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Future Forests: estimating biogenic emissions from net-zero aligned afforestation pathways in the UK

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Abstract

Woodlands sequester carbon dioxide from the atmosphere, which could help mitigate climate change. As part of efforts to reach net-zero greenhouse gas emissions by the year 2050, the UK's Climate Change Committee (CCC) recommend increasing woodland cover from a UK average of 13% to 17-19%. Woodlands also have the potential to degrade air quality, due to the emission of biogenic volatile organic compounds (BVOCs) which are precursors to major atmospheric pollutants, ozone (O_3) and particulate matter (PM). Here we make an estimate of the potential impact of afforestation in the UK on BVOC emissions, coupling information on tree species' emissions potential, planting suitability and policy-informed land cover change. We quantify the potential emission of BVOCs from five afforestation experiments using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (v2.1) in the Community Land Model (CLM) (v4.5) for the year 2050. Experiments were designed to explore the impact of the variation in BVOC emissions potentials between and within plant functional types (PFTs) on estimates of BVOC emissions from UK land cover, to understand the scale of change associated with afforestation to 19% woodland cover by the year 2050.

Our estimate of current annual UK emissions is 40 kt yr^{-1} for isoprene and 46 kt yr^{-1} for total monoterpenes. Broadleaf afforestation results in a change to UK isoprene emission of between -4% and +131%, and a change to total monoterpene emission of between +6% and +52%. Needleleaf afforestation leads to a change in UK isoprene emission of between -3% and +20%, and a change to total monoterpene emission of between +66% and +95%.

Our study highlights the potential for net-zero aligned afforestation to have substantial impacts on UK BVOC emissions, and therefore air quality, but also demonstrates routes to minimising these impacts through consideration of the emissions potentials of tree species planted.

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1 Introduction

The terrestrial biosphere plays a key part in pathways for mitigating climate change and helping to reach net-zero greenhouse gas emissions, due to the capacity for the biosphere to sequester and store carbon dioxide (CO_2) from the atmosphere. The 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated afforestation, reduced deforestation and ecosystem restoration could mitigate nearly 3 $GtCO_2e$ yr^{-1} globally by 2030 (Shukla et al., 2022). In 2019, the UK Climate Change Committee (CCC) set out a series of pathways to achieving net-zero GHG emissions by 2050, including a large increase in rates of afforestation to expand the land carbon sink (Climate Change Committee, 2019). To achieve their 'further ambition' scenario (a pathway estimated to reduce emissions by 96%), the CCC recommended planting at least 30,000 hectares of trees per year (ha yr^{-1}) in the UK until 2050, whilst their 'speculative scenario' (a pathway estimated to reduce emissions by 100% by 2050), recommended increased planting at 50,000 ha yr^{-1} (Climate Change Committee, 2019). Planting at this rate would increase woodland cover from the current UK average of 13% to between 17 and 19%, a relative increase of up to 45%. Following these recommendations, the UK Government committed to increase planting to 30,000 ha yr^{-1} by 2024, and rising from thereafter (Department for Business, Energy and Industrial Strategy, 2021). Planting at this scale requires a doubling of the rate of afforestation in the UK, which has averaged 15,000 ha yr^{-1} between 2019 and 2024 (Forest Research, 2024b). Increasing forest cover to such an extent could not only bring benefits for climate change mitigation but also a series of co-benefits including habitat creation, flood risk reduction, improving access for people to trees and woodlands (with the associated economic and health benefits), and local temperature reductions (Bolund and Hunhammar, 1999; Costanza et al., 1997; D'Alessandro et al., 2015; Monger et al., 2022; Nowak, 2022; Wang et al., 2023). There is also the potential for delivery of trade-offs, such as the degradation of air quality potentially associated with the emission of biogenic volatile organic compounds (BVOCs). In addition to influencing atmospheric concentrations of CO_2, vegetation exchanges carbon in the form of BVOCs. BVOCs are gaseous compounds synthesised within the chloroplast of the plant, and in some cases, stored in the leaf until volatilised. Examples of BVOC compound classes are isoprene (C_5H_8, 2-methyl 1,3-butadiene) and monoterpenes ($C_{10}H_{16}$). Plants use a large amount of energy in the production of BVOCs but appear to derive resilience against pests, disease and other environmental stressors from their emission (Dicke, 2009; Dudareva et al., 2006; Fitzky et al., 2019; Sharkey, 1996). Trees' emissions of BVOCs are controlled largely by temperature and light, but also leaf age, atmospheric CO_2 concentrations and soil moisture (Guenther et al., 1993; Potosnak et al., 2014; Sharkey, 1996; Zeng et al., 2023). Plant BVOC emissions can be induced by stress from pests and disease; globally the rate at which new tree diseases are reported is doubling approximately every 11 years (Gougherty, 2023), with implications for the quantity and composition of future BVOC emissions. Algorithms have been developed to capture the dependency of BVOCs on the environmental factors mentioned above and to quantify ecosystem- or global-scale emissions of BVOCs (Guenther et al., 1995a, 1993, 2012; Martin et al., 2000; Niinemets et al., 1999). Global emissions of BVOCs are estimated at 1000 Tg yr^{-1}, of which ~500 Tg yr^{-1} comes from isoprene and ~150 Tg yr^{-1} from total monoterpenes (Guenther et al., 2012). For isoprene, as temperature increases, emissions increase until a maximum temperature ~35 °C after which emissions steeply decline following denaturing of the enzyme isoprene synthase (Monson et al., 1992). Evidence also shows the suppression of isoprene emissions when plants are exposed to elevated atmospheric CO_2 concentrations, due to the inhibition of the enzyme responsible for the synthesis of dimethylallyl diphosphate (DMADP) from hydroxymethylbutenyl diphosphate (HMBDP) (Sahu et al., 2023). The emission of monoterpenes is also affected by temperature and light, but the storage of monoterpenes within plants causes distinct patterns in emissions compared to other BVOCs. The emission of BVOCs varies through the day, with a peak in the daytime when incoming solar radiation is at its highest. However, the storage of monoterpenes means their emission is less variable with light. Elevated CO_2 has been found to have little effect on monoterpene emissions (Feng et al., 2019). A global modelling study by Heald et al. (2009) concluded that the enhanced emission of BVOCs attributed to a warmer climate could be almost entirely offset by CO_2 inhibition, despite elevated CO_2 enhancing rates of photosynthesis (e.g. Feng et al., 2019; Pegoraro et al., 2004). The climate forcing impact that a large change in forest cover and associated BVOC emissions may have is uncertain, as the response of vegetation to elevated CO_2 concentrations and temperature, and the point at which these become inhibiting factors, varies between species and when interacting with other controls, such as moisture availability (e.g. Fortunati et al., 2008; Pegoraro et al., 2004).

BVOCs are highly reactive, oxidised by the hydroxyl radical (OH), ozone (O_3) and nitrate radical (NO_3). BVOCs influence the production of O_3 through a cycle between nitric oxide (NO) and nitrogen dioxide (NO_2), with peroxy radicals derived from BVOC oxidation enabling NO to cycle to NO_2 without depleting O_3 and therefore enabling net O_3 formation (Sillman et al., 1990; Wennberg et al., 2018). The oxidation of BVOCs also generates secondary organic aerosol (SOA), which contributes to formation of particulate matter (PM) which has negative impacts on human health. Of particular concern are particles less than 2.5 micrometres in diameter ($PM_{2.5}$) due to the capacity of these particles to travel further into the human body than larger particles such as PM_{10} (Committee on the Medical Effects of Air Pollutants, 2015).

Following the rise in ambitions to plant trees for climate change mitigation, several studies have begun examining the impact of afforestation on BVOCs and air quality (e.g. Gai et al., 2024; Gu et al., 2021; Purser et al., 2023). Gu et al., (2021) quantified the increase in BVOC emissions from urban greening scenarios in Los Angeles. They illustrate the potential for the increase in BVOCs to offset the benefits of a reduction in anthropogenic volatile organic compounds (AVOCs). In the UK context, Stewart et al., (2003) previously constructed a BVOC inventory for Great Britain, and estimated that BVOC emissions are 10% of those of AVOCs, though recognising this may change with a warmer climate. Purser et al., (2023) present an assessment of the potential air quality impact of BVOCs associated with large-scale afforestation for bioenergy in the UK. Based on four planting scenarios, each of single tree species (*Eucalyptus gunnii*, *Populus tremulus*, *Alnus cordata* and *Picea sitchensis*) and delivering up to 164% more woodland cover than present day coverage, Purser et al. (2023) estimated isoprene emissions to increase between 53% and 135%, except with Alder where emissions declined by 14% due to its lower emissions potentials relative to the grassland and agriculture being replaced. An increase in monoterpene emissions between 5% and 94% was simulated, except for Aspen where a decline of 8% was again attributed to the lower emissions potential of the trees relative to the land cover being replaced (Purser et al., 2023). To best understand the potential scale of BVOC emissions associated with afforestation, we need to understand the role that the mixture of tree species planted plays in determining BVOC emissions.

In this work, we quantify for the first time the emission of BVOCs from UK afforestation scenarios that represent achievement of the estimated 19% woodland cover with mixed species afforestation. We model for afforestation in line with recent and committed afforestation rates for the four UK nations. We present five afforestation experiments for the UK which represent different pathways to achieving woodland cover of 19% in 2050, with varying contributions from high and low BVOC emitting tree species. Our study seeks to improve understanding of the relative impact of different tree species mixtures on the BVOC emissions associated with afforestation in the UK. Estimating potential changes in BVOC emissions will help guide policy decisions regarding species prioritisation for planting, particularly when considered in the context of minimising air-quality side-effects associated with afforestation.

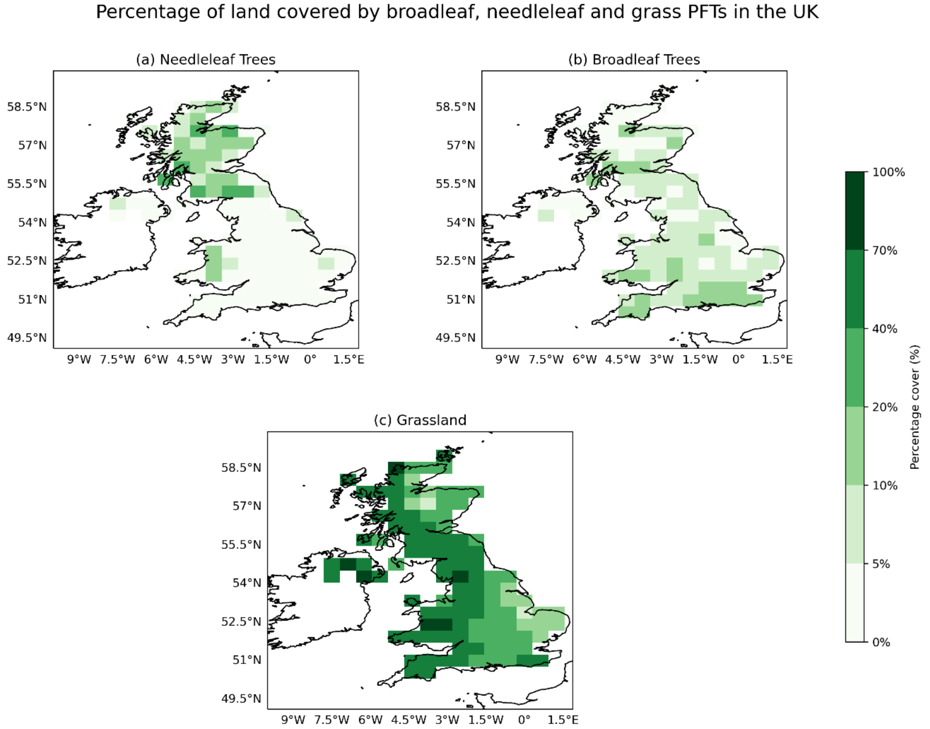
2 Methods and data

To quantify the emissions of BVOCs from a range of afforestation experiments, we model emissions using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 1993, 2012). This approach requires datasets of: European, compound class specific BVOC emissions potential data for tree species; tree species distribution information; meteorological and CO_2

concentration data for the estimation of BVOCs; and land cover data for quantifying the distribution of natural vegetation biomass.

2.1 Representing the land surface

We use the Community Land Model v4.5 (CLM) (Oleson et al., 2013) at a resolution of 0.47 ° x 0.63 ° with land surface data from the UKCEH land cover map for 2021 (Marston et al., 2022). The UKCEH map is produced at a resolution of 1 km, combining Sentinel-2 seasonal composite images and 10 context layers to map 21 land cover classes based on the Biodiversity Action Plan broad habitats (Marston et al., 2022). We use the 1 km percentage product, which details the percentage cover for each of 21 land cover classes within each 1 km pixel. The UKCEH dataset was regridded to the 0.47 ° x 0.63 ° resolution of our CLM configuration. As land surface categories vary between the UKCEH and the CLM, variables of the UKCEH map were reassigned to the closest matching plant functional type (PFT) or land surface category in the CLM, including the urban, natural vegetation, crops and lake land surface categories. Details of this recategorization can be found in the Supplementary Information. Figure 1 illustrates the percentage cover of needleleaf and broadleaf tree PFTs and grassland PFTs in the resulting CEH-CLM dataset which represents present day UK land cover informed by the UKCEH land cover map, at the resolution of the CLM. In this dataset, woodlands cover approximately 13% of UK land, and of this 52% is broadleaf woodland and 48% needleleaf woodland (Forest Research, 2024b). Grassland makes up approximately 40% of UK land cover (Marston et al., 2022).


Percentage of land covered by broadleaf, needleleaf and grass PFTs in the UK

(a) Needleleaf Trees

(b) Broadleaf Trees

(c) Grassland

Figure 1. Percentage share of land covered by broadleaf and needleleaf trees, and grass PFTs. The distribution of PFTs presented here is inferred from the UKCEH, reassigned to the land cover categories of the CLM to produce the CEH-CLM dataset (Marston et al., 2022; Oleson et al., 2013).

2.2 Identifying land for afforestation

The exact locations for afforestation in the UK are undetermined, though the individual four nations (England, Northern Ireland, Scotland, Wales) have their own ambitions relating to the net-zero aligned planting recommendations. For our study, we present five afforestation experiments equivalent to the achievement of 19% woodland cover by 2050 in the UK. We assume a direct replacement of grasslands for woodlands as a simplified land cover change. In reality, detailed assessments are required to establish the suitability (ecologically, socially and culturally) of any site for woodland creation; conversion to woodland in our study is used only to estimate the impact on BVOC emissions and should not be used to infer the suitability of any specific site.

To determine the distribution of additional woodland to be planted in the scenarios, historical planting rates and future planting commitments of all four nations of the UK are considered. Table 1 details the rates of afforestation observed for each nation during the past five decades, their current commitments to afforestation and the proposed share of afforestation implemented in this study. Our experiments assume the greater level of afforestation from the CCC's recommendations (equivalent to planting 50,000 ha yr^{-1}), as this enables estimation of the change in BVOCs associated with the greatest scale of afforestation in recent discourse for the UK. We assume 63% of the UK's new woodland is created in Scotland, 8% in Wales, 4% in Northern Ireland and 25% in England.

Table 1. Historical rates of afforestation in the UK by nation between 1976 and 2021 and current national ambitions for afforestation. These rates inform the share of UK afforestation at 50,000 ha yr^{-1} used in this study.

	Scotland	**Wales**	**Northern Ireland**	**England**
Mean share of UK afforestation 1976-2021 (Forest Research, 2023)	70%	4%	4%	22%
Most recent statement on afforestation ambitions (equivalent share of UK total given as percentage in brackets)	15,000 ha yr^{-1} by 2024 (63%) (Draft climate change plan: draft third report on policies and proposals 2017-2032, 2024)	2000 ha yr^{-1} from 2020 onwards (8%) (Welsh Government, 2018)	900 ha yr^{-1} from 2020 to 2030 (4%) (Northern Ireland planting pledge, 2024)	Trebling current rates (increasing from around 2000 to 6000 ha yr^{-1}) (25%) (Department for Environment, Food and Rural Affairs, 2021)
This study: share of UK afforestation at 50,000 ha yr^{-1}	31,500 ha yr^{-1} (63%)	4000 ha yr^{-1} (8%)	2000 ha yr^{-1} (4%)	12,500 ha yr^{-1} (25%)

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We use the presence of a tree PFT within a grid cell of the CEH-CLM dataset as indicative of climatic suitability of the land for new planting of that type. The tree PFTs considered in this study are Broadleaf Deciduous Temperate Trees (BDTT), Broadleaf Deciduous Boreal Trees (BDBT), Needleleaf Evergreen Temperate Trees (NETT) and Needleleaf Evergreen Boreal Trees (NEBT). For replacement with woodland to take place, grid cells are required to have some existing grassland (namely Cool C3 or Arctic C3 grass). New tree cover was created in proportion to the amount of grassland in any eligible grid cell and in the same ratio of temperate to boreal PFTs as was already present in the CEH-CLM dataset. Afforestation was implemented as either all needleleaf, or all broadleaf, to enable examination of the variation in emissions that would be generated by different planting decisions. This method does not account for the specific suitability of a given location for tree planting but provides the necessary scope to consider the scale of emissions changes across the UK associated with present ambitions for afforestation. Figure 2 shows the absolute change in percentage area of PFTs following afforestation. The quantities of change in PFT cover are consistent across both needleleaf and broadleaf afforestation experiments. Supplementary Fig. S1 and S2 illustrate the percentage change in area of PFTs following broadleaf and needleleaf afforestation respectively.

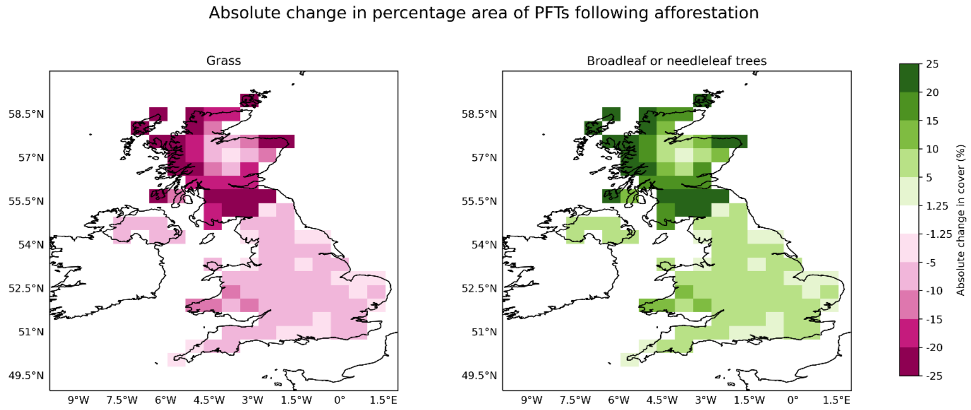

Figure 2- Absolute change in the percentage cover of grass and tree PFTs following either needleleaf or broadleaf afforestation.

2.3 Identifying tree species for afforestation

The subset of tree species represented in this study was informed by the Forest Research tree species database (Forest Research, 2024a) and associated Ecological Site Classification tool. This online tool enables users to identify suitable trees for planting in each part of the UK according to known or projected conditions for climate, lithology, ecology, soil moisture and soil nutrients (Pyatt et al., 2001). 60 tree species are considered in the ESC tool. Of these species, those classified as principal species (defined as species already widely used or increasing in deployment in the UK, and of continuing importance unless adversely affected by a new pest or disease, or climate change) (Forest Research, 2024a) were considered for representation in our study. We compare this subset of 25 tree species to statistics on current tree species composition in the UK (Forest Research, 2023) and the EU-Trees4F project which examines the changing distribution of European tree species under a selection of climate futures considering natural dispersal and planting (Mauri et al., 2022). Based on these requirements, we selected 18 tree species to include in our review of emissions potentials data (details of included tree species can be found in Supplementary Table 1).

2.4 Preparing UK specific emissions potential data

https://doi.org/10.5194/egusphere-2024-3895
Preprint. Discussion started: 8 January 2025

We generate a bespoke UK-specific emissions potential dataset to capture isoprene and monoterpene emissions from UK-specific tree species. We use this dataset to adjust estimates of BVOC emission from tree species for our present-day land cover and afforestation experiments. Tree species specific emissions potentials were used to generate PFT emissions potential scenarios based on both present-day tree species abundance in the UK, and a range of hypothetical planting mixtures that demonstrate the variation within and between PFTs. We reviewed European or UK specific emissions potentials of tree species to identify values representative of UK trees. Emissions data were obtained for isoprene and monoterpene compound classes, as the BVOCs dominating VOC chemistry in Great Britain (Atkinson, 1990). If data was available for tree species in our subset, emissions values were recorded (applicable studies are summarised in Table 2). The review returned emissions potential data for isoprene and monoterpenes for 6 needleleaf and 10 broadleaf tree species (listed in Table 3; additional details can be found in Supplementary Table 1) which make up existing UK woodland cover and/or are expected to play a role in afforestation in the future.

Monoterpenes have pool emissions (previously synthesised compounds emitted from storage pools) as well as synthesis (or *de novo;* compounds synthesised and emitted in response to light) emissions. The review of emissions potential literature highlighted inconsistencies in the level of differentiation between pool and synthesis emissions. In MEGANv2.1, the relative light dependence of BVOC compound class emissions is managed by assigning a light dependent fraction (Guenther et al., 2012). We account for this by taking the sum, where synthesis and pool emission potentials are explicit in the published dataset, and reapplying the existing light dependent fractions in MEGANv2.1.

The emissions potentials values obtained from different studies were used to calculate a mean emission potential for isoprene and total monoterpenes for each tree species. Figures 3 and 4 show the relationship between isoprene and total monoterpene emissions potentials for broadleaf (Fig. 3) and needleleaf (Fig. 4) tree species and the emissions potential of corresponding PFTs from MEGAN (namely BDTT and BDBT for broadleaf species and NETT and NEBT for needleleaf species) (Guenther et al., 2012). MEGAN provides values as emissions factors. To enable comparison, we converted emissions factors from MEGAN (v2.1) (Guenther et al., 2012) to emissions potentials using the Eq 1., where E_f = emissions factor (µg m^{-2} hr^{-1}), E_p = emissions potential (µgC gDW^{-1} hr^{-1}) and F_d = foliar density, given as 560 gDW m^{-2} for deciduous trees and 1100 gDW m^{-2} for conifer trees (Guenther et al., 1995).

Equation 1

$$E_p = \frac{E_f\left(\frac{60}{68}\right)}{F_d}$$

Table 2. Overview of tree emissions potential studies reviewed, including the number of tree species that data were presented for, and the number of tree species incorporated into this study.

Study number	**Study**	**Study region**	**Number of tree species presented**	**Tree species from the study incorporated in this work**
1	Simpson *et al.*, 1999	Europe	37	15
2	Hewitt, 2003	Great Britain	1100	10
3	Stewart *et al.*, 2003	Great Britain	1100	5
4	Karl *et al.*, 2009	Europe	112	15
5	Churkina *et al.*, 2017	Berlin	11	6
6	Purser *et al.*, 2021	United Kingdom	3	1
7	Purser *et al.*, 2023	United Kingdom	4	2

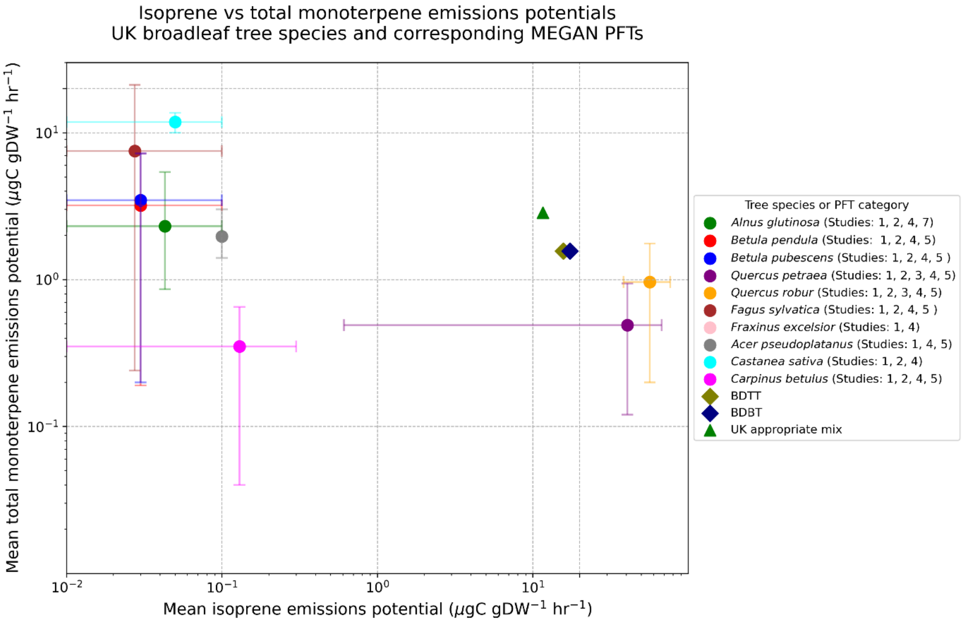

Figure 3. Relationship between the mean isoprene and mean total monoterpene emissions potentials for UK appropriate broadleaf tree species. Circular markers represent the mean of values obtained for a given broadleaf tree species from the literature (see Table 2). Triangular markers represent a UK appropriate value calculated as a mean of broadleaf species emissions potentials weighted according to their present-day abundance in the UK (Forest Research, 2023). Diamond markers represent the emissions potentials of corresponding PFT categories within the default release version of MEGANv2.1 (BDTT and BDBT). Numbers in the figure legend correspond to the study number detailed in Table 2.

https://doi.org/10.5194/egusphere-2024-3895
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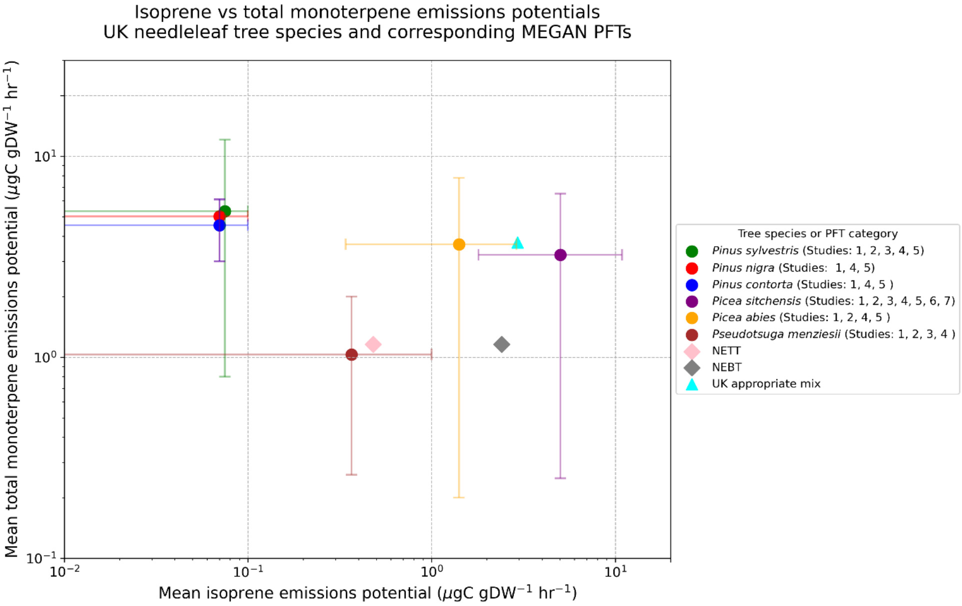
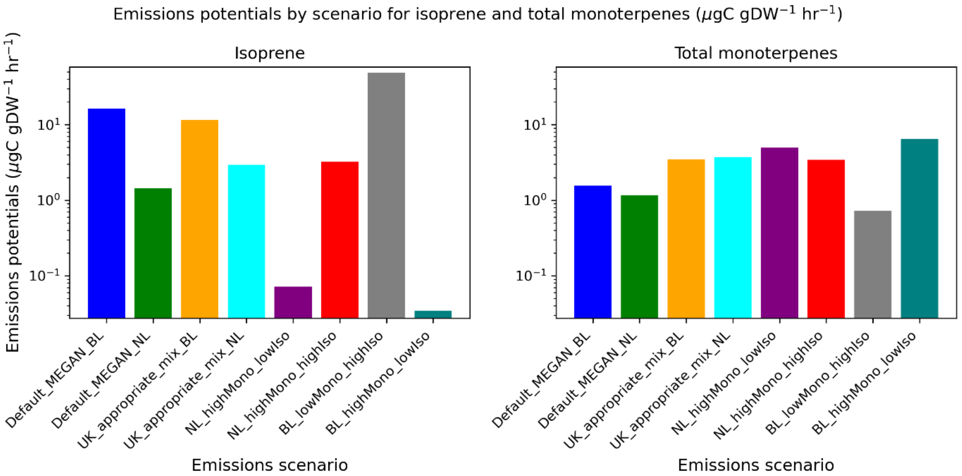


Figure 4. Relationship between the mean isoprene and mean total monoterpene emissions potentials for UK appropriate needleleaf tree species. Circular markers represent the mean of values obtained for a given needleleaf tree species from the literature (see Table 2). Triangular markers represent a UK appropriate value calculated as a mean of needleleaf species emissions potentials weighted according to their present-day abundance in the UK (Forest Research, 2023). Diamond markers represent the emissions potentials of corresponding PFT categories within the default release version of MEGANv2.1 (NETT and NEBT). Numbers in the figure legend correspond to the study number detailed in Table 2.

In the case of broadleaf species (Fig. 3), emissions potentials suggest three broad categories, where higher emitters of monoterpenes are generally lower emitters of isoprene (e.g. *Fagus sylvatica* and *Betula pendula*), higher emitters of isoprene are generally lower emitters of monoterpenes (e.g. *Quercus spp.*) and some are low emitters of both (e.g. *Fraxinus excelsior*). To reflect these groupings, we designed two broadleaf emissions scenarios, *BL_highMono_lowIso* and *BL_lowMono_highIso* (described in Table 3). Needleleaf tree species (Fig. 4) seem to be generally high emitters of monoterpenes, but either lower emitters of isoprene (e.g. *Pinus spp.*) or higher emitters of isoprene (e.g. *Picea spp.*). To reflect these groupings, we designed two needleleaf emissions scenarios: *NL_highMono_lowIso* and *NL_highMono_highIso*. The emission potentials used in each scenario are calculated as a mean of the tree species in that group, based on the mean of values presented in the literature. We developed a fifth emissions scenario, *UK_appropriate_mix*, with values calculated as a mean of species emission factors weighted according to their present-day abundance in the UK, based on the 2023 Woodland Statistics (Forest Research, 2023). A scenario using the existing emissions factors for these PFTs in MEGANv2.1 is referred to as the *Default_MEGAN* scenario. Emissions potentials for each scenario are illustrated in Fig. 5. For use in MEGANv2.1, emissions potentials are converted to emissions factors. The emissions factors of each scenario are detailed in Table 3 for isoprene and total monoterpenes. For use in MEGAN, values for total monoterpene emissions factors were allocated to compound classes according to the ratio of those classes in Default MEGAN emissions factors.



269 *Figure 5. Emissions potentials for isoprene and total monoterpene compound classes, across the emissions scenarios described in Table 3. For default MEGAN and UK appropriate mix scenarios, values are provided for both broadleaf (BL) and needleleaf (NL). For all other scenarios, when broadleaf or needleleaf is unspecified, UK appropriate mix values have been used.*

Table 3. Emission scenario short name and description, related PFT, example representative UK tree species informing the scenario, and emissions factors by BVOC compound class for isoprene and total monoterpene. The emissions scenarios are: Default_MEGAN, UK_appropriate_mix, NL_highMono_lowIso, NL_highMono_highIso, BL_lowMono_highIso and BL_highMono_lowIso. Where PFT is specified as broadleaf, this includes BDTT and BDBT PFTs. Where PFT is specified as needleleaf, this includes NETT and NEBT PFTs.

Emission scenario short name and description	**PFT**	**Species**	**Emissions Factors (µg m^{-2} hr^{-1})**	
			Isoprene	**Total monoterpenes**
Default MEGAN: Emissions factors as provided in MEGANv2.1 default set up	BDBT	Unspecified	7000	1300
	BDTT	Unspecified	10,000	990
	NEBT	Unspecified	3000	1450
	NETT	Unspecified	600	1450
UK_appropriate_mix: Emissions factors represent present-day abundance of dominant tree species	Broadleaf	*Alnus glutinosa, Betula pendula, Betula pubescens, Quercus petraea, Quercus robur, Fagus sylvatica, Fraxinus excelsior, Acer pseudoplatanus, Castanea sativa, Carpinus betula*	7359	1808
	Needleleaf	*Pinus sylvestris, Pinus nigra, Pinus contorta, Picea sitchensis, Picea abies, Pseudotsuga menziesii.*	3660	4643
NL_highMono_lowIso: Mean emissions factors from high monoterpene - low isoprene emitting needleleaf trees	Broadleaf	UK appropriate mix	7359	1808
	Needleleaf	*Pinus sylvestris, Pinus nigra, Pinus contorta*	89	6188
NL_highMono_highIso: Mean emissions factors from high monoterpene - high isoprene emitting needleleaf trees	Broadleaf	UK appropriate mix	7359	1808
	Needleleaf	*Picea sitchensis, Picea abies*	4014	4282
BL_low_Mono_highIso: Mean emissions factors from low monoterpene - high isoprene emitting broadleaf trees	Broadleaf	*Quercus robur, Quercus petraea*	30892	460
	Needleleaf	UK appropriate mix	3660	4643
BL_highMono_lowIso: Mean emissions factors from high monoterpene - low isoprene emitting broadleaf trees	Broadleaf	*Castanea sativa, Fagus sylvatica, Betula pubescens, Betula pendula*	22	4124
	Needleleaf	UK appropriate mix	3660	4643

https://doi.org/10.5194/egusphere-2024-3895
Preprint. Discussion started: 8 January 2025

2.5 Model set up

Simulations were undertaken at 0.47 ° x 0.63 ° resolution with the CLMv4.5 component of Community Earth System Model (CESM) version 2.2.0 (Danabasoglu et al., 2020; Oleson et al., 2013). BVOC emissions are calculated by MEGANv2.1 (Guenther et al., 1993; 2012). Land surface input data for CLMv4.5 was modified to reflect the CEH-LCM distribution of PFTs over the UK, generating the land surface dataset CEH-CLM used in this study, as detailed in Sec. 2.1. Meteorological data is from the Global Soil Wetness Project (see Dirmeyer *et al.*, (2006)), for the year 2003. Values of leaf area index (LAI) are those developed for the CLM from the 1 km MODIS product as detailed in Lawrence and Chase (2007). Detailed information on model component sets for CESM2.2.0 is available from NCAR (https://docs.cesm.ucar.edu/models/cesm2/config/compsets.html). An initial experiment to estimate present-day BVOC emissions uses an atmospheric CO_2 concentration of 375 ppm, appropriate for the year 2003. We modify input CO_2 concentration data in all other simulations to 500 ppm based on the projected atmospheric CO_2 concentration in 2050 under SSP2-4.5 (Intergovernmental Panel on Climate Change, 2023).

2.6 Meteorology

The controls on BVOC emission include temperature, atmospheric CO_2 concentration and soil moisture (Guenther et al., 1993; Sharkey, 1996). To determine the appropriate meteorological data for simulating likely conditions in the year 2050, we compared observed and projected UK temperatures from the UK Climate Projections (UKCP) project (UKCP, 2023a, b). Based on examination of HadUK-Grid daily observations of maximum air temperature at 1.5 m averaged for the UK for the years 2000-2021 (UKCP, 2023b) and global projections of daily maximum temperatures at 1.5 m for the years 2045-2054 (UKCP, 2023a), we determined that meteorology for the year 2003 was the best representation of projected 2050 temperatures in the historical dataset. The heatwave periods of the year 2003 have previously been studied for impacts on air quality, so this period provides the opportunity for comparison of modelled data to observations (Lee et al., 2006; Stedman, 2004; Vautard et al., 2005).

2.7 Model simulations

Table 4 describes the configurations used in 12 experiments to explore changes in UK BVOC emissions with and without additional forests. We carry out seven experiments without any additional forest, and five with afforestation aligned with achievement of 19% UK woodland coverage.

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Table 4. Summary of model run configurations: afforestation experiment short name, experiment description and input data: land cover, emission scenario short name and associated emission factors and atmospheric CO_2 concentration data. In experiment names 'Present_day…' refers to the land cover. The latter half of the name refers to the emissions potentials.

Afforestation experiment short name	**Experiment description**	**Land data**	**Emission scenario short name**	**CO_2 concentration**
Baseline	Present day land cover with UK appropriate emission factors and 2003 CO_2	CEH-CLM (13% woodland cover)	UK_appropriate_mix	375 ppm
Present_day_Default_MEGAN	Present day land cover with default MEGAN emissions factors and elevated CO_2	CEH-CLM (13% woodland cover)	Default_MEGAN	500 ppm
Present_day_Current_UK_mix	Present day land cover with UK appropriate emission factors and elevated CO_2	CEH-CLM (13% woodland cover)	UK_appropriate_mix	500 ppm
Present_day_NL_highMono_lowIso	Present day land cover with high monoterpene emission factors from needleleaf trees and elevated CO_2	CEH-CLM (13% woodland cover)	NL_highMono_lowIso	500 ppm
Present_day_NL_highMono_highIso	Present day land cover with high monoterpene and isoprene emission factors from needleleaf	CEH-CLM (13% woodland cover)	NL_highMono_highIso	500 ppm

	trees and elevated CO_2			
Present_day_BL_lowMono_highIso	Present day land cover with high isoprene emission factors from broadleaf trees and elevated CO_2	CEH-CLM (13% woodland cover)	BL_lowMono_highIso	500 ppm
Present_day_BL_highMono_lowIso	Present day land cover with high monoterpene emission factors from broadleaf trees and elevated CO_2	CEH-CLM (13% woodland cover)	BL_highMono_lowIso	500 ppm
Afforested_Current_UK_mix	Afforested land surface with UK appropriate emission factors from broadleaf and needleleaf trees assuming planting in the current UK mix, and elevated CO_2	CEH-CLM afforested to 19% woodland cover (current UK ratio of broadleaf to needleleaf).	UK_appropriate_mix	500 ppm
Afforested_BL_lowMono_highIso	Afforested land surface with new broadleaf trees of high isoprene emission factors and elevated CO_2	CEH-CLM afforested to 19% woodland cover (100% broadleaf)	BL_lowMono_highIso	500 ppm

Afforested_BL_highMono_lowIso	Afforested land surface with new broadleaf trees of high monoterpene emission factors and elevated CO_2	CEH-CLM afforested to 19% woodland cover (100% broadleaf)	BL_highMono_lowIso	500 ppm
Afforested_NL_highMono_lowIso	Afforested land surface with new needleleaf trees of high monoterpene emission factors and elevated CO_2	CEH-CLM afforested to 19% woodland cover (100% needleleaf)	NL_highMono_lowIso	500 ppm
Afforested_NL_highMono_highIso	Afforested land surface with new needleleaf trees of high monoterpene and isoprene emission factors and elevated CO_2	CEH-CLM afforested to 19% woodland cover (100% needleleaf)	NL_highMono_highIso	500 ppm

311

3 Results and Discussion

3.1 Estimating present-day annual UK emissions of isoprene and total monoterpenes

Figure 6 illustrates the distribution of annual UK emissions for isoprene and total monoterpene compound classes from our *Baseline* experiment (Table 4). We present an estimate of present-day UK annual isoprene emission of 40 kt yr^{-1} and total monoterpene emission of 46 kt yr^{-1}. Our estimates of BVOC emissions with present-day land cover fall within the range of values presented in previous studies for the UK or Great Britain, i.e. 8 - 110 kt yr^{-1} for isoprene and 31 - 145 kt yr^{-1} for total monoterpenes (Guenther et al., 1995; Hayman et al., 2017; Purser et al., 2023; Simpson et al., 1999; Stewart et al., 2003). The spatial distribution of emissions is similar to that illustrated in previous UK studies, such as Purser et al., (2023) and Stewart et al., (2003), with the greatest isoprene emission rates located in the southern-most parts of England and around the Scotland-England border, whilst monoterpene emissions are concentrated in Scotland, and parts of Wales.

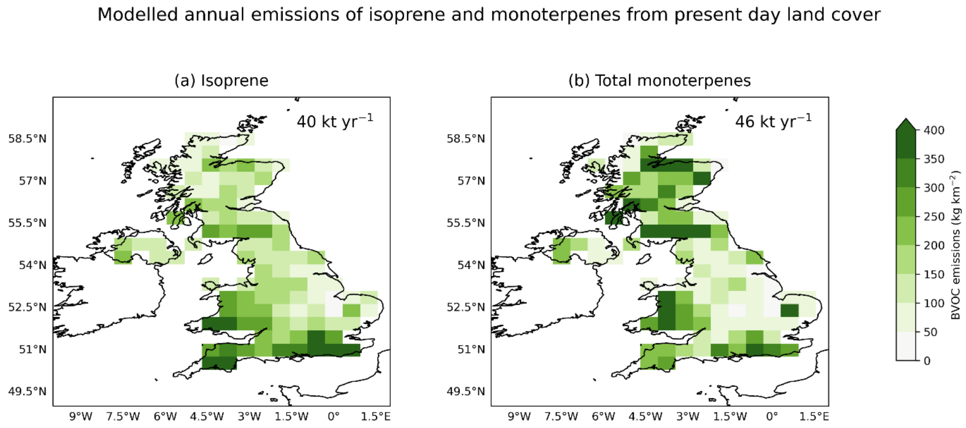

Figure 6. Modelled distribution of emissions of isoprene (kg km^{-2}) and total monoterpene (kg km^{-2}) from present day UK land cover. Figures 6a and 6b show the emissions generated from the Baseline experiment. The UK total (thousand tonnes) is given in the text overlay.

3.2 Investigating the impact of emissions factors and CO_2 concentration

Figure 7 illustrates the distribution of annual UK emissions for isoprene and total monoterpenes from present day land cover for experiments *Present_day_Current_UK_mix* (Fig. 7a and 7b) and *Present_day_Default_MEGAN* (Fig. 7c and 7d). In these experiments CO_2 concentrations are elevated to those projected for the year 2050 to enable calculation of the estimated change in emissions attributed to afforestation only in afforested experiments (Sect. 3.3). Experiment *Present_day_Current_UK_mix* simulates isoprene emissions lower than our *Baseline* experiment, at 35 kt yr^{-1}, whilst emissions of total monoterpene are increased marginally, at 47 kt yr^{-1}. The decline of 13% in isoprene emissions can be attributed to the CO_2 inhibition effect on the rate of isoprene emission from trees.

Estimates of BVOCs have been made on the global scale and continental scale (Guenther et al., 1995; Simpson et al., 1999), but few estimates have been made for the UK (e.g. Purser et al., 2023; Simpson et al., 1999; Stewart et al., 2003). Further, studies have demonstrated the impact of providing localised tree species information on estimates of BVOCs for a given location, compared to coarser resolution forest data. For example, Luttkus et al. (2022) examined the impact of detail in land use data on air quality predictions, showing substantial differences between estimates of BVOC emissions, and their distribution, when detail on tree species distribution was improved. The review of emissions potential data presented in Sect. 2.4 illustrated that emissions potentials of isoprene from broadleaf PFTs in our *UK_appropriate_mix* scenario are lower than those in the *Default_MEGAN* scenario, whilst values for needleleaf PFTs were slightly higher in the *UK_appropriate_mix* scenario than those in the *Default_MEGAN* scenario (Fig. 5). Combined, these variations result in the small decrease of 5% in isoprene overall in our experiment (to 35 kt yr^{-1}) when emissions data is adapted to reflect UK tree species (Fig. 7). In contrast, the emissions potentials data found values for monoterpenes in both broadleaf and needleleaf PFTs to be largely underestimated in MEGANv2.1 when compared to a range of UK tree species (Fig. 7). This is reflected in the estimate of total monoterpene emissions from our *Present_day_Current_UK_mix* experiment (at 47 kt yr^{-1}) being more than twice that of our *Present_day_Default_MEGAN* experiment. Adjusting emissions factors to represent the current relative abundance of tree species in the UK delivers approximately 147% extra monoterpene emissions. This demonstrates the importance of preparing bespoke input data for examining BVOC emissions, where regionally appropriate emissions factors can be applied.

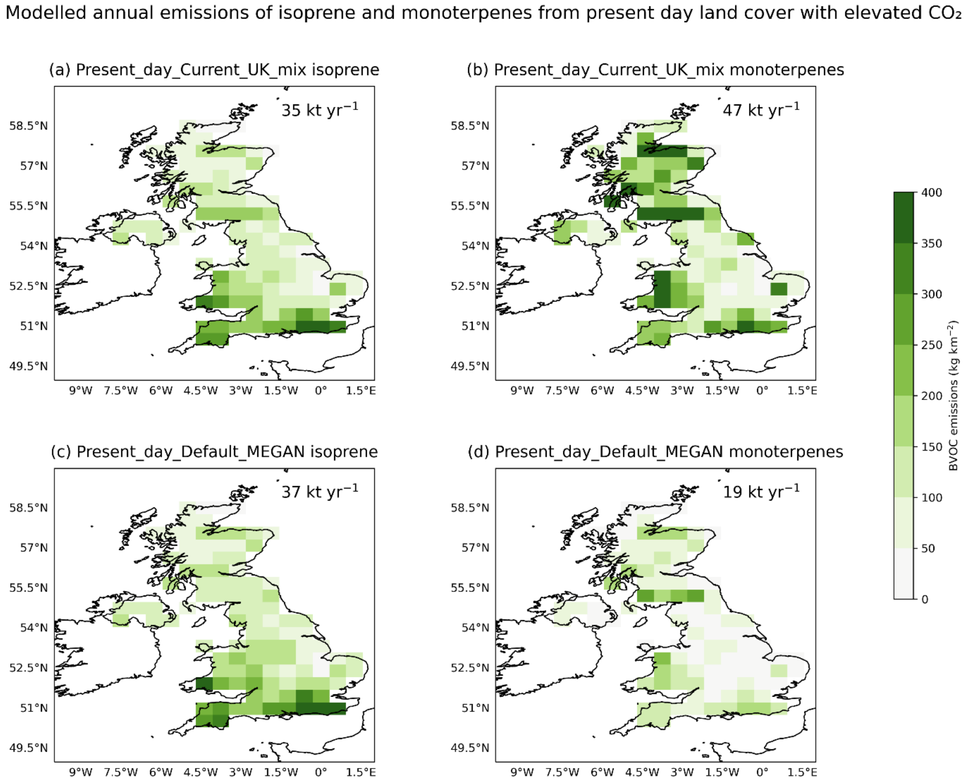

Figure 7. Modelled distribution of emissions of isoprene (kg km^{-2}) and total monoterpene (kg km^{-2}) from present day UK land cover. Figures 7a and 7b show the emissions generated from the Present_day_UK_appropriate_mix experiment. Figures 7c and 7d show the emissions generated with the Present_day_Default_MEGAN experiment. The UK total (thousand tonnes) is given in the text overlay.

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3.3 Estimating BVOC emissions attributed to UK afforestation

Figure 8 illustrates the percentage change in annual UK emissions of isoprene and total monoterpenes across the five afforestation experiments relative to present day land cover. All experiments here use elevated CO_2 as projected for 2050. Modelled estimates of total annual UK emissions of isoprene and total monoterpene compound classes are given in the text overlay. Values of percentage change in annual UK emissions and total annual estimates are also summarised in Table 5.

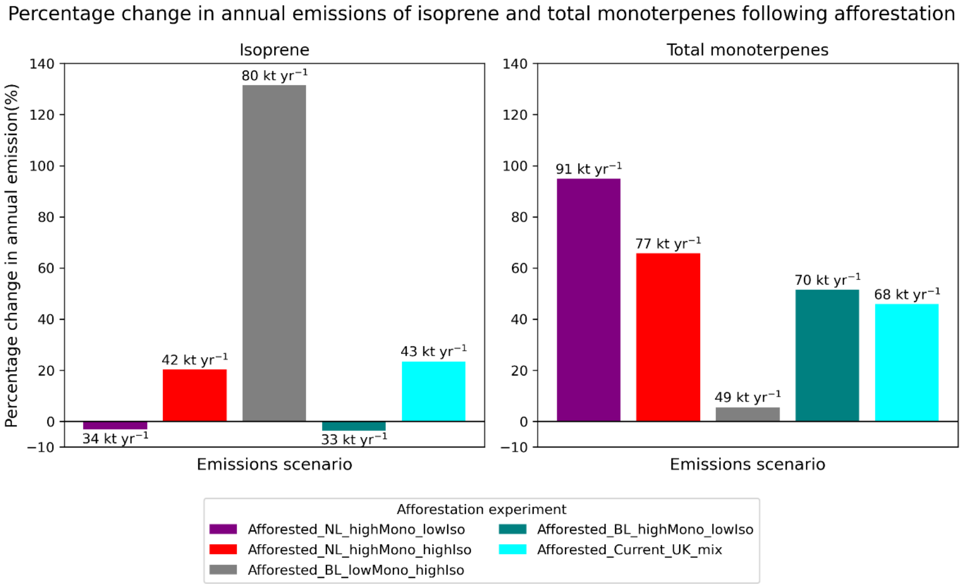

Figure 8. Percentage change in modelled annual UK emissions of isoprene and total monoterpene following afforestation to 19% woodland cover for five afforestation experiments: Afforested_BL_lowMono_highIso, Afforested_BL_highMono_lowIso, Afforested_NL_highMono_lowIso, Afforested_NL_highMono_highIso and Afforested_Current_UK_mix as detailed in Table 6. The total annual UK emissions of isoprene and total monoterpenes of each experiment are given in the text overlay.

In all scenarios, the larger increases in emissions are concentrated in Scotland (see Supplementary Fig. S3 and S4 for maps of percentage change in emissions, due to the scale of planting introduced there relative to the other UK nations (Table 1). The greatest increase in isoprene was observed in the experiment *Afforested_BL_lowMono_highIso*, where individual grid cells experienced up to a 250% increase in emissions, and total emissions increased by 131%. In experiments *Afforested_BL_highMono_lowIso* and *Afforested NL_highMono_lowIso*, the replacement of grassland with tree cover results in a reduction of isoprene emissions, of -4% and -3% respectively, and as much as -50% on an individual grid cell level. This is attributed to the lower emission factors applied to tree PFTs relative to those representing grass PFTs. The adaptations to prepare bespoke UK appropriate emissions potential values were not also made for non-tree PFTs. Therefore, our study may not present the best possible representation of UK non-tree PFTs, and so the decline in emissions attributed to replacement of grassland with woodland may not accurately reflect the case of UK grasses. However, similar outcomes were found by Purser et al., (2023), with a decline in isoprene emissions of 14% when examining the impact of large-scale planting of alder. In Fig. 8, we see an increase in monoterpene emissions under all scenarios. The greatest changes are observed in the *Afforested_NL_highMono_lowIso* scenario where some grid cells experience an increase above 250%, and total monoterpene emissions increased by 95%. Experiments *Afforested_NL_highMono_highIso*, *Afforested_NL_highMono_lowIso* and *Afforested_Current_UK_mix* demonstrate moderate increases in monoterpene emissions, between 46% and 66%. The smallest change in monoterpene emissions is observed in our *Afforested_BL_lowMono_highIso* experiment, where a 6% increase is simulated.

Our modelled estimates of isoprene emission for the UK with 19% woodland coverage vary between 33 kt yr^{-1} and 80 kt yr^{-1} across the experiments; modelled estimates of total monoterpene emission are between 49 kt yr^{-1} and 91 kt yr^{-1}. Overall, our results indicate that emission factors and tree species mixture substantially change estimates of BVOC emissions from the UK's future forests.

Table 5. Modelled estimates of annual UK isoprene and total monoterpene emissions (thousand tonnes) and percentage change (relative to Present_day_UK_appropriate mix) following afforestation to 19% woodland cover for five afforestation experiments.

Afforestation experiment	**Estimated annual emission (**kt species yr^{-1}**)**	
	Isoprene	**Total monoterpenes**
Afforested_Current_UK_mix	43 (+24%)	68 (+46%)
Afforested_BL_lowMono_highIso	80 (+131%)	49 (+6%)
Afforested_BL_highMono_lowIso	33 (-4%)	70 (+52%)
Afforested_NL_highMono_lowIso	34 (-3%)	91 (+95%)
Afforested_NL_highMono_highIso	42 (+20%)	77 (+66%)

Figure 9 illustrates the relationship between changes in isoprene and total monoterpene emissions across the five afforestation experiments. With the combination of species mixtures examined, we demonstrate the possibility for isoprene emission to be reduced whilst delivering ambitious afforestation by 2050. However, in experiments where isoprene is reduced (by as much as -4%), monoterpenes increase by at least 52%. All experiments result in an increase in monoterpenes. Our experiment *Afforested_BL_lowMono_highIso* demonstrates the potential to minimise the increase in monoterpenes, with an increase of just 6%, however this is estimated to deliver the most extreme change across all experiments in relation to isoprene, which increases by over 130%. We compare our rates of change to estimates of BVOC emissions from Purser et al., (2023) for the UK. When scaled to the same level of afforestation, their scenarios estimate changes in isoprene between -4 and +53%, whilst the change in monoterpenes in their scenarios is between approximately -3 and +42% (Purser et al., 2023). This further demonstrates the impact of representation of different tree species on emission estimates, as these results were generated by single species afforestation.

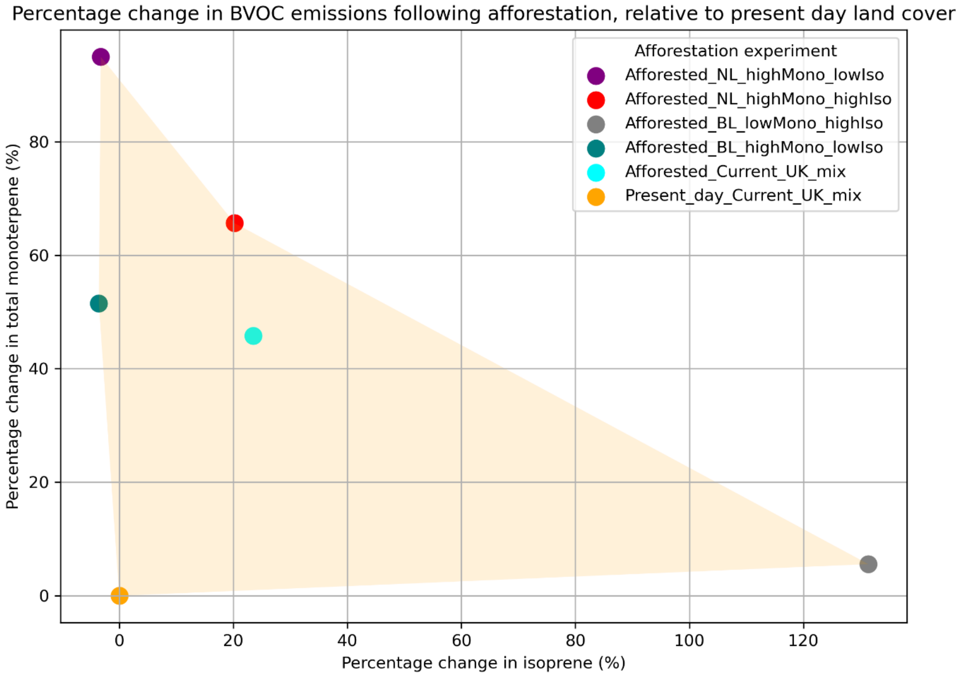

Figure 9. Relationship between the percentage change in modelled estimates of annual UK isoprene and total monoterpene emissions by afforestation experiment, compared to present day land cover.

Our experiments demonstrate the range of futures that net-zero aligned UK afforestation could deliver for BVOC emission from natural vegetation. Estimates of BVOC emissions used in this study are limited by assumptions regarding the age of trees and therefore the calculation of rate of emission in MEGAN (Guenther et al., 1993, 2012). The trees contributing to the achievement of 19% woodland cover by 2050 would be planted gradually over decades rather than all being one age. MEGAN makes assumptions about the age of trees based on information regarding biomass, PFT distribution and leaf age activity factors which inform the values estimated here (Guenther et al., 1993, 2012). Further, estimates of BVOC emissions will be impacted by localised variations, such as tree health, leaf area index, exposure to stress such as drought, and infestation with tree pests or disease. These unknowns will further impact the overall change in emissions that are observed in the future from increased woodland cover. Two of our experiments (*Afforested_NL_highMono_lowIso* and *Afforested_BL_highMono_lowIso*) suggest that a reduction in isoprene emissions is possible with an increase in woodland cover of around 50% (or 6% absolute additional woodland cover), when the increase is achieved through planting of either broadleaf or needleleaf species.

4. Conclusion

This study presents, for the first-time, estimates of BVOC emissions that are consistent with net-zero aligned afforestation in the UK using tree species suitability information coupled with regionally appropriate emissions data. Using the CLMv4.5 and MEGANv2.1, we estimate present-day emissions of isoprene and total monoterpenes, and examine changes to emissions that may occur with around a 50% increase in woodland cover, delivering absolute woodland cover of approximately 19%. We present a new estimate for present-day emissions of isoprene at 40 kt yr^{-1}, and 46 kt yr^{-1} for monoterpenes, which is within the range of previous estimates for this region.

Whilst recommendations for afforestation within pathways to net-zero GHG emissions vary between 30,000 and 50,000 ha yr^{-1}, this study chooses to investigate the potential impact on BVOCs associated with the higher rate of planting, equivalent to delivering UK woodland cover of 19% by the year 2050. This enables us to present an estimate of the potential greatest change in BVOCs relevant to the UK and representative of the greatest ambition for planting referenced in literature and policy published to date. Our experiments show that changes in UK emissions of isoprene vary between -4 and 131%, and between 6 and 95% for total monoterpene emissions, with the outcome depending on the species mixtures selected for planting. Afforestation in the UK should be informed by best-available knowledge on the resilience of different tree species to climate change and pests and diseases, as well as their potential to deliver co-benefits in the landscape. Our study demonstrates how emissions of BVOCs from the UK's future forests will vary with species selection, by examining variation within and between broadleaf and needleleaf tree species mixtures.

Our experiments rely on large scale conversion of grasslands to woodlands to achieve afforestation targets. We apply this conversion as a simplified approach to sourcing sufficient land cover for delivering afforestation to estimate the impact on BVOC emissions, and this should not be used to infer the suitability of any specific location. We recognise that in reality, afforestation will occur following decisions around land use and the environmental, social and economic impact of the changes. The land cover that trees replace ultimately will determine the change in emissions that occurs; as demonstrated here, a decrease in emissions may be seen if woodland cover replaces a land cover type with greater potential to emit BVOCs. We show that incorporating regionally appropriate emissions factors, information about present day abundance of tree species, and the likely role of different species in the UK's future forests, can substantially alter estimates of emissions. Our study will support future work to estimate the complex interactions between afforestation and atmospheric composition, including changes in concentrations of atmospheric pollutants.

Code availability:

This study used the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN, guidance and access to model code are available at https://sites.google.com/uci.edu/bai/megan/data-and-code) (Guenther et al., 2012), and the Community Land Model version 4.5 (CLM, model code is available at https://www2.cesm.ucar.edu/models/cesm1.2/) ((Oleson et al., 2013).

Data availability:

Data from this study will be made available at the point of publication with a DOI provided.

Author contributions

Conceptualization of the study was led by HM, with supervision from CS, SA and PF. HM developed the methodology, curated input data and model configurations and carried out all programming and formal data analysis. BS supported HM with elements of input data preparation. HM prepared the paper with editorial contributions from CS, SA, BS and PF.

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Competing interests:

Piers M Forster is the current chair of the Climate Change Committee. All other authors have no competing interests to declare.

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