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OPINION

Building forests for the future

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Abstract
Many governments have set ambitious targets for tree planting and increased woodland cover as a key part of actions to reach net-zero carbon emissions by 2050. However, many uncertainties remain concerning how and where to expand tree cover, what species to plant, and how best to manage new plantations. Much contemporary forestry has been based on even-aged monocultures, largely because of perceived advantages for timber production. However, in order to play a key role in climate change mitigation future forests will have to achieve timber production (and wider ecosystem service provision) alongside resilience to biotic and abiotic challenge. It is therefore crucial that appropriate informed decisions are made with regard to the structure, composition, and planning of future forests, in order to provide sustainable solutions that provide environmental, economic, and health benefits to society. Genetically diverse, mixed, and irregular forests, with their higher biodiversity and niche complementarity, are promising new forest configurations for regulating the water cycle, storing carbon, and delivering other goods and services. In the following discussion, we have used UK information to illustrate the benefits of mixed woodland versus monocultures and highlighted current issues related to government initiatives and policies for current and future forests. However, similar issues and problems are encountered globally.

KEYWORDS
continuous cover forestry, elevated CO_2, forest genetic resource, mixed planting

1 | INTRODUCTION

Trees are vital to human health and well-being, as well as helping to protect the environment against the negative impact of climate change. Governments across the world have initiated ambitious and well-meaning tree-planting policies. Tree planting is perceived by many as an engaging, environmentally friendly activity that can enhance air quality (e.g., Hewitt et al., 2020; Jones et al., 2019), while helping to reduce flooding, provide shade, and remove carbon dioxide from the atmosphere (e.g., Luyssaert et al., 2008; Pan et al., 2011). For example, tree-planting projects such as that at Honeydale Farm in the Cotswolds (UK), which encompasses an 8-acre planting of native trees, shrubs, and hedges, undersown with a mixture of wildflowers, have been undertaken to enhance natural flood alleviation works (Figure 1). Riparian planting has been encouraged because it has numerous benefits when introduced across slopes or beside rivers to intercept run-off and reduce pollution from entering nearby waterways. Woodland shelterbelts can slow flood flows and reduce sediment and bankside erosion, while increasing underground water storage, providing an effective buffer zone, and acting as a physical barrier to spray drift, reducing the amount of pesticide entering watercourses. People who live near trees experience many benefits such as improvement in their quality of life (van den Berg & Staats, 2018) with a positive impact on mental and physical health by reducing stress and encouraging outdoor activities (Barlagne et al., 2021; Benner et al., 2014; Venhoeven et al., 2018). However, important concerns remain that large-scale tree planting may not optimise benefits to the environment, particularly if the wrong species or environment is selected (see, e.g., Bateman et al., 2023).

Woodland currently covers about 12% of the United Kingdom (2.84 million ha), a figure that is below the European average of 37%. Nevertheless, the pivotal importance of forests and forest diversity in sequestering carbon has taken centre stage with ambitious projects across the United Kingdom designed to greatly increase tree planting and bring existing forests into management. The 2021 Environment Act sets environmental targets including an increase of tree and woodland cover to 16.5% of total land area in England by 2050, but the 2023 report of the UK Climate Change Committee felt sufficiently unsure of the level and delivery of this target to recommend (The UK Climate Change Committee, 2023) that funding and support must be "set at the correct level to meet the UK Government afforestation target of 30,000 hectares per year by 2025 and the illustrative net-zero strategy targets of 40,000 hectares and 50,000 hectares by 2030 and 2035, respectively. Further clarity is required regarding funding beyond 2025. Support for delivery of new woodland creation should integrate with nature and adaptation objectives and also address contractor availability, capacity to process funding applications, and advice for farmers to transition to woodland management approaches".

FIGURE 1 Emerging tree plantation in Honeydale Farm, Cotswold, England (UK). Large saplings are planted widely spaced (5 m apart as a guess) and protected from grazing animals (particularly deer) by tree guards that will be removed soon now that the trees have escaped the danger of being grazed to extinction.

Significant gaps exist in our current knowledge concerning the relative benefits of planting different tree species. For example, there is a lack of information concerning the benefits or disadvantages of monocultures compared to mixed plantations, particularly regarding resilience and productivity under climate change conditions and the pressures of globalised tree disease. Nevertheless, there are reasons for optimism. For example, there is unequivocal evidence that the Earth has become significantly greener since the 1980s (Chen et al., 2019; Zhu et al., 2016), with plants, particularly trees, producing greater leaf area, a result of the global increases in carbon dioxide (CO_2) and increased reactive N deposition fertilising forest (Tipping et al., 2017).

Forests are an increasingly important component of national carbon budgets, but their future is subject to a highly uncertain spectrum of risks (Anderegg et al., 2022). As with any asset, responsible risk management requires a portfolio approach, often colloquially known as 'spreading your bets' (e.g., Brunette et al., 2017). This has the positive benefit of enhancing productivity through diversity–productivity relations (Mori et al., 2021) (see below). Unfortunately, the current types of forest assets in countries such as the United Kingdom are too narrow to allow this approach. In his seminal text '*On the Origin of Species*', Darwin famously described evolution by natural selection, laying the foundations of modern genetics. Unfortunately, for the planet, the pace of human-induced environmental change outstrips that of natural selection for many organisms, especially larger, slower reproducing species that are often the keystones in an ecosystem (Settele et al., 2014). While modern gene-editing techniques can help once key genes have been identified, only evolution of the many and varied aspects of human practice, especially behaviour change to reduce emissions of greenhouse gases and nitrogen-containing gases and particles, is fast and far-reaching enough to reduce climate forcing, rebalance the carbon cycle, and bring us back within other planetary boundaries such as the planetary nitrogen cycle (Steffen et al., 2015). An observation by Charles Darwin in chapter 4 of his famous book over 150 years ago might offer a way to plant new forests that store carbon securely while enhancing biodiversity and increasing the social benefits of the timber supply chain.

The observation, here called the 'Darwin Effect', that a mixture of species planted together often yield more than the average of areas planted with each species individually, now has experimental verification (discussed below), but it is still sufficiently outside of the forestry mainstream to require extensive funding to bring the community together to promulgate results and catalyse practice (through, e.g., the European Union [EU] European Cooperation in Science and Technology [COST] Action project FP1206, called '*European mixed forests – Integrating Scientific Knowledge in Sustainable Forest Management* [EuMIXFOR])'. The co-occurring climate and biodiversity crises may force policymakers and landowners to take Darwin seriously.

2 | BETTER TREE GROWTH AND SEQUESTRATION OF CARBON IN MIXED WOODLAND

Accumulating evidence demonstrates the importance of employing a diversity of tree species in current and future planting strategies (Liang et al., 2016). There are convincing data showing that mixed woodland can act as an effective carbon sink, increasing land carbon stock, that is, the total amount of carbon stored on the land in plants and in soils (Chen & Hu, 2023, and references therein), in the coming decades. For example, canopy packing efficiency was reported to be significantly increased in response to species richness across a range of forest types and species combinations (Jucker et al., 2015). Moreover, a case study conducted on the 1500-acre (600 hectares) Norbury Park estate in central England has provided evidence that mixed planting has enormous benefits in terms of tree growth and resilience (Bradwell, 2021). However, the conclusions were based on an initial year of data collection (2020) and must be corroborated by repeated measurements of soil organic carbon to improve the accuracy of the calculations, as well as longer term measurements of growth patterns in the young woodlands. Implementing mixed-species forestry requires careful management and ecological awareness, and we cannot yet be sure how successful, economically and environmentally, the strategy will be over one or more harvest cycles, but early signs continue to be promising (A. J. Bradwell, private communication, May 2023).

Sectoral surveys have identified a skills gap in UK forestry (Biotechnology and Biological Sciences Research Council and Medical Research Council, 2017; Forestry Skills Forum, 2019) with too few practitioners being trained even to implement current investment in tree planting (National Audit Office, 2022), let alone to care for and maintain plantations for the decades to come. Current evidence supports the use of genetically diverse (Jump et al., 2009; Koskela et al., 2013; Schaberg et al., 2008), species-mixed (Brun et al., 2019; Cannell et al., 1992; Liang et al., 2016; Mori et al., 2021), and uneven aged (Lafond et al., 2014) forests to maximise carbon capture while increasing resilience to biotic and abiotic threats and sharing resources efficiently. Genetic diversity provides populations optimally selected for current conditions, with genepool backup for the yet-to-be-experienced future (Jump et al., 2009). Each species in an intimately mixed forest environment has its own genetically programmed abilities for light harvesting, capture and light use efficiency, as well as accessing different soil nutrient sources, leading to higher yields overall. Highly diverse mixed forests are also often more resilient to disease by diluting pest (Guo et al., 2019) and pathogen (Hantsch et al., 2014) populations. Uneven age, that is, a near-constant age pyramid, ensures that germinated seeds refresh forest genetics. Succession planting continuously provides harvestable timber and so steady jobs, in stark contrast to the cut-and-move-on dynamic of clear-felling, which causes periodic environmental and economic 'shocks' that are hard to deal with (see, e.g., Hemingway, 1925). This may also allow commercial production with scope for natural regeneration of restored forests that are not destined for timber.

3 | CARBON SEQUESTRATION

The results reported above come predominantly from studies of forests under existing climate conditions. To study the dynamics of forest under changed climate, experiments modifying temperature (Rustad et al., 2001), water availability (e.g., Santonja et al., 2022), or atmospheric composition (Norby et al., 2016; United States Department of Energy, 2020) are required. Of these environmental modification experiments, Free-Air CO_2 Enrichment (FACE) is the most technically difficult for mature forest stands and also tests the most direct physiological connection between forest productivity and the human-perturbed atmosphere (i.e., changing atmospheric CO_2 as a substrate for photosynthesis and, hence, the terrestrial food web).

The Birmingham Institute for Forest Research (BIFoR) FACE facility (Figure 2) has accumulated six consecutive years of measurements (2017–2022 inclusive) describing the details of how a mature oak forest responds to elevated concentrations of CO_2. Accumulating evidence supports the conclusion that mature oak-dominated temperate deciduous mixed forests grown under eCO_2 can effectively capture more carbon dioxide and grow faster than those grown under ambient conditions. This contrasts with results from a mature but highly phosphorus-limited eucalyptus forest (Jiang et al., 2020), highlighting the importance of multiple studies across mature forest biomes as argued by Norby et al. (2016) and Caldararu et al. (2023). The BIFoR FACE facility is the world's largest climate change experiment and the only forest FACE facility in the northern hemisphere (Figure 2). Over a season, the deciduous woodland patches exposed to elevated CO_2 at BIFoR FACE show about a 25% increase in photosynthesis compared to the woodland in contemporary air (Gardner, Ellsworth, et al., 2022). The general trends and patterns are clear. The 'water cost of carbon gain' is reduced by ~40% under elevated CO_2 (Gardner, Ellsworth, et al., 2022; Gardner, Mingkai, et al., 2022). The enhanced carbon gain influences tree physiology, leading, at least initially, to greater fine root production (Ziegler et al., 2022) and enhanced release of nutritious exudate into the surrounding soil for priming nutrient acquisition for sustaining C capture. This in turn benefits the soil microbiome leading to increased microbial biomass and more carbon belowground overall. The benefits delivered by woodland are determined by location and can be scientifically modelled across landscapes using data from BIFoR FACE and other experimental manipulations to ground-truth model predictions (Norby et al., 2016), thereby increasing our confidence in our strategies for climate-resilient future forests.

FIGURE 2 Aerial photograph of the BIFoR FACE facility in the Norbury Park estate (UK). Image courtesy Dr Rick Thomas, University of Birmingham.

4 | TREE SPECIES CHOICE

There is no definitive evidence of which species will reap the maximum benefits under changing environmental conditions. Mixtures of native and non-native should be considered as a matter of simple risk management (see, e.g., Bateman et al., 2023, Future forest that contain mixtures etc). While conifers are key components of mixed woodland because they grow and sequester carbon more rapidly than broadleaves, they have a smaller total carbon stock as mature woodland (De Vries et al., 2003; Jandl et al., 2007; and as estimated, for example, by the UK Woodland Carbon Code Carbon Calculation spreadsheet). Including a variety of native and foreign species in future woodlands is controversial, requiring careful observation and monitoring to obviate concerns about conservation of biodiversity (Quine & Humphrey, 2010) and invasiveness of the aliens (Ennos et al., 2019). Clearly, care is needed not to produce incentives to rush to large monocultures of fast-growing foreign species at the expense of native woodland (and other) biodiversity. Nevertheless, the palette of UK native trees is narrow (e.g., Tansley, 1968) and some opportunities for judicious deployment of foreign species arise (as explored, e.g., in Reynolds et al., 2021). For example, in intimate mixture, the growth rates of oak and hybrid larch planted in mixtures exceeded that of oak and European larch planted in monocultures (Figure 3).

Diseases and pests harmful to trees are important elements in forest landscapes and ecosystems. Many large native species such as oak, beech, and ash are vulnerable to pests and diseases, and hence, planting several species in intimate mixtures, managed by halo-pollarding, may provide high rates of carbon sequestration and add resilience to climate change (Chavardès et al., 2021; Millar et al., 2007). Although good in-country seed orchards and nurseries can minimise risks, diseases and pests that are already spreading across Europe (Pötzelsberger et al., 2021) have the potential to damage or kill large numbers of trees in forest and urban landscapes. In

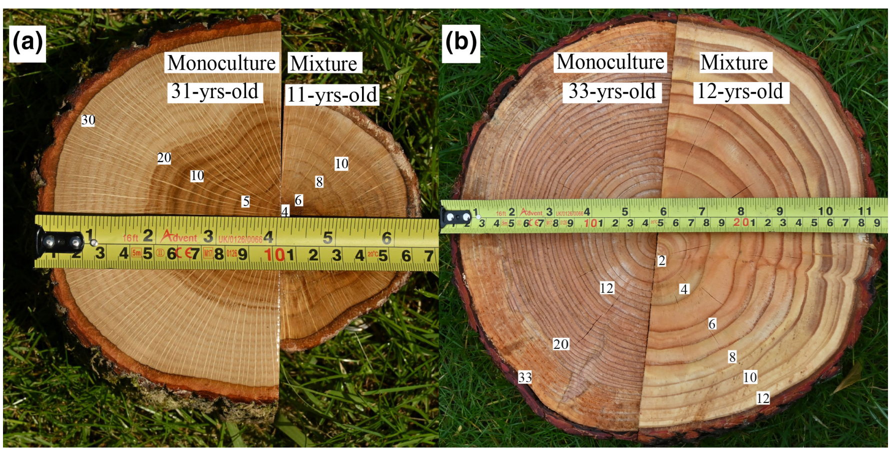

FIGURE 3 A comparison of the accumulation of biomass in the trunks of oak (a) and larch (b) trees either grown in monocultures managed conventionally or in halo-pollarded mixtures.

addition, the threat to native trees from invasive diseases and pests is growing because of climate change, the transport of live trees and wood products, and the expansion of international trade and travel. Many introduced herbivore species are likely to remain undiscovered until a serious outbreak occurs (MacLachlan et al., 2021). The delay in the discovery of insect pests is partially attributable to the low detectability of less economically important insect species.

Forestry standards in the United Kingdom and other countries require diverse planting, with a maximum of 75% of one species in woodland. Climate change will affect the suitability of tree species in the United Kingdom, both directly through changes in temperature and precipitation, and indirectly through altered frequency and severity of fire, and outbreaks of pests and diseases. Native tree species are genetically diverse. As has already been undertaken for crop wild relatives (Castañeda-Álvarez et al., 2016), strategies for tree genetic diversity must be developed to allow native species to adapt to climate change (Jump et al., 2009; Koskela et al., 2013; Schaberg et al., 2008). Breeding programmes may need to be amended to maintain greater genetic diversity in commercial, non-native stock (Tumas et al., 2021). Nitrogen-fixing species, such as alder (*Alnus glutinosa*) and black locust (*Robinia pseudoacacia*), deliver nitrogen nutrition into forests, particularly during early succession (Boring & Swank, 1984). Such nitrogen delivery may be particularly important for forest growth under elevated CO_2 when progressive nitrogen limitation can occur (Norby et al., 2010).

5 | VALUES, SKILLS, EXPERTISE, CAREERS, AND CLIMATE ACTIVISM

The perceived lack of forestry-related skills and expertise in the United Kingdom (Biotechnology and Biological Sciences Research Council and Medical Research Council [UK], 2017; Forestry Skills Forum, 2019) and advanced machinery (e.g., robotics, Bayne & Parker, 2012; Oliveira et al., 2021) required to establish and manage woodland is likely to limit the success of current tree-planting efforts and lead to the ultimate failure of new forested areas to achieve carbon sequestration goals. The dearth of skilled forestry contractors is a barrier to success and expansion plans of existing woodland owners. Next-generation researchers and practitioners are likely to be highly knowledgeable about climate-related issues and hopefully enthusiastic for higher education in which climate change is embedded (Padhra & Tolouei, 2023). However, they may not be aware of the challenging and rewarding careers available in forest-facing industries (public, private, and third sector). Based on decades of experience in student recruitment in a wide variety of UK higher education institutes, we speculate that forest-facing education is not appealing to young scientists and practitioners often because of outmoded and educationally indefensible caricatures of some practice-based learning (e.g., land-based disciplines) compared to others (e.g., music, medicine, or veterinary science). The diminution of practice-based land-based disciplines, particularly in stark contrast to medicine and veterinary sciences, will, ironically, hinder significantly the establishment of 'One Health' (Rüegg et al., 2018) responses to the climate and nature emergencies. Reinvented land-based education, coupling intellectual rigour with challenging hands-on practice in a blue-riband academic offering, may be one way to harness and direct climate anxiety and activism in students (cf. Pellitier et al., 2023).

6 | CONCLUSIONS AND PERSPECTIVES

Accumulating evidence demonstrates that planting intimately mixed woodland enhances tree growth and productivity compared to monoculture stands. Intimately mixed woodland plantations should, therefore, play a leading role in enabling many countries to meet 2050 net-zero greenhouse gas emission targets. However, no re-afforestation strategy can remove the requirement for deep societal decarbonisation worldwide (IPCC, 2018). Climate change is predicted to exert a strong influence on woodland composition across the United Kingdom (Yu et al., 2021). We can expect both positive and negative effects of climate change on forest structure and functions, as well as growth patterns, productivity, and composition depending on the type of forest and its location. Positive effects on European wood production are predicted, especially for trees in high latitudes due to the dual benefits of CO_2 fertilisation and a high rainfall. The threat posed by climate change to forest ecosystems is less certain, especially in Mediterranean regions, which may suffer increased fire risks and experience higher tree mortality rates due to increasing global temperatures.

The carbon fertilisation effect of elevated atmospheric CO_2 concentrations (eCO_2) on photosynthesis is an essential feature of the urgency to regenerate and manage forests and have an improved road map for land use, but it will not be, by itself, sufficient, for increased carbon storage in forests if forest carbon turnover also accelerates. Nevertheless, remote sensing data have revealed a significantly increased greening of the Earth over the last 30 years that together with grasslands is related to an increased forest tree leaf area. Such findings demonstrate that forests are effective sinks for carbon, at least on decadal to centennial timescales (Jandl et al., 2007), as well as improving soil health and water quality. Undisturbed forests eventually reach carbon balance over time and space scales large enough to accommodate mortality and recruitment. They may continue to provide long-term carbon sequestration and storage by building soil carbon over many decades (Jandl et al., 2007; Nabuurs & Schelhaas, 2002; Vesterdal et al., 2002).

To secure and enhance long-term sequestration and storage in the forest canopy above ground, wood products must be taken from the forest and stored long-term. If possible, woodland planning must incorporate harvesting for timber and other wood products in order to contribute to long-term carbon budgeting, biodiversity enhancement, and the delivery of societal benefits. Current afforestation and forest management regulations and guidelines are innovation-averse and highly vulnerable to globalised disease and climate risks. Private actors are currently leading the way in re-colonisation and silvicultural portfolio approaches to increase resilience and manage social risks such as 'carbon colonialism', but the government must act to secure long-term benefits. Such policies are likely to have wide public acceptance, not least because people generally appreciate the benefits of trees and are naturally drawn to wooded areas and forests. The benefits of woodland creation are inherently context dependent. Similarly, what tree species are used is inherently dependent on the environment and climate. Adding nitrogen-fixing tree species will be an asset that enhances woodland carbon sequestration rates under most circumstances, especially in newly created woodland landscapes.

In the above considerations, we have used the UK example to illustrate current issues related to afforestation and related government policies, but similar problems are encountered globally. Moreover, the difficulty in enacting the UK afforestation policy (see above and the UK National Audit Office 2022) demonstrates that there is an urgent need for forest-facing apprenticeships and degree training in silviculture and environmental economics to balance optimally making land available for forest without compromising agricultural productivity (Bateman et al., 2023). Many countries are committed to achieving net-zero targets by 2050, as part of a broader ambition for a green transition that would power economic growth, create high-paying employment, and contribute to building a more resilient and prosperous society. Realising this commitment will require significant adjustment and transformation across all sectors including land use. Within this context, science and policy must work in synchrony (Cammarano et al., 2023; McGuire et al., 2023). This requires a more efficient and effective communication of science-based messages and possible solutions to policymakers, to enable appropriate responses to global climate change adaptation and mitigation challenges.

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CONFLICT OF INTEREST STATEMENT

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

DATA AVAILABILITY STATEMENT

All of the data reported in this manuscript are available upon request to the authors.

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