 km grid cell are marked in the respective SPC colour. Green colours mark areas where local seed sources are the most productive seed provenances. SPC selections are shown for contemporary climate (1991–2010) and future climate under the RCP 8.5 scenario

in the period 2061–2080. Best-suited SPC in the RCP 8.5 scenario was identified by URFs predicted for the mean climate of the five RCMs (Supplementary Table 2). See Supplementary Fig. 11 for other species. For better visualization, the maps present every 1×1 km grid cell of the contemporary distribution of the species, while the CSs reported in the study are restricted only to forested grid cells of Europe.

The scenarios for AM (Supplementary Fig. 4) of the seven main tree species focused on optimizing the CS potential of the regenerated forests. On the basis of extensive range-wide provenance trials, our models indicate that the CS for most of the tree species can be optimized if non-local SPC suitable for projected CC scenarios are being planted (Fig. 1 and Supplementary Figs. 9 and 11).

Local seed provenances offer optimal CS in regenerated forests only on restricted parts of their range (Supplementary Table 11). In contemporary climate, local seed provenances provide higher CS compared to adapted seed provenances only in 3–4% of the total suitable area of *P. abies* and *P. sylvestris*, 15–18% in *L. decidua* and *A. alba*, 8–16% in the two oak species (8–17%) but 50% in case of *F. sylvatica* (Supplementary Table 11). Under the strong CC scenario RCP 8.5, the suitable area for deployment of local seed provenances decreased to 2–19% of the respective species distribution. The strongest decline in suitable areas for local material was observed in *F. sylvatica* (5% of the area) and *Q. petraea* (8%) (Supplementary Table 11). The suitable area for deploying local seeds remained largely constant for *L. decidua*, *P. sylvestris* and *A. alba* and slightly increased from 8% to 15% for *Q. robur* (Supplementary Table 11). Under contemporary climate, the uncertainty in the share of suitable area for local and adapted seed sources is small ranging from 0.1% to 1.2% of the total area for local material and from 0.6% to 2.1% for adapted material (Supplementary Table 11). For future climate scenarios, uncertainty increased to between 0.5% and 4.0% for local seed sources and 3.4% and 30.9% of the total area for adapted seed sources. The poor performance of many local seed sources regarding CS even under contemporary climate might be explained by the incomplete expansion of many European tree species after the last glaciation²¹ and by adaptation lags of many tree populations observed particularly

within marginal populations^{23,33,43–46}. Previously, such adaptation lags were mainly found for growth and productivity⁴⁵ but more recently also for phenological or physiological traits^{23,44,46}.

Following AM, the best seed provenances of *A. alba* originate from the cold and dry regions of the Carpathians, whereas for *L. decidua*, the best seed provenances originate from lower elevations of mountain regions of eastern central Europe and the Polish lowlands, where the native range consists of small scattered populations⁴⁷. For *P. abies* (Fig. 1) and *P. sylvestris* (Supplementary Fig. 11), conifers with a large geographic range, a variety of SPC from the Carpathians, central and atlantic Europe are suitable each for a specific region. For the deciduous species *F. sylvatica* (Fig. 1) and *Q. petraea*, SPC from the alpine and atlantic regions performed best over a large part of the future distribution, while for *Q. robur*, SPC from central and partly southeastern Europe outperformed others (Supplementary Fig. 11). Irrespective of variations in their recommended cultivation area due to underlying SDM–RCM–URF combinations, the relative ranking of productive SPC remains largely constant with a few SPC being most suitable across large parts of the future distribution areas (Supplementary Figs. 9 and 11).

Assisted migration can maintain European forest carbon sequestration

Tree species change and seed provenance selections have strong effects on the annual CS of forest regrowth (Table 3). If local seed provenances are selected, the change from predominantly coniferous species to deciduous trees is expected to decrease the overall CS of the reforestation⁴⁸ from 39.76 ± 1.14 TgC yr⁻¹ to 23.46 ± 0.98 TgC yr⁻¹ under RCP 4.5 and 21.67 ± 2.54 TgC yr⁻¹ under RCP 8.5 scenarios in the period 2061–2080 (Fig. 2 and Table 2).

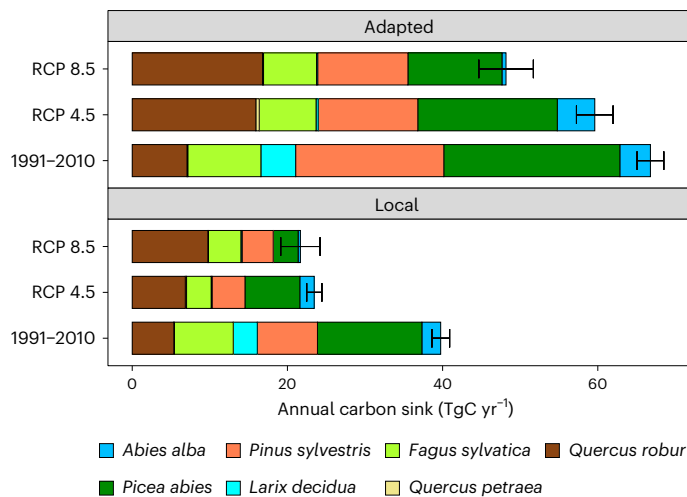


Fig. 2 | Effects of assisted migration on the annual CS of European forests.

Total annual above-ground CS (TgC yr^{-1}) for the seven tree species under the two seed source scenarios 'adapted' and 'local' seed provenances. Local are those seed provenances that are geographically proximate to the planting locations and where the climate of the planting location and the historical climate of seed origin are identical. Adapted seeds are those SPC producing the highest annual CS for the climate of the planting location irrespective of their climatic similarity and geographic proximity to the planting location. CS from local and adapted seed sources in RCP 4.5 and 8.5 scenarios were identified by URFs predicted for the mean climate of five RCMs (Supplementary Table 2). The error bars represent the standard deviation of the annual CS (TgC yr^{-1}) of the sum of the seven species and are calculated from the different combinations of SDMs, URFs and RCMs.

If instead, the most productive SPC according to AM for the respective climate is planted, reforestation could contribute to an increase of annual CS to $66.78 \pm 1.72 \text{ TgC yr}^{-1}$ under contemporary climate and $59.61 \pm 2.36 \text{ TgC yr}^{-1}$ under the RCP 4.5 scenario during 2061–2080. Moreover, even under the pessimistic CC scenario RCP 8.5, AM would allow increasing the annual CS slightly to $48.18 \pm 3.52 \text{ TgC yr}^{-1}$ during 2061–2080 (Fig. 2 and Table 3). Despite variations in CS due to various combinations of SDMs, URFs and RCMs (Supplementary Tables 12 and 13) all models indicate a higher annual CS of adapted seed sources compared to local seed sources and the relative contribution of the seven species on annual CS remained constant (Fig. 2, Table 2 and Supplementary Table 12).

Under contemporary climate, the CS of the modelled forest stands would account for about 26% of the observed annual CS (155 TgC yr^{-1}) of European forests³ if planted with local seed materials and for about 43% if adapted seed sources are used (Table 2). Given that the seven species encompass around two-thirds of the European forest area³ and that our models encompass forest regrowth until the age of 40 years, these model predictions cover the approximate magnitude of observed CSs realistically.

In contemporary climate, a substantial portion of this CS in regrowing forests is attributable to conifers, irrespective of the seed provenances being planted (Fig. 2 and Table 2). Under CC (scenario RCP 8.5), the contribution of conifers to the CS, especially of *P. abies* and *P. sylvestris*, declines from 75 to 50% if adapted seed sources are planted and from 40 to 15% if local seed sources are used. This is due to their decreasing suitable area, whereas the contribution of broadleaved species to CS increases (Fig. 2 and Table 2). Although the suitable areas for conifers decline in CC, AM contributes more to higher CS of conifers as compared to broadleaved species (Table 3).

In general, all species gained in annual CS when adapted seed provenances were planted but the benefits of AM were more evident under CC (Table 3) despite increasing uncertainties (Table 3). For regrowing conifers, AM results in a gain of 150–200% (RCP 4.5) annual

Table 2 | Effect of seed origin on annual CS of European forests

AM scenario	Species	Contemporary	RCP 4.5	RCP 8.5
		1991–2010	2061–2080	2061–2080
Adapted seed sources	<i>A. alba</i>	3.94 ± 0.23	4.83 ± 0.89	0.52 ± 0.18
	<i>P. abies</i>	22.69 ± 0.8	17.98 ± 2.37	12.12 ± 2.93
	<i>P. sylvestris</i>	19.09 ± 0.85	12.83 ± 1.42	11.63 ± 1.83
	<i>L. decidua</i>	4.48 ± 0.38	0.28 ± 0.05	0.15 ± 0.04
	<i>F. sylvatica</i>	9.42 ± 1	7.32 ± 1.26	6.83 ± 1.67
	<i>Q. petraea</i>	0.1 ± 0.01	0.44 ± 0.09	0.13 ± 0.04
	<i>Q. robur</i>	7.06 ± 0.78	15.93 ± 2.26	16.79 ± 1.9
	Annual CS (TgCyr^{-1})	66.78 ± 1.72	59.61 ± 2.36	48.18 ± 3.52
	Annual CO_2 removal ($\text{TgCO}_2\text{yr}^{-1}$)	244.85 ± 6.3	218.57 ± 8.65	176.64 ± 9.52
Local seed sources	<i>A. alba</i>	2.42 ± 0.16	1.85 ± 0.3	0.29 ± 0.1
	<i>P. abies</i>	13.46 ± 0.52	7.07 ± 0.89	3.21 ± 1.88
	<i>P. sylvestris</i>	7.75 ± 0.4	4.25 ± 0.55	4.02 ± 0.79
	<i>L. decidua</i>	3.1 ± 0.27	0.11 ± 0.02	0.15 ± 0.02
	<i>F. sylvatica</i>	7.62 ± 0.73	3.17 ± 0.53	4.19 ± 1.02
	<i>Q. petraea</i>	0.04 ± 0	0.16 ± 0.03	0.06 ± 0.02
	<i>Q. robur</i>	5.36 ± 0.54	6.84 ± 0.95	9.75 ± 1.4
	Annual CS (TgCyr^{-1})	39.76 ± 1.14	23.46 ± 0.98	21.67 ± 2.54
	Annual CO_2 removal ($\text{TgCO}_2\text{yr}^{-1}$)	145.79 ± 4.15	86.03 ± 3.6	79.46 ± 9.33

Annual CS (TgCyr^{-1}) and CO_2 removal ($\text{TgCO}_2\text{yr}^{-1}$) $\pm$ s.d. when best-suited species are planted with local or adapted seed provenances. Annual CS from local and adapted seed sources in RCP 4.5 and 8.5 scenarios were identified by URFs predicted for the mean climate of five RCMs (Supplementary Table 2). Standard deviations of the annual CS and CO_2 removal were estimated from the combination of SDMs, URFs and RCMs.

CS as compared to local seed provenances, while for broadleaved species a gain of 130–172% can be expected (Table 3). The higher gains in conifers are in contrast to the lower genetic differentiation among populations as compared to broadleaved trees⁴⁹. This might be explained either by the lesser coverage of the broadleaved species' niches by the provenances and trial sites within our dataset (Supplementary Figs. 2 and 3) or by the broader climatic niche of the conifer species resulting in stronger selection and more local adaptations to manifold regional climates or by higher phenotypic plasticity^{46,50–52}. The observed CS differences between local and adapted SPC are not restricted to a certain geographic region and adapted SPC outperforms local provenances within all bioclimatic regions of Europe (Supplementary Fig. 12). However, the gains of adapted SPC are more pronounced in central and northern Europe such as in alpine, boreal and atlantic than in the Pannonian and Mediterranean regions mainly because the seven selected species will have only low suitability in southern Europe in CC. Also, the spatial analysis of components of uncertainty did not reveal notable geographical variation. The components contributed by the AM scenario, explained in total 91% of the variance observed in CS (Supplementary Table 13 and Supplementary Figs. 16–18). However, uncertainties due to modelling framework, that is the choice of RCMs and the SDM algorithms were more pronounced in northern and northeastern Europe than elsewhere (Supplementary Table 13 and Supplementary Figs. 19–22).

Our empirical data are based on provenance trials mostly established with seed lots from natural unimproved forests. Tree breeding

Table 3 | Relative gains in annual CS by assisted migration

Species	Contemporary	RCP 4.5	RCP8.5
	1991–2010	2061–2080	2061–2080
<i>A. alba</i>	62.6±5.2	160.27±14	75.01±19.9
<i>P. abies</i>	68.53±6.1	154.27±15.1	70.27±10.2
<i>P. sylvestris</i>	146.41±8.0	202.06±23.3	146.15±21.3
<i>L. decidua</i>	44.23±3.0	150.00±11.3	0.10±18
<i>F. sylvatica</i>	23.55±2.8	130.77±15.2	63.16±22
<i>Q. petraea</i>	150.00±1.1	172.73±6.1	100.01±17.6
<i>Q. robur</i>	31.77±3.9	132.78±11.3	72.31±22.1

The gain in annual CS (%) by changing seed procurement from local to adapted seed provenances. CS from local and adapted seed sources in RCP 4.5 and 8.5 scenarios were identified by the URFs predicted for the mean climate of five RCMs (Supplementary Table 2). Standard deviations of relative gains (%) were estimated by the combination of the various SDMs, URFs and RCMs.

programmes, where productivity gains of 10–25% are typically achieved within a breeding generation⁵³ allow for a further increase of annual CS if AM is considered^{54,55}. Scientific studies across disciplines such as genecological experiments⁵⁶, provenance trials^{57–59}, dendroclimatic analysis⁶⁰ and genome studies^{43,61}, although limited in their geographic scale, have indicated that adapted seed provenances are required to avoid maladaptation and mitigate consequences of CC. Our recommendation for AM based on range-wide empirical data confirms this overarching scientific agreement across disciplines regarding CS.

Limitations and conflicts

Our analysis may be subject to potential limitations, which encompass deficiencies in the available data and constraints associated with the models. Although our transfer models are built upon one of the largest continental tree provenance datasets, we were only able to model the provenance transfer of seven main tree species common to central and northern Europe, which dominate, however, within two-thirds of Europe's forests⁶². This is because past provenance experiments with a valid representation of full distribution areas are limited to few stand-forming and commercially important species⁶³. Data for rare and scattered distributed trees are rarely available and this limits the extension of our predictions to mixed forest types. Another uncertainty could be the inclusion of data from non-autochthonous seed sources because forests in Europe have been managed for centuries and seed provenances mainly of conifers have been transferred historically^{64,65}. Thus, our data may include a certain amount of non-autochthonous seed sources, where the known seed origin might be different from the original local adaptation. However, a high number of non-autochthonous seed sources in the dataset is expected to weaken the relationship between climate and provenance origin and would result in a possible underestimation of AM effects. Also, we limit the uncertainty of imperfect empirical data by grouping provenances into large-scale SPC. Our analysis also leaves out Mediterranean forests, where similar adaptation lags due to growth decline were reported^{33,66,67}.

The applied transfer models focus on productivity and carbon sequestration for expected future long-term mean climate; therefore, they may not account for extreme climate events or biotic/abiotic disturbances, which pose a serious risk for the future provision of ecosystem services^{4,5,9,68,69}. Moreover, productivity and CS might not be the only traits for which tree populations developed local adaptations. It can be expected that trade-offs exist between productivity and other traits, such as tolerance to frost⁶⁹, drought or insect outbreaks, which are not explicitly considered here and may reduce the resilience of forests with transferred populations. Therefore, provenance trials need to be further exploited for developing several trait models for

AM as a basis for potential implementation. This would complement increasing evidence for local adaptations and future maladaptation in traits related to phenology and drought tolerance^{23,25,70}, which suggests that seed sources from more southern and drier sites are more drought tolerant and may be used also in core areas of species distributions^{25,71,72}. Also, drought recovery and resilience were recently found to be positively correlated to growth and competitive ability in provenance trials established at the warm and dry distribution edges of the species^{73,74}, suggesting that selecting trees for higher carbon stocks under future conditions might also improve drought performance.

Since the main focus of our analysis was to demonstrate the role of AM on CS, simplified assumptions of selecting the single species with the highest climatic suitability in each 1 × 1 km forested grid cell were made. Although it is widely considered that mixed forests may increase productivity and CS through higher yields and can reduce drought sensitivity and mortality^{15,16}, this simplification was required because mixed forests across Europe are composed of different species combinations with species-specific mixture–productivity relationships^{75,76} and range-wide models to quantify mixture effects are not available yet⁷⁷.

To quantify the uncertainty of model choice and the source of climate data, best-suited species and provenances were identified for five RCMs, different SDMs and the subsequent URFs. Although the uncertainty of the various model predictions increased from the current climate to the most extreme CC scenario, the cultivation areas for the best-suited tree species and SPC as well as their relative contribution to annual CS remained stable irrespective of the model combination. Our transfer models are applied only within the changing climatic niche of the target species as modelled by state-of-the-art SDMs³⁵. While this allows us to model the forest CS within the climatic space of the past species distribution and avoids predictions beyond the climate conditions of our trial observations (Supplementary Fig. 2 and 3), it does predict changes in tree species and provenances across large geographic distances. Such drastic changes in the forest might have genetic⁷⁸, ecological^{79,80}, social^{81,82} and economic¹⁶ consequences, which need to be weighed against the outcomes of inaction⁸³. Given the overwhelming evidence from distribution models^{19,35,84} and increasing forest disturbances^{6,68}, changing forest species compositions and species distributions are the most widely accepted measure to adapt forests to CC^{78,10}. However, the limited migration capacities of many species to reach suitable areas^{22,85} and the increasing population maladaptation^{23,86} will ultimately limit natural species reshuffling and endanger forest ecosystem services⁸⁵ if increasingly mismatching local adaptations are ignored. Therefore, inaction in species and provenance selection may increase the vulnerability of current tree populations to CC^{10,83,87,88} and endanger valuable genetic resources^{89,90}.

Conclusion

Reforestation and restoration needs in European forests⁶ require decisions on the selection of tree species and seed provenances. Despite evidence of large-scale species shifts and increasing genetic maladaptation in forest trees, there has been little effort to incorporate this knowledge into ongoing tree plantation initiatives, forest restoration programmes and national and transnational regulations. Preventing maladaptation of current forests can provide a major boost to nature-based solutions for CC mitigation such as forest restoration while ensuring resilience and preserving the forest CS^{12,60,91}. Our results provide evidence for strong effects of seed provenance selection on the CS under future climate and demonstrate that improving forest resilience by planting species for future climate needs to be combined with adequate provenance selection to preserve the annual CS of European forests. Changing species composition alone will result in decreasing CS and the risk of failing the European Union target for climate neutrality⁹². This evidence calls for further research and transnational cooperation to develop and implement AM and to quantify possible trade-offs

between productivity and other traits to avoid unknown risks of AM implementation.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41558-024-02080-5>.

References

- IPCC. Summary for Policymakers. In *Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) 3–24 (Cambridge Univ. Press, 2018).
- Bastin, J. F. et al. The global tree restoration potential. *Science* **365**, 76–79 (2019).
- State of Forests 2020 (Forest Europe, 2020); https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf
- Seidl, R., Schelhaas, M. J., Rammer, W. & Verkerke, P. J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Change* **4**, 806–810 (2014).
- Thom, D. & Seidl, R. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. *Biol. Rev. Camb. Philos. Soc.* **91**, 760–781 (2016).
- Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A. & Cescatti, A. Emerging signals of declining forest resilience under climate change. *Nature* **608**, 534–539 (2022).
- Bolte, A. et al. Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. *Scand. J. Res.* **24**, 473–482 (2009).
- Spathelf, P. et al. Adaptive measures: integrating adaptive forest management and forest landscape restoration. *Ann. For. Sci.* **75**, 55 (2018).
- Millar, C. I. & Stephenson, N. L. Temperate forest health in an era of emerging megadisturbance. *Science* **349**, 823–826 (2015).
- Jandl, R., Spathelf, P., Bolte, A. & Prescott, C. E. Forest adaptation to climate change—is non-management an option? *Ann. For. Sci.* **76**, 48 (2019).
- Bastin, J. F. et al. *Tree Restoration Potential in the European Union* <https://doi.org/10.13140/RG.2.2.24811.67368/1> (FAO and European Commission Directorate General for Environment (DG ENV), 2020).
- Matthews, H. D. et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. *Commun. Earth Environ.* **3**, 65 (2022).
- Nabuurs, G. J. et al. First signs of carbon sink saturation in European forest biomass. *Nat. Clim. Change* **3**, 792–796 (2013).
- Liang, J. et al. Positive biodiversity–productivity relationship predominant in global forests. *Science* <https://doi.org/10.1126/science.aaf8957> (2016).
- Ammer, C. Diversity and forest productivity in a changing climate. *New Phytol.* **221**, 50–66 (2019).
- Hanewinkel, M., Cullmann, D. A., Schelhaas, M. J., Nabuurs, G. J. & Zimmermann, N. E. Climate change may cause severe loss in the economic value of European forest land. *Nat. Clim. Change* **3**, 203–207 (2013).
- Duveiller, G. et al. Revealing the widespread potential of forests to increase low level cloud cover. *Nat. Commun.* **12**, 4337 (2021).
- Thuiller, W., Lafourcade, B., Engler, R. & Araújo, M. B. BIOMOD—a platform for ensemble forecasting of species distributions. *Ecography* **32**, 369–373 (2009).
- Dyderski, M. K., Paž, S., Frelich, L. E. & Jagodziński, A. M. How much does climate change threaten European forest tree species distributions? *Glob. Change Biol.* **24**, 1150–1163 (2018).
- Thurm, E. A. et al. Alternative tree species under climate warming in managed European forests. *For. Ecol. Manag.* **430**, 485–497 (2018).
- Svenning, J. C. & Skov, F. Limited filling of the potential range in European tree species. *Ecol. Lett.* **7**, 565–573 (2004).
- Nathan, R. et al. Spread of North American wind-dispersed trees in future environments. *Ecol. Lett.* **14**, 211–219 (2011).
- Frank, A. et al. Risk of genetic maladaptation due to climate change in three major European tree species. *Glob. Change Biol.* **23**, 5358–5371 (2017).
- Aitken, S. N., Yeaman, S., Holliday, J. A., Wang, T. & Curtis-McLane, S. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evol. Appl.* **1**, 95–111 (2008).
- Isaac-Renton, M. et al. Northern forest tree populations are physiologically maladapted to drought. *Nat. Commun.* **9**, 5254 (2018).
- Kremer, A. et al. Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecol. Lett.* <https://doi.org/10.1111/j.1461-0248.2012.01746.x> (2012).
- Alberto, F. J. et al. Potential for evolutionary responses to climate change—evidence from tree populations. *Glob. Change Biol.* <https://doi.org/10.1111/gcb.12181> (2013).
- Aitken, S. N. & Bemmels, J. B. Time to get moving: assisted gene flow of forest trees. *Evol. Appl.* **9**, 271–290 (2016).
- Pedlar, J. H. et al. Placing forestry in the assisted migration debate. *Bioscience* **62**, 835–842 (2012).
- Williams, M. I. & Dumroese, R. K. Preparing for climate change: forestry and assisted migration. *J. For.* <https://doi.org/10.5849/jof.13-016> (2013).
- McLachlan, J. S., Hellmann, J. J. & Schwartz, M. W. A framework for debate of assisted migration in an era of climate change. *Conserv. Biol.* **21**, 297–302 (2007).
- Hällfors, M. H. et al. Coming to terms with the concept of moving species threatened by climate change—a systematic review of the terminology and definitions. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0102979> (2014).
- Fréjaville, T., Vizcaíno-Palomar, N., Fady, B., Kremer, A. & Benito Garzón, M. Range margin populations show high climate adaptation lags in European trees. *Glob. Change Biol.* **26**, 484–495 (2020).
- Sáenz-Romero, C. et al. Assisted migration of forest populations for adapting trees to climate change. *Rev. Chapingo Ser. Cienc.* **22**, 303–323 (2016).
- Chakraborty, D., Móricz, N., Rasztovits, E., Dobor, L. & Schueler, S. Provisioning forest and conservation science with high-resolution maps of potential distribution of major European tree species under climate change. *Ann. For. Sci.* **78**, 26 (2021).
- Gunia, K., Van Brusselen, J., Päivinen, R., Zudin, S. & Zudin, E. *Forest Map of Europe* (European Forest Institute, 2012).
- Cook-Patton, S. C. et al. Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
- Chakraborty, D. et al. Selecting populations for non-analogous climate conditions using universal response functions: the case of Douglas-fir in Central Europe. *PLoS ONE* **10**, e0136357 (2015).
- Wang, T. et al. Integrating environmental and genetic effects to predict responses of tree populations to climate. *Ecol. Appl.* **20**, 153–163 (2010).
- Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* **42**, 153–168 (2017).
- Diniz-Filho, J. A. F. et al. Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate change. *Ecography* **32**, 897–906 (2009).
- McGrath, M. J. et al. Reconstructing European forest management from 1600 to 2010. *Biogeosciences* **12**, 4291–4316 (2015).
- Browne, L., Wright, J. W., Fitz-Gibbon, S., Gugger, P. F. & Sork, V. L. Adaptational lag to temperature in valley oak (*Quercus lobata*) can be mitigated by genome-informed assisted gene flow. *Proc. Natl Acad. Sci. USA* **116**, 25179–25185 (2019).

44. Etterson, J. R., Cornett, M. W., White, M. A. & Kavajecz, L. C. Assisted migration across fixed seed zones detects adaptation lags in two major North American tree species. *Ecol. Appl.* **30**, e02092 (2020).
45. Mátyás, C. Adaptation lag: a general feature of natural populations (invited lecture). Paper no. 2.226. In *Joint Meeting of Western Forest Genetics Association and IUFRO Working Parties, Douglas-fir, Contorta Pine, Sitka Spruce, and Abies Breeding and Genetic Resources* 20–24 (Weyerhaeuser Company, 1990).
46. Leites, L. & Benito Garzón, M. Forest tree species adaptation to climate across biomes: building on the legacy of ecological genetics to anticipate responses to climate change. *Glob. Change Biol.* <https://doi.org/10.1111/gcb.16711> (2023).
47. Pâques, M. J. *Technical Guidelines for Genetic Conservation and use for European Larch* (*Larix decidua*) (EUFORGEN, 2008).
48. Luyssaert, S. et al. Trade-offs in using European forests to meet climate objectives. *Nature* **562**, 259–262 (2018).
49. Petit, R. J. et al. Comparative organization of chloroplast, mitochondrial and nuclear diversity in plant populations. *Mol. Ecol.* <https://doi.org/10.1111/j.1365-294X.2004.02410.x> (2005).
50. Valladares, F. et al. The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecol. Lett.* **17**, 1351–1364 (2014).
51. Kapeller, S., Dieckmann, U. & Schueler, S. Varying selection differential throughout the climatic range of Norway spruce in Central Europe. *Evol. Appl.* **10**, 25–38 (2017).
52. Müller, M., Kempen, T., Finkeldey, R. & Gailing, O. Low population differentiation but high phenotypic plasticity of European beech in Germany. *Forests* **11**, 1354 (2020).
53. Jansson, G., Hansen, J. K., Haapanen, M., Kvaalen, H. & Steffenrem, A. The genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland. *Scand. J. For. Res.* <https://doi.org/10.1080/02827581.2016.1242770> (2017).
54. Milesi, P. et al. Assessing the potential for assisted gene flow using past introduction of Norway spruce in southern Sweden: local adaptation and genetic basis of quantitative traits in trees. *Evol. Appl.* **12**, 1946–1959 (2019).
55. Poupon, V. et al. Accelerating adaptation of forest trees to climate change using individual tree response functions. *Front. Plant Sci.* **12**, 758221 (2021).
56. Frank, A. et al. Distinct genecological patterns in seedlings of Norway spruce and silver fir from a mountainous landscape. *Ecology* **98**, 211–227 (2017).
57. Kapeller, S., Lexer, M. J., Geburek, T., Hiebl, J. & Schueler, S. Intraspecific variation in climate response of Norway spruce in the eastern Alpine range: selecting appropriate provenances for future climate. *For. Ecol. Manag.* **271**, 46–57 (2012).
58. Berlin, M. et al. Scots pine transfer effect models for growth and survival in Sweden and Finland. *Silva Fenn.* **50**, 1562 (2016).
59. Pedlar, J. H., McKenney, D. W. & Lu, P. Critical seed transfer distances for selected tree species in eastern North America. *J. Ecol.* **109**, 2271–2283 (2021).
60. Girardin, M. P. et al. Annual aboveground carbon uptake enhancements from assisted gene flow in boreal black spruce forests are not long-lasting. *Nat. Commun.* **12**, 1169 (2021).
61. Gougherty, A. V., Keller, S. R. & Fitzpatrick, M. C. Maladaptation, migration and extirpation fuel climate change risk in a forest tree species. *Nat. Clim. Change* **11**, 166–171 (2021).
62. Brus, D. J. et al. Statistical mapping of tree species over Europe. *Eur. J. Res.* **131**, 145–157 (2012).
63. Pâques, L. E. (ed.) *Forest Tree Breeding in Europe: Current State-of-the-Art and Perspectives* (Springer, 2013).
64. Jansen, S. & Geburek, T. Historic translocations of European larch (*Larix decidua* Mill.) genetic resources across Europe—a review from the 17th until the mid-20th century. *For. Ecol. Manag.* <https://doi.org/10.1016/j.foreco.2016.08.007> (2016).
65. Jansen, S., Konrad, H. & Geburek, T. The extent of historic translocation of Norway spruce forest reproductive material in Europe. *Ann. For. Sci.* **74**, 56 (2017).
66. Benito Garzón, M. & Vizcaino-Palomar, N. in *Pines and Their Mixed Forest Ecosystems in the Mediterranean Basin* (eds Ne'eman, G. & Yagil Osem, Y.) 71–82 (Springer, 2021).
67. Benito-Garzón, M. & Fernández-Manjarrés, J. F. Testing scenarios for assisted migration of forest trees in Europe. *New For.* <https://doi.org/10.1007/s11056-015-9481-9> (2015).
68. Hlásny, T. et al. Devastating outbreak of bark beetles in the Czech Republic: drivers, impacts and management implications. *For. Ecol. Manag.* **490**, 119075 (2021).
69. Montwé, D., Isaac-Renton, M., Hamann, A. & Spiecker, H. Cold adaptation recorded in tree rings highlights risks associated with climate change and assisted migration. *Nat. Commun.* **9**, 1574 (2018).
70. George, J. P. et al. Inter- and intra-specific variation in drought sensitivity in *Abies spec.* and its relation to wood density and growth traits. *Agric. For. Meteorol.* **214–215**, 430–443 (2015).
71. Stojnić, S. et al. Variation in xylem vulnerability to embolism in European beech from geographically marginal populations. *Tree Physiol.* **38**, 173–185 (2018).
72. Bansal, S., Harrington, C. A., Gould, P. J. & St.Clair, J. B. Climate-related genetic variation in drought-resistance of Douglas-fir (*Pseudotsuga menziesii*). *Glob. Change Biol.* **21**, 947–958 (2015).
73. George, J. P. et al. Genetic variation, phenotypic stability and repeatability of drought response in European larch throughout 50 years in a common garden experiment. *Tree Physiol.* **37**, 33–46 (2017).
74. Trujillo-Moya, C. et al. Drought sensitivity of Norway Spruce at the species' warmest fringe: quantitative and molecular analysis reveals high genetic variation among and within provenances. *G3* **8**, 1225–1245 (2018).
75. Baeten, L. et al. Identifying the tree species compositions that maximize ecosystem functioning in European forests. *J. Appl. Ecol.* **56**, 733–744 (2019).
76. Vospernik, S. Basal area increment models accounting for climate and mixture for Austrian tree species. *For. Ecol. Manag.* **480**, 118725 (2021).
77. Pretzsch, H., Forrester, D. I. & Rötzer, T. Representation of species mixing in forest growth models: a review and perspective. *Ecol. Model.* <https://doi.org/10.1016/j.ecolmodel.2015.06.044> (2015).
78. Grummer, J. A. et al. The immediate costs and long-term benefits of assisted gene flow in large populations. *Conserv. Biol.* **36**, e13911 (2022).
79. Kranabetter, J. M., Stoeck, M., & O'Neill, G. A. Ectomycorrhizal fungal maladaptation and growth reductions associated with assisted migration of Douglas-fir. *New Phytol.* **206**, 1135–1144 (2015).
80. Winder, R. S., Kranabetter, J. M. & Pedlar, J. H. in *Soils and Landscape Restoration* (eds Stanturf, J. A. & Callahan, Mac A.) 275–297 (Academic Press, 2021).
81. Klenk, N. L. The development of assisted migration policy in Canada: an analysis of the politics of composing future forests. *Land Use Policy* **44**, 101–109 (2015).
82. Pelai, R., Hagerman, S. M. & Kozak, R. Whose expertise counts? Assisted migration and the politics of knowledge in British Columbia's public forests. *Land Use Policy* **103**, 105296 (2021).
83. Rodríguez-Labajos, B. Climate change, ecosystem services and costs of action and inaction: scoping the interface. *WIREs Clim. Change* <https://doi.org/10.1002/wcc.247> (2013).
84. Sykes, M. T., Prentice, I. C. & Cramer, W. A bioclimatic model for the potential distributions of north European tree species under present and future climates. *J. Biogeogr.* **23**, 203–233 (1996).

85. Mauri, A. et al. Assisted tree migration can reduce but not avert the decline of forest ecosystem services in Europe. *Glob. Environ. Change* **80**, 102676 (2023).
86. St Clair, J. B. & Howe, G. T. Genetic maladaptation of coastal Douglas-fir seedlings to future climates. *Glob. Change Biol.* **13**, 1441–1454 (2007).
87. Hornsey, M. J. & Fielding, K. S. Understanding (and reducing) inaction on climate change. *Soc. Issues Policy Rev.* **14**, 3–35 (2020).
88. Kracke, I., Essl, F., Zulka, K. P. & Schindler, S. Risks and opportunities of assisted colonization: the perspectives of experts. *Nat. Conserv.* **45**, 63–84 (2021).
89. Schueler, S. et al. Vulnerability of dynamic genetic conservation units of forest trees in Europe to climate change. *Glob. Change Biol.* **20**, 1498–1511 (2014).
90. Petit-Cailleux, C. et al. Tree mortality risks under climate change in Europe: assessment of silviculture practices and genetic conservation networks. *Front. Ecol. Evol.* **9**, 706414 (2021).
91. Sha, Z. et al. The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. *Commun. Earth Environ.* **3**, 8 (2022).
92. *Fit for 55: Parliament Agrees to Higher EU Carbon Sink Ambitions by 2030* (European Parliament, 2022); <https://www.europarl.europa.eu/news/en/press-room/20220603IPR32133/fit-for-55-parliament-agrees-to-higher-eu-carbon-sink-ambitions-by-2030>
93. Assisted translocation of tree populations preserves the European forest carbon sink in climate change. *Figshare* <https://figshare.com/s/98e405d56bb789b08cb0> (2022).
94. Chakraborty, D., Dobor, L., Zolles, A., Hlásny, T. & Schueler, S. High-resolution gridded climate data for Europe based on bias-corrected EURO-CORDEX: the ECLIPS-2.0 dataset. *Zenodo* [10.5281/zenodo.3952158](https://zenodo.org/record/3952158) (2020).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024

¹Department of Forest Growth, Silviculture and Genetics, Austrian Research Centre for Forests (BFW), Vienna, Austria. ²Faculty of Forestry, University of Sarajevo, Sarajevo, Bosnia and Herzegovina. ³Department of Forest Physiology and Genetics, Slovenian Forestry Institute (SFI), Ljubljana, Slovenia. ⁴Academy of Sciences and Arts of Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina. ⁵UMR BIOGECO, INRAE, University of Bordeaux, Bordeaux, France. ⁶Thünen Institute of Forest Ecosystems, Eberswalde, Germany. ⁷Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic. ⁸Bavarian Office for Forest Genetics (AWG), Teisendorf, Germany. ⁹Bavarian Academy for Nature Conservation and Landscape Management (ANL), Laufen, Germany. ¹⁰Natural Resources Institute Finland (LUKE), Helsinki, Finland. ¹¹Department of Forest Genetic Resources, Northwest German Forest Research Institute (NW-FVA), Hann. Münden, Germany. ¹²Department for Genetics, Forest Tree Breeding and Seed Husbandry, Croatian Forest Research Institute, Jastrebarsko, Croatia. ¹³Department of Silviculture and Genetics, Forest Research Institute (IBL), Sękocin Stary, Poland. ¹⁴National Forest Centre, Zvolen, Slovakia. ¹⁵Mendel University in Brno, Faculty of Forestry and Wood Technology, Brno, Czechia. ¹⁶Forest Genetics and Tree Breeding Department, 'Marin Dracea' National Institute for Research and Development in Forestry, Ilfov, Romania. ¹⁷Forest Research Institute, University of Sopron, Gödöllő, Hungary. ¹⁸University of Forestry, Sofia, Bulgaria. ¹⁹Forest Research Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria. ²⁰Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway. ²¹Institute of Lowland Forestry and Environment, University of Novi Sad, Novi Sad, Serbia. ²²Deceased: Emil Popov. ✉e-mail: silvio.schueler@bfw.gv.at

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The provenance trials dataset is available via Figshare at <https://figshare.com/s/98e405d56bb789b08cb0> (ref. 93). The ECLIPS 2.0 dataset is available via Zenodo at <https://doi.org/10.5281/zenodo.3952159> (ref. 94).

Code availability

R codes developed for and used in this study are available upon request.

Acknowledgements

This research was supported by the INTERREG Central Europe Programme, Project SUSTREE: Conservation and sustainable utilization of forest tree diversity in climate change (grant no. CE614) and the SUPERB project funded by the European Union Horizon 2020 research and innovation programme under grant agreement no. 101036849. We are thankful to G. Schnabel (BFW) for help in graphical layout. We also acknowledge the support of COST Action CA19128 (PEN-CAForR) ‘Pan-European Network for Climate Adaptive Forest Restoration and Reforestation’ for co-authors G.B., M.I. and M.K. Funding for M.L. was received from the EEA/Norway grants 2014–2021 and the Technology Agency of the Czech Republic. We recognize the IUFRO Task Forces on Forest Adaptation and Restoration under Climate Change and Transforming Forest Landscapes for Future Climates and Human Well-Being represented by co-author A.B. We also acknowledge the Slovenian Research and Innovation Agency through research programme P4-0107 and research project V4-2222 co-financed by the Ministry of Agriculture, Forestry and Food received by co-author G.B. A.K. and A.D. received funding support from the EC-Grants FAIROAK (no. PL95-0297), MOTIVE (no. 226544)

and FORGER (no. 289119) We are also thankful to all the scientists and institutions that established and maintained provenance trials throughout the past century and supported the data collection within the SUSTREE project.

Author contributions

D.C. conceived the idea of the paper, formulated research questions, developed and carried out analysis and wrote the paper. A.C. supported analysis in the revised paper. D.B., G.B., E.C., A.H., A.D., M.I., R.L., G.M., K.P., E.P., R.S., T.M.S., T.S., A.S., S. Stojnic and K.V. provided provenance trial data. M.B.G., A.K. and L.N. provided provenance trial data and edited the paper. A.B. provided computing resources and edited the paper. R.B., J.C., J.G., J.P.G., M.K., J.K. and J.S. contributed to running URF models. M.L. contributed to running URF models and edited the paper. A.S. carried out paper revisions. S. Schueler conceived the idea of the paper and analysis, obtained research funding, contributed trial data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41558-024-02080-5>.

Correspondence and requests for materials should be addressed to Silvio Schueler.

Peer review information *Nature Climate Change* thanks Sally Aitken, Gert-Jan Nabuurs and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Please do not complete any field with "not applicable" or n/a. Refer to the help text for what text to use if an item is not relevant to your study. For final submission: please carefully check your responses for accuracy; you will not be able to make changes later.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed
☐	☒ The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒ The statistical test(s) used AND whether they are one- or two-sided <i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>
☐	☒ A description of all covariates tested
☐	☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒ For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted <i>Give P values as exact values whenever suitable.</i>
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒ Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	NA
Data analysis	R codes for analysis will be made available upon request

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

- All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
 - A description of any restrictions on data availability
 - For clinical datasets or third party data, please ensure that the statement adheres to our policy

The dataset of provenance trials is available at: <https://figshare.com/s/98e405d56bb789b08cb0>.
The climate data of the ECLIPS 2.0 dataset are accessible at <https://doi.org/10.5281/zenodo.3952159>.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender

Reporting on race, ethnicity, or other socially relevant groupings

Population characteristics

Recruitment

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences

☐ Behavioural & social sciences

☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size

Data exclusions

Replication

Randomization

Blinding

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

Research sample

Sampling strategy

Data collection

Timing

Data exclusions

Non-participation

Randomization

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Collection of published and unpublished tree provenance data and modelling
Research sample	NA
Sampling strategy	NA
Data collection	Collecting all available provenance data from the seven species available from the author team and publications
Timing and spatial scale	Analysed provenance trial data include datasets from the 20 and the 21 century, Europe, partly Asia
Data exclusions	Incomplete dataset and data from implausible coordinates
Reproducibility	Dataset will be made available
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Field work, collection and transport

Field conditions	
Location	
Access & import/export	
Disturbance	

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☐	☐ Antibodies
☐	☐ Eukaryotic cell lines
☐	☐ Palaeontology and archaeology
☐	☐ Animals and other organisms
☐	☐ Clinical data
☐	☐ Dual use research of concern
☐	☒ Plants

Methods

n/a	Involved in the study
☐	☐ ChIP-seq
☐	☐ Flow cytometry
☐	☐ MRI-based neuroimaging

Antibodies

Antibodies used	
Validation	

Eukaryotic cell lines

Policy information about [cell lines and Sex and Gender in Research](#)

Cell line source(s)

Authentication

Mycoplasma contamination

Commonly misidentified lines
(See [ICLAC](#) register)

Palaeontology and Archaeology

Specimen provenance

Specimen deposition

Dating methods

☐ Tick this box to confirm that the raw and calibrated dates are available in the paper or in Supplementary Information.

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Animals and other research organisms

Policy information about [studies involving animals; ARRIVE guidelines](#) recommended for reporting animal research, and [Sex and Gender in Research](#)

Laboratory animals

Wild animals

Reporting on sex

Field-collected samples

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Clinical data

Policy information about [clinical studies](#)

All manuscripts should comply with the ICMJE [guidelines for publication of clinical research](#) and a completed [CONSORT checklist](#) must be included with all submissions.

Clinical trial registration

Study protocol

Data collection

Outcomes

Dual use research of concern

Policy information about [dual use research of concern](#)

Hazards

Could the accidental, deliberate or reckless misuse of agents or technologies generated in the work, or the application of information presented in the manuscript, pose a threat to:

No	Yes
☒	☐ Public health
☒	☐ National security
☒	☐ Crops and/or livestock
☒	☐ Ecosystems
☒	☐ Any other significant area

Experiments of concern

Does the work involve any of these experiments of concern:

No	Yes
☒	☐ Demonstrate how to render a vaccine ineffective
☒	☐ Confer resistance to therapeutically useful antibiotics or antiviral agents
☒	☐ Enhance the virulence of a pathogen or render a nonpathogen virulent
☒	☐ Increase transmissibility of a pathogen
☒	☐ Alter the host range of a pathogen
☒	☐ Enable evasion of diagnostic/detection modalities
☒	☐ Enable the weaponization of a biological agent or toxin
☒	☐ Any other potentially harmful combination of experiments and agents

Plants

Seed stocks	
Novel plant genotypes	
Authentication	

ChIP-seq

Data deposition

- ☐ Confirm that both raw and final processed data have been deposited in a public database such as [GEO](#).
- ☐ Confirm that you have deposited or provided access to graph files (e.g. BED files) for the called peaks.

Data access links <i>May remain private before publication.</i>	
Files in database submission	
Genome browser session (e.g. UCSC)	

Methodology

Replicates	
Sequencing depth	
Antibodies	
Peak calling parameters	
Data quality	

Flow Cytometry

Plots

Confirm that:

- ☐ The axis labels state the marker and fluorochrome used (e.g. CD4-FITC).
- ☐ The axis scales are clearly visible. Include numbers along axes only for bottom left plot of group (a 'group' is an analysis of identical markers).
- ☐ All plots are contour plots with outliers or pseudocolor plots.
- ☐ A numerical value for number of cells or percentage (with statistics) is provided.

Methodology

Sample preparation

Instrument

Software

Cell population abundance

Gating strategy

- ☐ Tick this box to confirm that a figure exemplifying the gating strategy is provided in the Supplementary Information.

Magnetic resonance imaging

Experimental design

Design type

Design specifications

Behavioral performance measures

Imaging type(s)

Field strength

Sequence & imaging parameters

Area of acquisition

Diffusion MRI

☐ Used

☐ Not used

Preprocessing

Preprocessing software

Normalization

Normalization template

Noise and artifact removal

Volume censoring

Statistical modeling & inference

Model type and settings

Effect(s) tested

Specify type of analysis: ☐ Whole brain ☐ ROI-based ☐ Both

Statistic type for inference

(See [Eklund et al. 2016](#))

Correction

Models & analysis

n/a | Involved in the study

☐ ☐ Functional and/or effective connectivity

☐ ☐ Graph analysis

☐ ☐ Multivariate modeling or predictive analysis

Functional and/or effective connectivity

Graph analysis

Multivariate modeling and predictive analysis