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 can also have benefits for air quality. However, they ~~also have the potential to degrade air quality, due to the~~ emi~~ts~~ssion of biogenic volatile organic compounds (BVOCs) which are precursors to ~~major~~ atmospheric pollutants, such as ozone (O_3) and particulate matter (PM), which have the potential to degrade air quality. 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 variation in BVOC emissions potentials between and within plant functional types (PFTs) on estimates of BVOC emissions from UK land cover, in a future warmer climate under elevated atmospheric CO_2 concentrations, 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 39 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 -3% and +123%, and a change to total monoterpene emission of between +5% and +~~47~~48%. Needleleaf afforestation leads to a change in UK isoprene emission of between -3% and +22%, and a change to total monoterpene emission of between +60% and +86%.

Our study highlights the potential for net-zero aligned afforestation, in a likely warmer and drier future UK climate, to have substantial impacts on ~~UK~~ BVOC emissions~~, and therefore air quality, but~~. However, the results highlight possible pathways to achieving 19% woodland cover without requiring large increases in isoprene emissions. The emissions estimates presented here provide the opportunity to quantify future impacts on air pollution associated with changes in biogenic emissions, as well as how these impacts would be affected by concurrent changes in anthropogenic emissions.

~~also demonstrates routes to minimising these impacts through consideration of the emissions potentials of tree species planted.~~

1 Introduction

The terrestrial biosphere plays a key part in suggested pathways for mitigating climate change and helping to reach net-zero greenhouse gas (GHG) emissions, due to the capacity for the biosphere to sequester and store carbon dioxide (CO₂) from the atmosphere. The Sixth6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) estimated that 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 31-46up 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, 2024). 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), reducing concentrations of particulate matter through deposition, and local temperature reductions (Bolund and Hunhammar, 1999; Costanza et al., 1997; D'Alessandro et al., 2015; Department for Environment, Food and Rural Affairs, 2018; Monger et al., 2022; Nowak, 2022; Purser et al., 2023; Wang et al., 2023). There is also the potential for side-effects and delivery of trade-offs, such as the degradation of air quality potentially associated with the emission of biogenic volatile organic compounds (BVOCs) (e.g. Chameides et al., 1988; Churkina et al., 2017; Gu et al., 2021; Rasmussen, 1972).

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 BVOCsBVOC emission from trees is 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 (e.g. Dicke, 2009; Ghimire et al., 2022; Irmisch et al., 2014; Jaakkola et al., 2023; Trowbridge and Stoy, 2013). 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., 1995, 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 has historically been thought to be dependent mostly on temperature (Guenther al., 1993), but increasingly evidence shows a light dependence in monoterpene emission for some plant species (e.g. Bao et al., 2008; Ghirardo et al., 2010; Jardine et al., 2015). Some plants have a store of monoterpenes (referred to as pool emissions), which are produced and stored within the leaf until temperatures are high enough for the liquid compound to volatilise (Tingey et al., 1980). De novo emissions are those synthesised in response to both light and temperature without a period of storage in the plant; due to the dependence on light, emissions rates of de novo emissions tend to follow day light patterns (Ghirardo et al., 2010) within plants causes distinct temperature driven 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. The response of monoterpene emissions to climate change is influenced by the behaviour of individual enantiomers. Byron et al. (2022) found that drought affects monoterpene enantiomers differently, depending on both the severity and duration of the drought. Since enantiomers can help distinguish between emissions from de novo synthesis and those from storage pools, differing enantiomeric responses introduce uncertainty in future emission estimates—especially if the balance between de novo and storage-derived emissions shifts.

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 (Scott et al., 2018; Weber et al., 2024), as is the response of vegetation to elevated CO_2 concentrations and temperature. The point at which temperature or CO_2 concentration, and the point at which these become inhibiting factors for vegetation growth and BVOC emission, 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 and, oxidised in the atmosphere 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 the 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 examineding the impact of afforestation on BVOC emissionss 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,

128 Stewart et al., (2003) previously constructed a BVOC inventory for Great Britain, and estimated that
129 BVOC emissions are 10% of those of AVOCs, though recognising this may change with a warmer
130 climate. Using the WRF-EMEP4UK modelling framework, Purser et al., (2023) present an assessment
131 of the potential air quality impact of BVOCs associated with large-scale afforestation for bioenergy and
132 short rotation forestry in the UK. Based on four planting scenarios, each of single tree species
133 (*Eucalyptus gunnii*, *Populus tremulus*, *Alnus cordata* and *Picea sitchensis*) and delivering up to 164%
134 more woodland cover than present day coverage, Purser et al. (2023) estimated isoprene emissions to
135 increase between 53% and 135%, except with Alder where emissions declined by 14% due to its lower
136 emissions potentials relative to the grassland and agriculture being replaced. An increase in
137 monoterpene emissions between 5% and 94% was simulated, except for Aspen where a decline of 8%
138 was again attributed to the lower emissions potential of the trees relative to the land cover being
139 replaced (Purser et al., 2023). To best understand the potential scale of BVOC emissions associated
140 with afforestation, we need to understand the role that the mixture of tree species planted plays in
141 determining BVOC emissions.

142

143 In this work, we quantify for the first time the emission of BVOCs from UK afforestation scenarios under
144 which that represent achievement of the estimated 19% woodland cover is achieved with mixed tree
145 species afforestation. We assume that model for afforestation occurs in line with recent and committed
146 afforestation rates for the four UK nations. We present five afforestation experiments for the UK which
147 represent different pathways to achieving woodland cover of 19% in 2050, with varying contributions
148 from high and low BVOC emitting tree species. Our study seeks to explore the potential range of BVOC
149 emissions resulting from a net-zero consistent level of afforestation, if the afforestation was to occur
150 with feasible but extreme (in terms of BVOC emission potentials) mixtures of tree species improve
151 understanding of the relative impact of different tree species mixtures on the BVOC emissions
152 associated with afforestation in the UK. Estimating potential changes in BVOC emissions will help guide
153 policy decisions regarding species prioritisation for planting, particularly when considered in the
154 context of minimising air-quality side-effects associated with afforestation, a concern noted by The
155 Royal Society in their report on net-zero effects on air quality (The Royal Society, 2021). The potential
156 impact that increased emissions of BVOCs could have for air quality (associated with their role as
157 precursors to atmospheric pollutants) will depend also on the future of anthropogenic emissions and
158 other precursors, such as NO_x, which influence the formation of O_3. Our eEstimates of BVOC emissions
159 from future afforestation scenarios will facilitates this assessment of future air quality impacts.

160

161 ## 2 Methods and data
162 To quantify the emissions of BVOCs from a range of afforestation experiments, we use the Community
163 Land Model v4.5 (CLM) (Oleson et al., 2013), which includes has the algorithms of the Model of
164 Emissions of Gases and Aerosols from Nature v2.1 (MEGAN;) to estimate emissions of BVOCs from the
165 land surface (Guenther et al., 1993, 2012). When operating inside the CLM, MEGAN takes information
166 about vegetation type and fraction (PFT), LAI and meteorological variables from the CLM. These are
167 provided as input data when the CLM is operating offline. Within the CLM, these input variables are
168 used to calculate leaf temperature, soil moisture, soil temperature and humidity. The CLM also
169 calculates canopy variables, including the fraction of sunlit vs shaded leaves and the canopy
170 environment coefficient. To calculate BVOC emissions, MEGAN uses leaf temperature, soil moisture,
171 soil temperature, solar radiation and CO_2 concentrations (which are used to estimate CO_2 inhibition
172 ofin isoprene emission) as well as the canopy environment coefficient provided by the CLM. Further,

175   2.1 Representing the land surface

176   We use the CLM (Oleson et al., 2013) at a resolution of 0.47 ° x 0.63 ° with land surface data from the
177   UKCEH land cover map for 2021 (Marston et al., 2022). The UKCEH map is produced at a resolution of
178   1 km, combining Sentinel-2 seasonal composite images and 10 context layers to map 21 land cover
179   classes based on the Biodiversity Action Plan broad habitats (Marston et al., 2022). We use the 1 km
180   percentage product, which details the percentage cover for each of 21 land cover classes within each
181   1 km pixel. The UKCEH dataset was regridded to the 0.47 ° x 0.63 ° resolution of our CLM configuration.
182   As land surface categories vary between the UKCEH and the CLM, variables of the UKCEH map were
183   reassigned to the closest matching plant functional type (PFT) or land surface category in the CLM,
184   including the urban, natural vegetation, crops and lake land surface categories. Figure 1 illustrates the
185   percentage cover of needleleaf and broadleaf tree PFTs and grassland PFTs in the resulting CEH-CLM
186   dataset which represents present day UK land cover informed by the UKCEH land cover map, at the
187   resolution of the CLM. In this dataset, woodlands cover approximately 13% of UK land, and of this 52%
188   is broadleaf woodland and 48% needleleaf woodland (Forest Research, 2024). Grassland makes up
189   approximately 40% of UK land cover (Marston et al., 2022).

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

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191

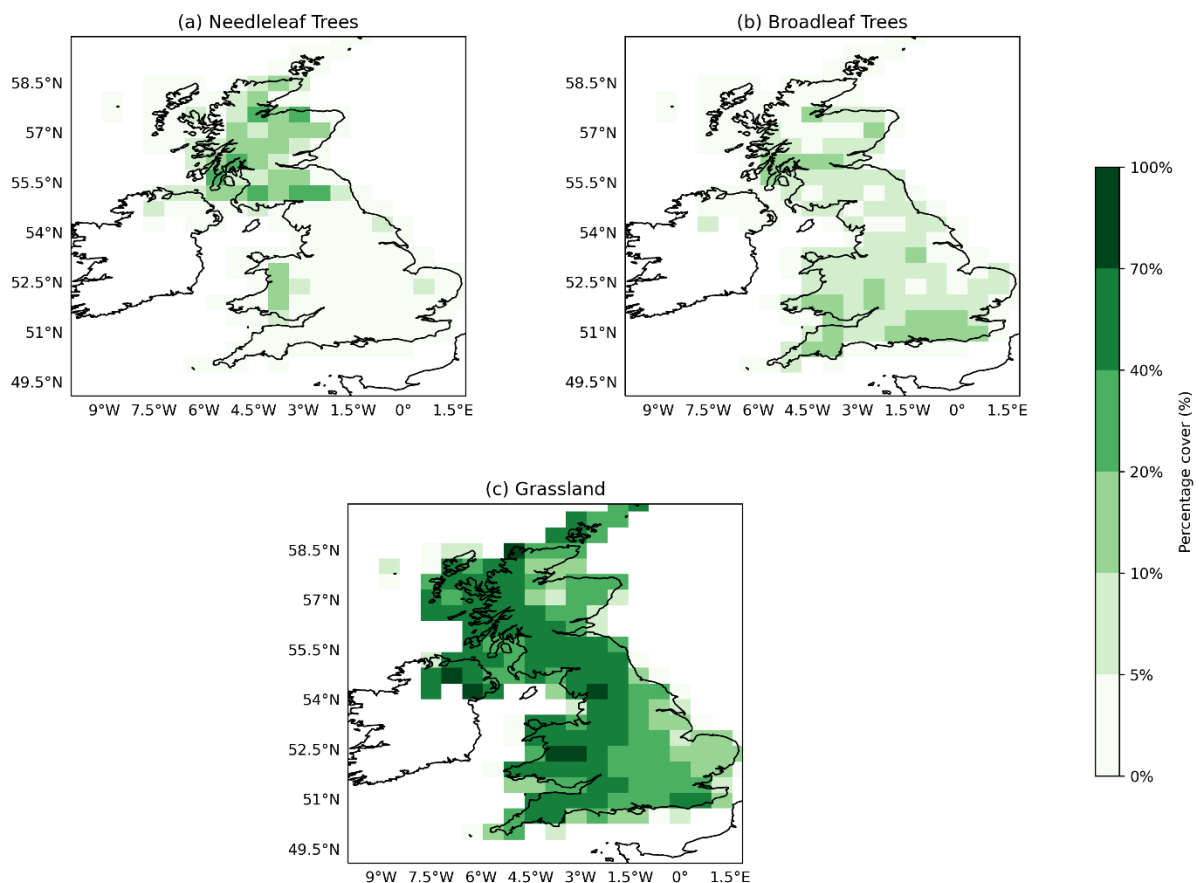



Figure 1. Percentage share of land in gridcell covered by a) broadleaf trees, b)and needleleaf trees, and c) grass PFTs. The distribution of PFTs presented here is inferred from the UKCEH landcover map (1 km x 1 km resolution) (Marston et al., 2022), reassigned to the land cover categories of the CLM (Oleson et al., 2013) to produce the CEH-CLM dataset.

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 and Wales) have their own ambitions relating to the net-zero aligned planting recommendations (Department for Agriculture, Environment and Rural Affairs, 2020; Department for Environment, Food and Rural Affairs, 2021; Scottish Government, 2017 and Welsh Government, 2018). 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 with 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.

Whilst a lack of specific locations for future additional woodland adds extra uncertainty to any estimates of future BVOC emissions, we seek to minimise this by distributing the new woodland in accordance with historical planting rates and future planting commitments across the four nations of the UK (Department for Agriculture, Environment and Rural Affairs, 2020; Department for Environment, Food and Rural Affairs, 2021; Forest Research, 2023; Scottish Government, 2017 and Welsh Government, 2018). Table 1 details the rates of afforestation reported 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.

219 *Table 1. Historical rates of afforestation in the UK by nation between 1976 and 2021 and current national ambitions for*
220 *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%) (Scottish Government, 2017)	2000 ha yr⁻¹ from 2020 onwards (8%) (Welsh Government, 2018)	900 ha yr⁻¹ from 2020 to 2030 (4%) (Department for Agriculture, Environment and Rural Affairs, 2020)	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%)

221

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

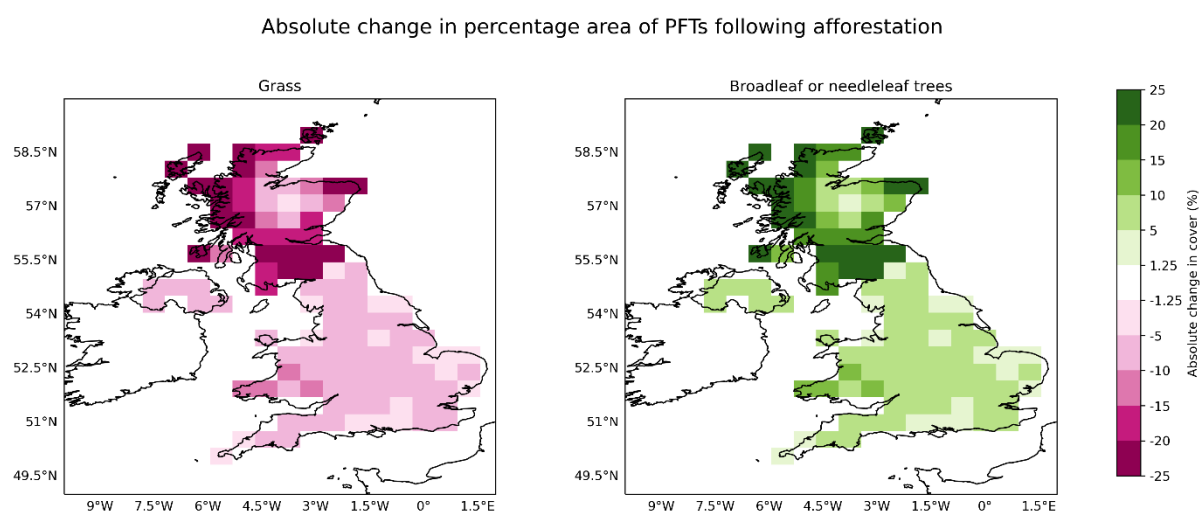



Figure 2. Absolute change in the percentage cover of grass and tree PFTs following either needleleaf or broadleaf afforestation.

237

238 2.3 Identifying tree species for afforestation

239 The subset of tree species represented in this study was informed by the Forest Research tree species
240 database (Forest Research, 2024a) and associated Ecological Site Classification (ESC) tool. This online
241 tool enables users to identify suitable trees for planting in each part of the UK according to known or
242 projected conditions for climate, lithology, ecology, soil moisture and soil nutrients (Pyatt et al., 2001).
243 60 tree species are considered in the ESC tool. Of these species, those classified as principal species
244 (defined as species already widely used or increasing in deployment in the UK, and of continuing
245 importance unless adversely affected by a new pest or disease, or climate change) (Tree Species
246 Database, 2024) were considered for representation in our study. We compare this subset of 25 tree
247 species to statistics on current tree species composition in the UK (Forest Research, 2023) and the EU-
248 Trees4F project which examines the changing distribution of European tree species under a selection
249 of climate futures considering natural dispersal and planting (Mauri et al., 2022). Based on these
250 requirements, we selected 18 tree species to include in our review of emissions potentials data (details
251 of included tree species can be found in Supplementary Table S1).
252

253 2.4 Preparing UK specific emissions potential data

254 We generate a bespoke UK-specific emissions potential dataset to capture isoprene and monoterpene
255 emissions from UK-specific tree species. We use this dataset to adjust estimates of BVOC emission
256 from tree species for our present-day land cover and afforestation experiments. Tree species specific
257 emissions potentials were used to generate PFT emissions potential scenarios based on both present-
258 day tree species abundance in the UK, and a range of hypothetical planting mixtures that demonstrate
259 the variation within and between PFTs. We reviewed European or UK specific emissions potentials of
260 tree species to identify values representative of UK trees. Emissions data were obtained for isoprene
261 and monoterpene compound classes, as the BVOCs dominating VOC chemistry in Great Britain
262 (Atkinson, 1990). If data was available for tree species in our subset, emissions values were recorded
263 (applicable studies are summarised in Table 2). The review returned emissions potential data for
264 isoprene and monoterpenes for 6 needleleaf and 10 broadleaf tree species (listed in Table 3; additional
265 details can be found in Supplementary Table S1) which make up existing UK woodland cover and/or
266 are expected to play a role in afforestation in the future.
267

268 Monoterpenes have pool emissions (previously synthesised compounds emitted from storage pools)
269 as well as synthesis (or *de novo;* compounds synthesised and emitted in response to light) emissions.
270 The review of emissions potential literature highlighted inconsistencies in the level of differentiation

271 between pool and synthesis emissions. In MEGAN, the relative light dependence of BVOC compound
272 class emissions is managed by assigning a light dependent fraction (Guenther et al., 2012). We account
273 for this by taking the sum, where synthesis and pool emission potentials are explicit in the published
274 dataset, and reapplying the existing light dependent fractions in MEGAN.
275
276 The emissions potentials values obtained from different studies were used to calculate a mean
277 emission potential for isoprene and total monoterpenes for each tree species. Figures 3 and 4 show
278 the relationship between isoprene and total monoterpene emissions potentials for broadleaf (Fig. 3)
279 and needleleaf (Fig. 4) tree species and the emissions potential of corresponding PFTs from MEGAN
280 (namely BDTT and BDBT for broadleaf species and NETT and NEBT for needleleaf species) (Guenther
281 et al., 2012). MEGAN provides values as emissions factors. To enable comparison, we converted
282 emissions factors from MEGAN (Guenther et al., 2012) to emissions potentials using the Eq 1., where
283 E_f = emissions factor (µg m^{-2} hr^{-1}), E_p = emissions potential (µgC gDW^{-1} hr^{-1}) and F_d = foliar density, given
284 as 560 gDW m^{-2} for deciduous trees and 1100 gDW m^{-2} for conifer trees (Guenther et al., 1995).
285 *Equation 1*

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

286

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

289

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

290

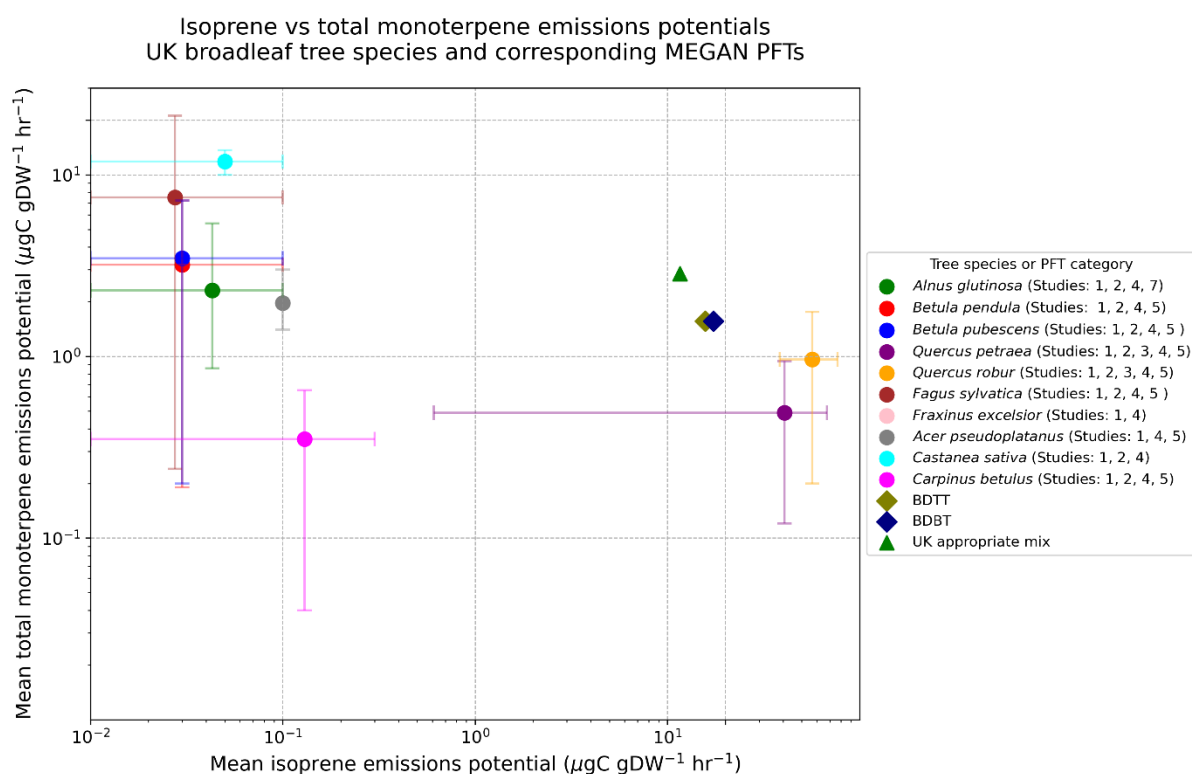



Figure 3. Relationship between the mean isoprene and mean total monoterpene emissions potentials for UK appropriate broadleaf tree species. Circular markers represent the mean of values obtained for a given broadleaf tree species from the literature (see Table 2). Triangular markers represent a UK appropriate 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. Error bars indicate the minimum and maximum values obtained from the literature.

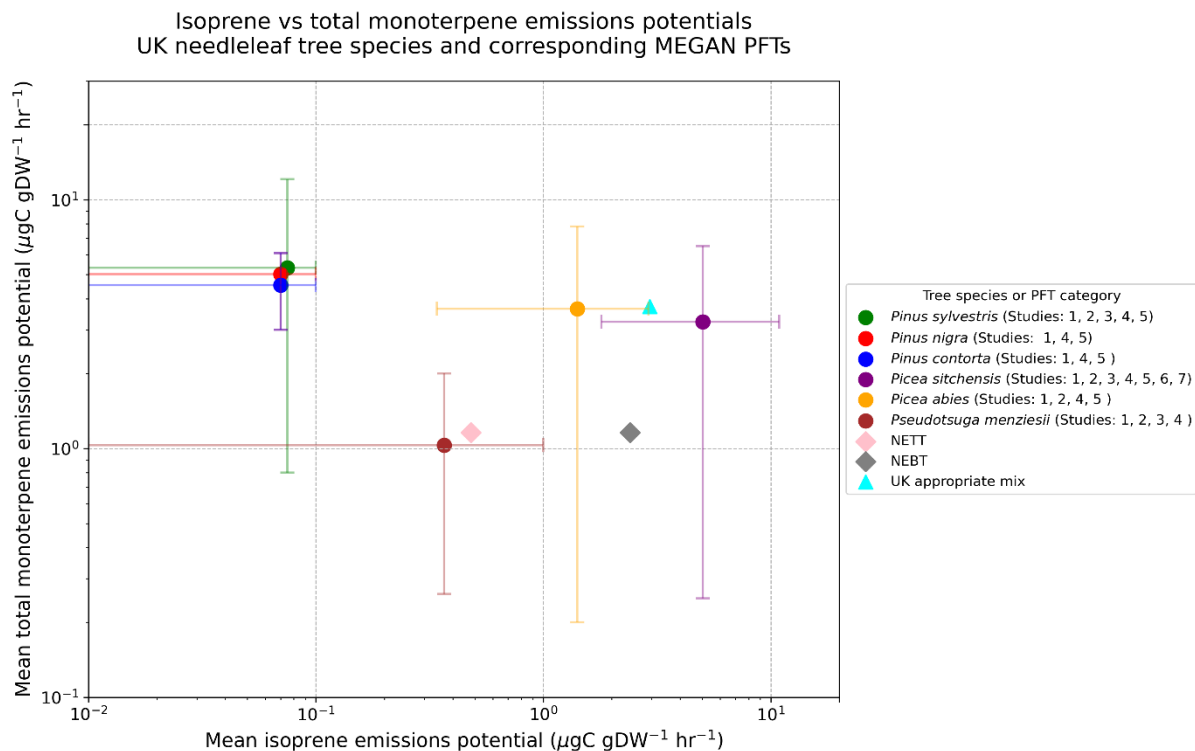
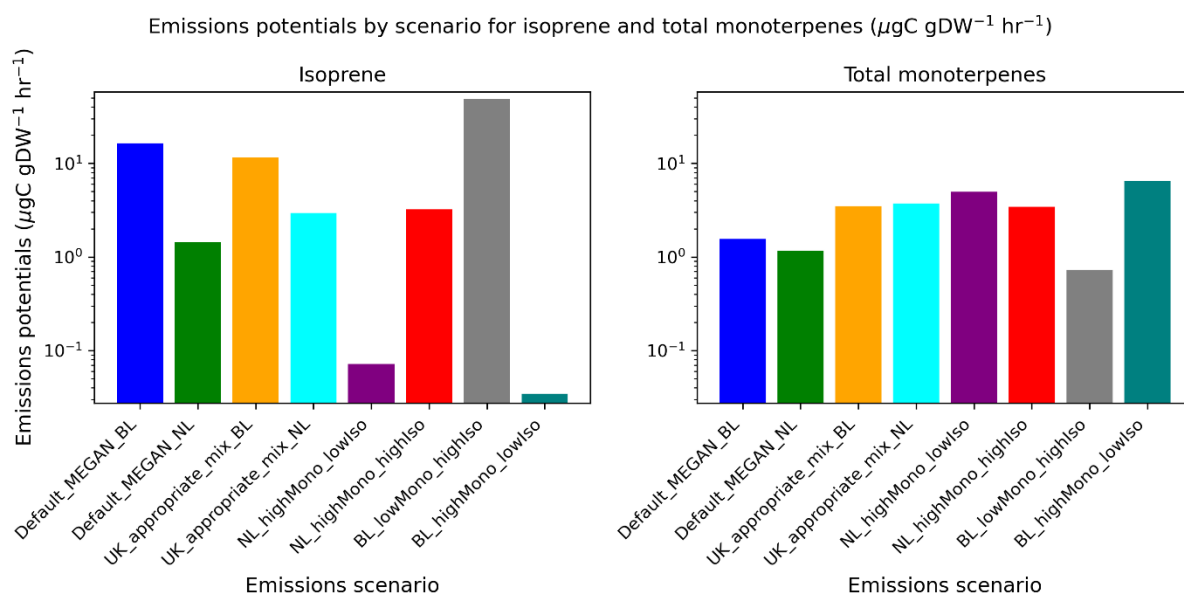



Figure 4. Relationship between the mean isoprene and mean total monoterpene emissions potentials for UK appropriate needleleaf tree species. Circular markers represent the mean of values obtained for a given needleleaf tree species from the literature (see Table 2). Triangular markers represent a UK 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. Error bars indicate the minimum and maximum values obtained from the literature.

298   In the case of broadleaf species (Fig. 3), emissions potentials suggest three broad categories, where
299   higher emitters of monoterpenes are generally lower emitters of isoprene (e.g. *Fagus sylvatica* and
300   *Betula pendula*), higher emitters of isoprene are generally lower emitters of monoterpenes (e.g.
301   *Quercus spp.*) and some are low emitters of both (e.g. *Fraxinus excelsior*). To reflect these groupings,
302   we designed two broadleaf emissions scenarios, *BL_highMono_lowIso* and *BL_lowMono_highIso*
303   (described in Table 3). Needleleaf tree species (Fig. 4) seem to be generally high emitters of
304   monoterpenes, but either lower emitters of isoprene (e.g. *Pinus spp.*) or higher emitters of isoprene
305   (e.g. *Picea spp.*). To reflect these groupings, we designed two needleleaf emissions scenarios:
306   *NL_highMono_lowIso* and *NL_highMono_highIso*. The emission potentials used in each scenario are
307   calculated as a mean of the tree species in that group, based on the mean of values presented in the
308   literature. We developed a fifth emissions scenario, *UK_appropriate_mix*, with values calculated as a
309   mean of species emission factors weighted according to their present-day abundance in the UK, based
310   on the 2023 Woodland Statistics (Forest Research, 2023). A scenario using the existing emissions
311   factors for these PFTs in MEGAN is referred to as the *Default_MEGAN* scenario. Emissions potentials
312   for each scenario are illustrated in Fig. 5. For use in MEGAN, emissions potentials are converted to
313   emissions factors. The emissions factors of each scenario are detailed in Table 3 for isoprene and total
314   monoterpenes. For use in MEGAN, values for total monoterpene emissions factors were allocated to
315   compound classes according to the ratio of those classes in Default MEGAN emissions factors.
316   Emissions factors are combined with information on vegetation type and distribution (PFTs), LAI, solar
317   radiation and atmospheric CO_2 concentration and (calculated by the CLM) soil moisture, soil
318   temperature, leaf temperature and the canopy environment coefficient for calculating emissions in
319   MEGAN.

320 *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.*

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

Emission scenario short name and description	PFT	Species	Emissions Factors ($\mu g\ m^{-2}\ hr^{-1}$)	
			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 menziesi*	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

326

2.5 Model set up

Simulations were undertaken at 0.47 ° x 0.63 ° resolution with the CLM component of Community Earth System Model (CESM) version 2.2.0 (Danabasoglu et al., 2020; Oleson et al., 2013). BVOC emissions are calculated by MEGAN (Guenther et al., 1993; 2012). Land surface input data for CLM 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). Previous studies have explored the impact of drought on BVOC emissions (e.g. Potosnak et al., 2014) and developed parameterisations to improve the representation of this process in MEGAN (e.g. Jiang et al., 2018; Wang et al., 2022). To enable quantification of the sensitivity of our results to the representation of the impact of drought on isoprene emissions, extra simulations were run with a modification to the soil moisture activity factor algorithm following Wang et al., (2022), see Supplementary Table S2.

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 approximately 19% UK woodland coverage. At this resolution, the resulting level of afforestation in model experiments from which emissions are estimate in equivalent to the achievement of 18.65% woodland cover by the year 2050.

366 *Table 4. Summary of model run configurations: afforestation experiment short name, experiment description and input data:*
367 *land cover, emission scenario short name and associated emission factors and atmospheric CO_2 concentration data. In*
368 *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 18.65% 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 18.65% 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 18.65% 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 18.65% 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 18.65% woodland cover (100% needleleaf)	NL_highMono_highIso	500 ppm

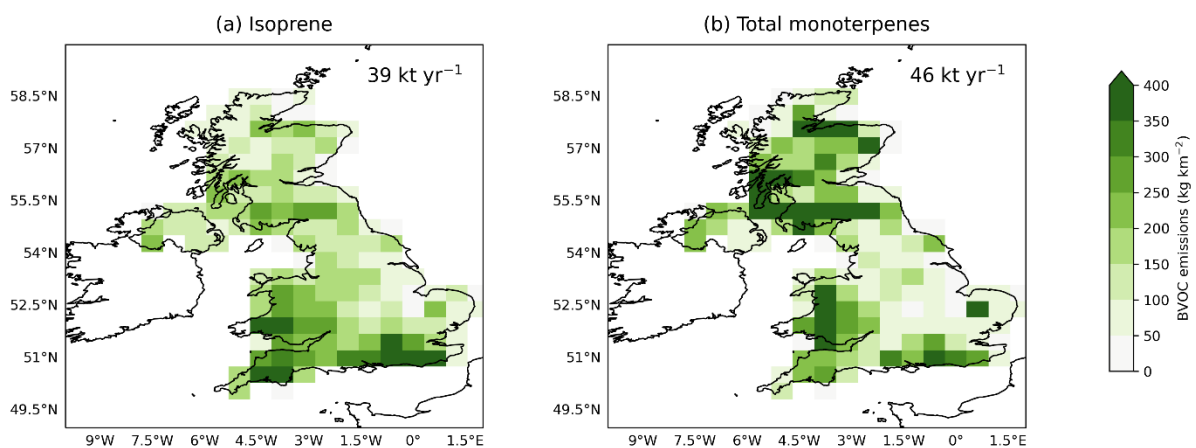
369

370 3 Results and Discussion

371 3.1 Estimating present-day annual UK emissions of isoprene and total monoterpenes

372 Figure 6 illustrates the distribution of annual UK emissions for isoprene and total monoterpene
373 compound classes from our *Baseline* experiment (Table 4). We present an estimate of present-day UK
374 annual isoprene emission of 39 kt yr^{-1} and total monoterpene emission of 46 kt yr^{-1}. Our estimates of
375 BVOC emissions with present-day land cover fall within the range of values presented in previous
376 studies for the UK or Great Britain, i.e. 8 - 110 kt yr^{-1} for isoprene and 31 - 145 kt yr^{-1} for total
377 monoterpenes (Guenther et al., 1995; Hayman et al., 2017; Purser et al., 2023; Simpson et al., 1999;
378 Stewart et al., 2003). The spatial distribution of emissions is similar to that illustrated in previous UK
379 studies, such as Purser et al., (2023) and Stewart et al., (2003), with the greatest isoprene emission
380 rates located in the southern-most parts of England and around the Scotland-England border, whilst
381 monoterpene emissions are concentrated in Scotland, and parts of Wales.

Modelled annual emissions of isoprene and monoterpenes from present day land cover

382

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

386 3.2 Investigating the impact of emissions factors and CO_2 concentration

387 Figure 7 illustrates the distribution of annual UK emissions for isoprene and total monoterpenes from
388 present day land cover for experiments *Present_day_Current_UK_mix* (Fig. 7a and 7b) and
389 *Present_day_Default_MEGAN* (Fig. 7c and 7d). In these experiments CO_2 concentrations are elevated
390 to those projected for the year 2050 to enable calculation of the estimated change in emissions
391 attributed to afforestation only in afforested experiments (Sect. 3.3). Experiment
392 *Present_day_Current_UK_mix* simulates isoprene emissions lower than our *Baseline* experiment, at
393 33 kt yr^{-1}, whilst emissions of total monoterpene are ~~increased marginally, at 47 kt yr^{-1}~~ unchanged. The
394 decline of 1~~5~~% in isoprene emissions, in the absence of any change to woodland coverage, can be
395 attributed to the CO_2 inhibition effect on the rate of isoprene emission from trees.

396 Estimates of BVOCs have been made on the global scale and continental scale (Guenther et al., 1995;
397 Simpson et al., 1999), but few estimates have been made for the UK (e.g. Purser et al., 2023; Simpson
398 et al., 1999; Stewart et al., 2003). Further, studies have demonstrated the impact of providing localised
399 tree species information on estimates of BVOCs for a given location, compared to coarser resolution
400 forest data. For example, Luttkus et al. (2022) examined the impact of detail in land use data on air
401 quality predictions, showing substantial differences between estimates of BVOC emissions, and their
402 distribution, when detail on tree species distribution was improved. The review of emissions potential

403 data presented in Sect. 2.4 illustrated that emissions potentials of isoprene from broadleaf PFTs in our
404 *UK_appropriate_mix* scenario are lower than those in the *Default_MEGAN* scenario, whilst values for
405 needleleaf PFTs were slightly higher in the *UK_appropriate_mix* scenario than those in the
406 *Default_MEGAN* scenario (Fig. 5). Combined, these variations result in the small decrease of ~~5~~6% in
407 isoprene overall in our experiment (to 33 kt yr^{-1}) when emissions data is adapted to reflect UK tree
408 species (Fig. 7). In contrast, the emissions potentials data found values for monoterpenes in both
409 broadleaf and needleleaf PFTs to be largely underestimated in MEGAN when compared to a range of
410 UK tree species (Fig. 7). This is reflected in the estimate of total monoterpene emissions from our
411 *Present_day_Current_UK_mix* experiment (at ~~47~~ 46 kt yr^{-1}) being more than twice that of our
412 *Present_day_Default_MEGAN* experiment. Adjusting emissions factors to represent the current
413 relative abundance of tree species in the UK delivers approximately ~~147~~142% extra monoterpene
414 emissions. This demonstrates the importance of preparing bespoke input data for examining BVOC
415 emissions, where regionally appropriate emissions factors can be applied.

Modelled annual emissions of isoprene and monoterpenes from present day land cover with elevated CO₂

416

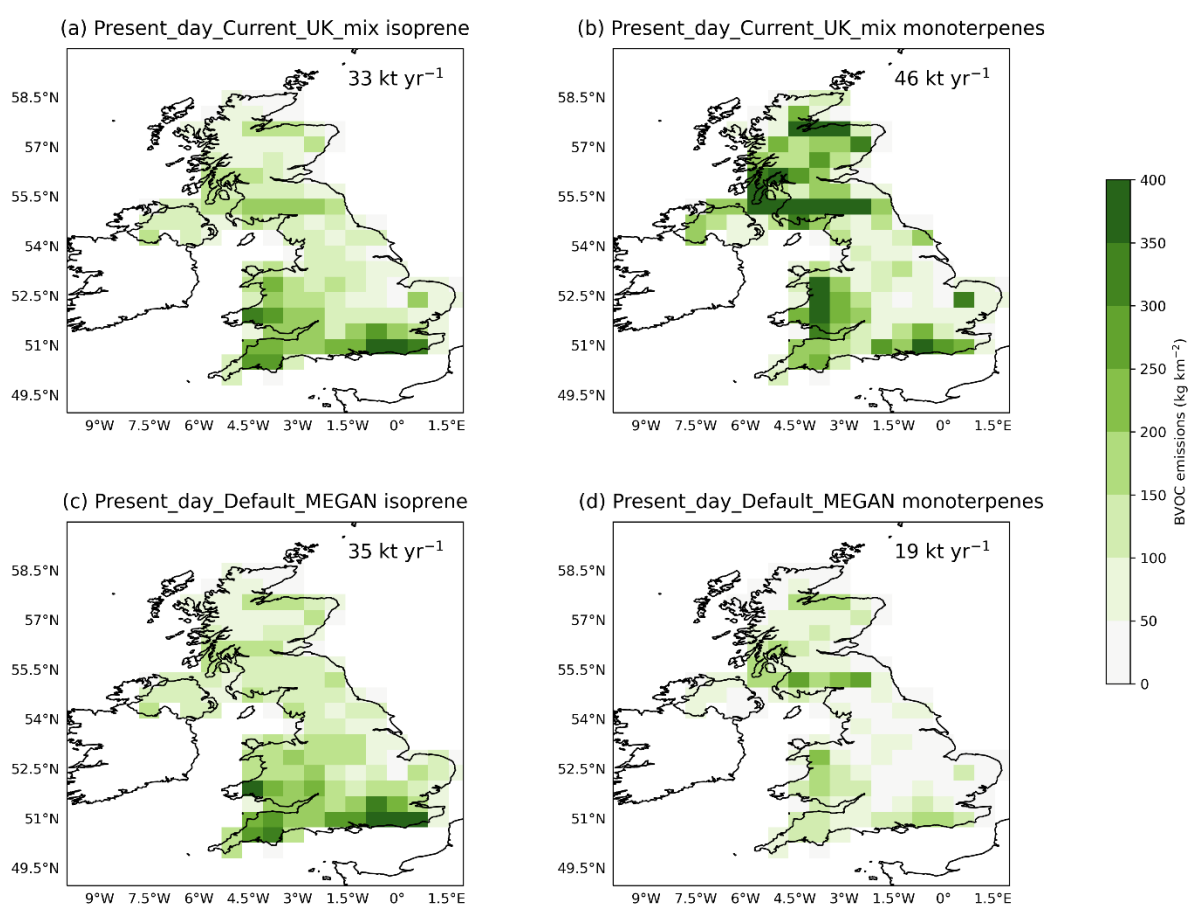
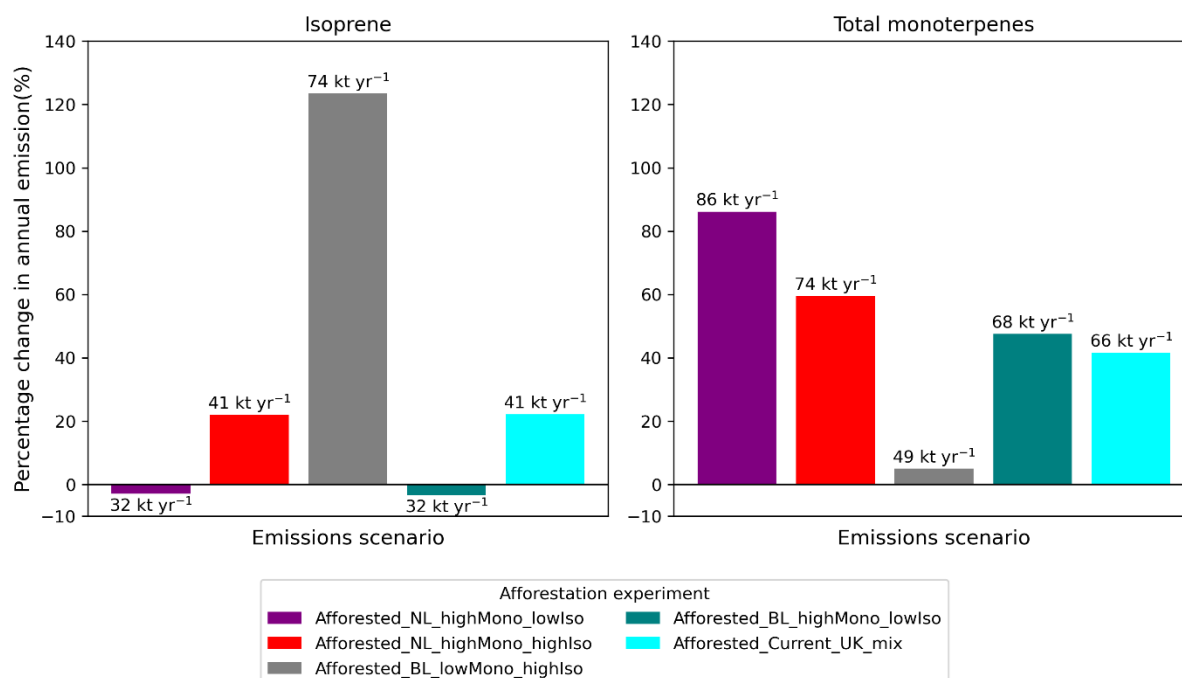



Figure 7. Modelled distribution of emissions of isoprene (kg km^{-2}) and total monoterpene (kg km^{-2}) from present day UK land cover. Figures 7a and 7b show the emissions generated from the Present_day_UK_appropriate_mix experiment. Figures 7c and 7d show the emissions generated with the Present_day_Default_MEGAN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

417 3.3 Estimating BVOC emissions attributed to UK afforestation

418 Figure 8 illustrates the percentage change in annual UK emissions of isoprene and total monoterpenes
419 across the five afforestation experiments relative to present day land cover. All experiments ~~here~~
420 ~~use~~used to estimate percentage change in emissions use elevated CO_2 as projected for 2050, therefore
421 all percentage changes in emissions are attributed to afforestation alone. Modelled estimates of total
422 annual UK emissions of isoprene and total monoterpene compound classes are given in the text
423 overlay. Values of percentage change in annual UK emissions and total annual estimates are also
424 summarised in Table 5.

Percentage change in annual emissions of isoprene and total monoterpenes following afforestation

425

426 *Figure 8. Percentage change in modelled annual UK emissions of isoprene and total monoterpene following afforestation to*
427 *19% woodland cover for five afforestation experiments: Afforested_BL_lowMono_highIso, Afforested_BL_highMono_lowIso,*
428 *Afforested_NL_highMono_lowIso, Afforested_NL_highMono_highIso and Afforested_Current_UK_mix as detailed in Table 6.*
429 *The total annual UK emissions of isoprene and total monoterpenes of each experiment are given in the text overlay. The*
430 *percentage change reported here is relative to our Present_day_Current_UK_mix experiment, with the change attributed to*
431 *the different in forest cover (all experiments using elevated CO_2 at 500 ppm).*

432 In all scenarios, the larger increases in emissions are concentrated in Scotland (see Supplementary Fig.
433 S3 and S4 for maps of percentage change in emissions, due to the scale of planting introduced there
434 relative to the other UK nations (Table 1). The greatest increase in isoprene was observed in the
435 experiment *Afforested_BL_lowMono_highIso*, where individual grid cells experienced up to a 250%
436 increase in emissions, and total emissions increased by 123%. In experiments
437 *Afforested_BL_highMono_lowIso* and *Afforested NL_highMono_lowIso*, the replacement of grassland
438 with tree cover results in a reduction of isoprene emissions, of -3%, and as much as -50% on an
439 individual grid cell level. This is attributed to the lower emission factors applied to tree PFTs relative
440 to those representing grass PFTs. The adaptations to prepare bespoke UK appropriate emissions
441 potential values were not also made for non-tree PFTs. Therefore, our study may not present the best
442 possible representation of UK non-tree PFTs, and so the decline in emissions attributed to
443 replacement of grassland with woodland may not accurately reflect the case of UK grasses. The
444 potential change in BVOC emissions from afforestation would vary with the type of land cover
445 replaced, bringing some uncertainty to the direction of change in emissions in the future. However,
446 similar outcomes were found by Purser et al., (2023) where afforestation was focused on short

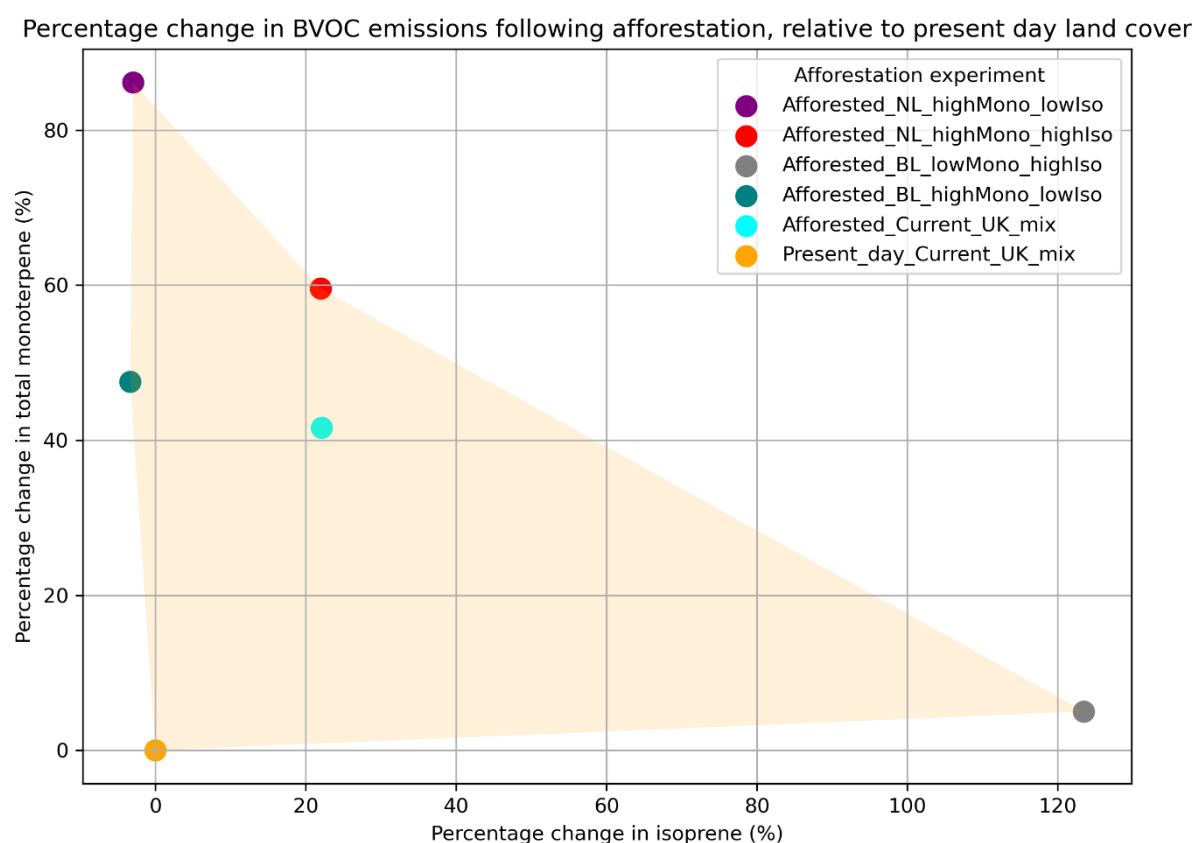
447 rotation forestry, with a decline in isoprene emissions of 14% when examining the impact of large-
448 scale planting of alder. In Fig. 8, we see an increase in monoterpene emissions under all scenarios. The
449 greatest changes are observed in the *Afforested_NL_highMono_lowIso* scenario where some grid cells
450 experience an increase above 250%, and total monoterpene emissions increased by 86%. Experiments
451 *Afforested_NL_highMono_highIso*, *Afforested_BL_highMono_lowIso* and
452 *Afforested_Current_UK_mix* demonstrate moderate increases in monoterpene emissions, between 42
453 and 60%. The smallest change in monoterpene emissions is observed in our
454 *Afforested_BL_lowMono_highIso* experiment, where a 5% increase is simulated.
455
456 Our modelled estimates of isoprene emission for the UK with 19% woodland coverage vary between
457 32 kt yr^{-1} and 74 kt yr^{-1} across the experiments; modelled estimates of total monoterpene emission are
458 between 49 kt yr^{-1} and ~~87~~ 86 kt yr^{-1}. Overall, our results indicate that emission factors and tree species
459 mixture substantially change estimates of BVOC emissions from the UK's future forests.
460
461 Table 5. Modelled estimates of annual UK isoprene and total monoterpene emissions (thousand tonnes) and percentage
462 change (relative to Present_day_UK_appropriate mix) following afforestation to 19% woodland cover for five afforestation
463 experiments.

Afforestation experiment	Estimated annual emission (kt species yr^{-1})	
	Isoprene	Total monoterpenes
Afforested_Current_UK_mix	41 (+22%)	66 (+42%)
Afforested_BL_lowMono_highIso	74 (+123%)	49 (+5%)
Afforested_BL_highMono_lowIso	32 (-3%)	~~69~~ 68 (+~~47~~48%)
Afforested_NL_highMono_lowIso	32 (-3%)	~~87~~ 86 (+86%)
Afforested_NL_highMono_highIso	41 (+22%)	~~75~~74 (+60%)

464

465 To isolate the impact of afforestation, the BVOC emissions changes presented in Table 5 are all
466 calculated from pairs of simulations with elevated atmospheric CO_2 concentration. It should be noted
467 that in the absence of any additional woodlands in our simulations, CO_2 inhibition leads to a 15%
468 decrease in isoprene emissions from 39 kt yr^{-1} in our *Baseline* experiment to 33 kt yr^{-1} in our
469 *Present_day_Current_UK_mix* experiment. When comparing the emissions from our *Baseline*
470 experiment to our *Afforested_Current_UK_mix* experiment with additional woodland and elevated
471 CO_2 (41 kt yr^{-1}), we see only a 5% increase in isoprene emissions because the CO_2 inhibition effect
472 offsets a portion of the increase in emission due to additional woodlands.
473
474 Figure 9 illustrates the relationship between changes in isoprene and total monoterpene emissions
475 across the five afforestation experiments. With the combination of species mixtures examined, we
476 demonstrate the possibility for isoprene emission to be reduced whilst delivering ambitious
477 afforestation by 2050. However, in experiments where isoprene is reduced (by as much as -3%),
478 monoterpenes increase by at least ~~47~~48%. All experiments result in an increase in monoterpenes. This

reflects the fact that all afforestation scenarios include tree PFTs that are higher emitters of monoterpenes than the grassland that has been replaced. Our experiment *Afforested_BL_lowMono_highIso* demonstrates the potential to minimise the increase in monoterpenes, with an increase of just 5%, however this is estimated to deliver the most extreme change across all experiments in relation to isoprene, which increases by over 120%. Our experiments demonstrate the range of futures that net-zero aligned UK afforestation could deliver for BVOC emission from natural vegetation. 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). The range of UK tree species explored in our paper captures greater extremes in emission potentials for both monoterpenes and isoprene than Purser et al. (2023) and we therefore estimate that more substantial relative changes in emissions are possible. However, the scale of change also depends on the land cover, and therefore emissions, that have been replaced, contributing uncertainty to estimates of relative change.

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

503 estimated here (Guenther et al., 1993, 2012). In addition, the specific location of new woodlands which
504 is unknown is an additional source of uncertainty in BVOC emissions.

505 Further, estimates of BVOC emissions will be impacted by localised variations, such as tree health, leaf
506 area index, exposure to stress such as drought, and infestation with tree pests or disease. These
507 unknowns will further impact the overall change in emissions that are observed in the future from
508 increased woodland cover. ~~Future work should examine the sensitivity of these projections to~~
509 ~~extremes such as heatwave and drought episodes, which are expected to increase in frequency in~~
510 ~~future.~~ Comparing simulated concentrations from our emissions to observations would help to
511 understand the ability of the model to capture these sensitivities. ~~This would aid our understanding of~~
512 ~~the uncertainty in changes in emissions and how this may vary with climate futures.~~

513 Studies have demonstrated that models, including MEGAN, represent ~~to be unable to reproduce~~
514 ~~observed~~ emissions of isoprene during episodes of drought poorly, ~~with MEGAN~~ both underestimating
515 and over-estimating ~~isoprene~~ depending on the severity and longevity of drought episodes (Jiang et
516 al., 2018; Otu-Larbi et al., 2020; Potosnak et al., 2014; Seco et al., 2015). For example, using the
517 FORCAsT model Otu-Larbi et al., (2020) demonstrated isoprene emissions could be underestimated by
518 as much as 40% during a drought episode. Modifications to account for drought have been found to
519 reduce residuals between simulated and observed emissions of BVOCs when estimated using MEGAN.
520 ~~For example,~~ Jiang et al. (2018) found isoprene emissions could be as much as 17% lower when MEGAN
521 was modified to better capture the physiological effects of drought on emissions and Wang et al. (2022)
522 found that global total isoprene emissions simulated by the CLM reduced by 10-11% with a
523 representation of water stress based on wilting factors. ~~However, Otu-Larbi et al., (2020) demonstrated~~
524 ~~isoprene emissions could be underestimated by as much as 40% during the drought episode. Whilst~~
525 ~~changing the drought parameterisation used here would impact the absolute emissions of BVOCs~~
526 ~~estimated, the change in emissions associated with afforestation should be less sensitive to this.~~ We
527 quantify the sensitivity of our *Baseline* and *Afforested_Current_UK_mix* experiments to the algorithm
528 of Wang et al. (~~Wang et al.,~~2022). In both cases, total annual emissions of isoprene are reduced,
529 by~~etween~~ 0.81 kt yr^{-1} (-2%; (*Afforested_Current_UK_mix*) and 1.06 kt yr^{-1} (-2.74%; (*Baseline*) compared
530 to our original estimates. When we consider how the Wang et al., (2022)~~new~~ algorithm ~~for soil~~
531 ~~moisture~~ affects~~impacts~~ the change in ~~difference in annual emissions by the year 2050 relative to our~~
532 ~~present-day forest scenario, the difference in~~ emissions due to afforestation and an increase in
533 atmospheric CO_2 concentration (for this particular pair of experiments), we find that it increases in
534 magnitude from 1.99 kt yr^{-1} (5.14%) to 2.24 kt yr^{-1} (5.95%; Supplementary Table S2). ~~With the original~~
535 ~~algorithm of Guenther et al., (2012)~~This suggests that despite the overall impact of the algorithm being
536 a lowering of isoprene emissions in individual scenarios, the emissions changes we present in Table 5
537 could all be slightly higher with the updated algorithm.

538 Two of our experiments (*Afforested_NL_highMono_lowIso* and *Afforested_BL_highMono_lowIso*)
539 suggest that a reduction in isoprene emissions is possible with an increase in woodland cover of around
540 50% (or 6% absolute additional woodland cover), when the increase is achieved through planting of
541 either broadleaf or needleleaf species. This is attributed to the lower isoprene emission factors applied
542 to tree PFTs in these experiments than those of the land cover that was replaced.

543

544 4. Conclusion
545 This study presents, for the first-time, estimates of BVOC emissions that are consistent with net-zero
546 aligned afforestation in the UK using tree species suitability information coupled with regionally
547 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 39 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. The Royal Society report 'Effects of Net-Zero Polices and Climate Change on Air Quality' noted planting high BVOC emitting tree species as part of net-zero policies as one of several areas of concern for trade-offs between climate change mitigation and air quality (The Royal Society, 2021). Our experiments illustrate the potential to minimise the increase of specific BVOC emissions whilst delivering net-zero aligned afforestation through species selection. Our results show that under elevated atmospheric CO_2 concentration, and in a warmer and drier climate, afforestation leads to changes in UK emissions of isoprene ~~vary~~ between -3% and 123%, and between 5% and 86% for total monoterpene emissions, with the outcome depending on the species mixtures selected for planting. However, limiting the increase in one type of BVOC (e.g. isoprene) appears to correlate with greater increase in others (e.g. monoterpenes) as shown in Figure 9. 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 assume~~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.

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

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

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

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597 NE/S007458/1 and NE/S015396/1].**

598 Competing interests:
599 At the time of initial submission, Piers M Forster ~~i~~was the interim~~current~~ C~~c~~hair of the UK's Climate
600 Change Committee. All other authors have no competing interests to declare.

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