Response to reviewer comments and summary of changes for manuscript: “Future Forests: estimating biogenic emissions from net-zero aligned afforestation pathways in the UK” by Mooney et al.

Referee #1:

Comment 1.1

This manuscript presents the modelling results of the changes in BVOC emissions from UK afforestation. It is an interesting research topic considering the roles of BVOCs in atmospheric composition and net-zero emission actions. My main struggle with this paper is about the method design.

Author response to comment 1.1

We thank the referees for their comments and for taking the time to carefully review the work submitted. We thank the editor for the opportunity to respond to these comments, which enables us add necessary details to justify the approach taken and how it relates to the intention and scope of this manuscript. We have done our best to address the concerns below. Where we are unable to address the comments directly in our revisions, we note our intentions for responding to the recommendations through ongoing and future work that follows.

Comment 1.2

First, the authors chose to estimate BVOC emissions from CLM with the embedded MEGAN model. To fit into the CLM or climate data resolution, the model ran at very coarse spatial resolution; many higher resolution inputs (emission factor, leaf area index, etc) have to be averaged, or species distribution data have to be lumped, which can bring large uncertainties to the emission estimations. There are a lot of higher resolutions of climate data, which are sufficient to run the MEGAN model alone to get much higher-resolution estimations of emissions.

Author response to comment 1.2

The resolution of modelling in this study is appropriate for the aim of the paper, which is to estimate the change in the total emission of BVOCs over the UK that would result from afforestation equivalent to planting 50,000 hectares of new woodland every year until 2050. Our study aims to estimate the overall change in emissions from an aspirational 19% UK tree cover, compared to the existing 13% UK tree cover, and to highlight the range of possible emission changes when different species mixtures are planted. Whilst we want to assess the impact of an increase in tree cover on BVOC emissions at national scale, we specifically did not want to prescribe exact locations for the new woodlands as this is a complex ecological and societal issue.

We chose to use the Community Land Model in order to simulate the impacts of afforestation in a more integrated way than can be achieved by running the MEGAN algorithm offline. The use of CLM as a framework for running MEGAN ensures consistency between driving meteorology (temperature, precipitation) and key land surface parameters (e.g. soil moisture) that drive variability in BVOC emissions in MEGAN. The work presented in this paper forms part of a wider body of work that will explore the relationships between environmental conditions and BVOC emissions in the UK, and this requires the use of a land surface model. For this reason, the resolution of our study is aligned with the configurations most suitable for our use of the CLM. Our simulations are preceded by a 30-year spin-up period to ensure that the model reaches a state of equilibrium where the fluxes of carbon, water and energy are balanced, for each land cover configuration. The embedding of MEGANv2.1 in CLM is detailed in Guenther et a., (2012) and Lawrence et al., (2011). This approach means emissions estimations are mapped specifically to the PFT scheme of the CLM.

On species distribution data and perceived lumping: we do not have individual tree species distribution data available for use in the UK, rather we use higher resolution land cover data (the UKCEH land cover map at 1 km x 1 km) to inform the distribution and abundance of Plant Functional Types used by MEGAN and the CLM. Further, we improve the application of CLM and MEGAN to the UK by calculating new emissions factors for PFTs to represent the tree species suitable for the UK (those currently making up woodland cover, as well as those likely to be planted in the future) (as detailed in Section 2.4). The impact of this change can be seen in Figure 7 where we demonstrate the difference in emissions estimates between the default MEGAN set up (panels (c) and (d)) and when using our more UK appropriate emission factors (panels (a) and (b)). In our response to Referee 2 comment 2.4 we provide more detail on how these emissions factors are adapted to reflect the relative abundance of UK tree species.

Comment 1.3

I did not get the idea of choosing the CLM model, and there is no clear description of what variables from CLM (if any) were fed into the MEGAN

Author response to comment 1.3

We have addressed the first part of this comment in our response to Comment 1.2. Detail has been added to Section 2 at lines 128-131: 'To quantify the emissions of BVOCs from a range of afforestation experiments, we use the Community Land Model v4.5 (CLM) (Oleson et al., 2013), which has the algorithms of the Model of Emissions of Gases and Aerosols from Nature v2.1 (MEGAN) embedded to estimate emissions of BVOCs from the land surface as categorised by the PFT scheme of the CLM (Guenther et al., 1993, 2012)'.

Regarding how MEGAN uses CLM variables, when operating inside the CLM, MEGAN takes information about vegetation type and fraction (PFT), LAI and meteorological variables from the CLM. These are provided as input data when the CLM is operating offline. Within the CLM, these input variables are used to calculate leaf temperature, soil moisture, soil temperature and humidity. The CLM also calculates canopy variables, including the fraction of sunlit vs shaded leaves and the canopy environment coefficient. To calculate BVOC emissions, MEGAN uses leaf temperature, leaf age, soil moisture, solar radiation (for estimating Photosynthetic Photon Flux Density) and CO_2 concentrations (which are used to estimate CO_2 inhibition in isoprene) as well as the canopy environment coefficient provided by the CLM. This explanation is reflected in additional corrections made to Section 2 at lines 131-140. Emissions are estimated for 147 BVOCs, with emission factors assigned to 19 compound classes for each of the 16 PFTs used in the CLM. We have added these details to Section 2.4, at lines 276-279: 'Emission factors are combined with information on vegetation type and distribution (represented by PFTs), LAI, solar radiation and atmospheric CO_2 concentration and (calculated by the CLM) soil moisture, leaf age, leaf temperature and the canopy environment coefficient for calculating emissions in MEGAN.'.

Comment 1.4

I don't think making decisions based on these coarse resolution maps is so informative. With the coarse resolutions and grouped species, it is still unknown where to grow what species (due to grouped species) to increase or decrease certain BVOC emissions, and the resolution is way too coarse to estimate any air quality impacts.

Author response to comment 1.4

In lines 157-165, 188-190 and 460-464 we specifically state that the intention of this paper is not to suggest exactly where species should or should not be planted and we acknowledge the broader societal issues around tree planting locations and land cover change overall. Secondly, the purpose of the paper is not to make specific recommendations about where trees should be planted to mitigate any air quality side effects, but to provide a first estimate of the likely scale of change in BVOC emissions if the levels of woodland creation national governments in the UK are currently aspiring to are realised in 2050.

The spatial resolution of our calculated BVOC emissions is similar to that of emissions datasets commonly used for atmospheric chemistry and air quality modelling simulations (e.g. 0.5 x 0.5° ECLIPSE emissions: https://iiasa.ac.at/models-tools-data/global-emission-fields-of-air-pollutants-and-ghgs). We plan to use these emissions to investigate the impacts of changes in BVOC emission magnitudes on regional ozone and aerosol abundances across the UK, using regional modelling at a similar spatial scale. Our intention is not to resolve fine-scale local-scale air quality changes, since this would be highly dependent on the detailed distribution of tree planting associated with the afforestation scenarios, which is not the focus of our work (see response to Comment 1.2).

Further, we wish to stress that this is a nationwide study, and therefore there are tradeoffs between the spatial coverage and resolution of this work to ensure the overall experiments align with the research questions we wanted to address, which are UK wide.

Comment 1.5

Then, when converting grass to trees, the model should consider the removed emissions from grass as well.

Author response to comment 1.5

Our modelling framework means that when afforestation occurs, the increased area of forest PFTs in a grid cell is balanced by an equivalent reduction in the area of grass PFTs (for the UK in the CLM these are C3 grass and Arctic C3 grass). We discuss this at lines 374-378 where we comment on the fact that, in some of our afforestation experiments, grass PFTs have higher emission potentials than the forest PFTs we are replacing them with. This is also illustrated in Figures 8 and S3.

Comment 1.6

Lastly, it is unclear why the authors chose to run for one future year, i.e., 2050 and even used the meteorological conditions from 2003. The authors' argument for selecting the meteorological condition from 2003 was based on comparing the maximum 1.5 m air temperature. This does not seem correct to me, considering that temperature is not the only factor influencing BVOC emissions. The year-to-year meteorological variations will undoubtedly affect your current estimations; it does not make sense to only look at 1-year outputs.

Author response to comment 1.6

The referee is correct, that the justification for using 2003 as the year of meteorological data for these experiments was based on a comparison of observed and projected maximum 1.5 m air temperatures for the UK, and they are correct that temperature is not the only factor influencing BVOC emissions. However, the choice was based on a desire to examine a year which contained a comparable range of temperatures in the UK to those projected for the year 2050, when it is expected the UK government will have achieved the 19% tree cover modelled in our simulations. The year 2003 featured several heatwaves in the UK, including a major heatwave in early August, which has been studied in the literature for its impacts on pollutant formation, such as O_3. Using the year 2003 was based both on this opportunity to later consider how the emission of BVOCs during these extremes influences air quality (future work) but also on the alignment of 2003 temperatures with those projected for 2050. Our main objective was to capture the scale of change in BVOC emissions attributed to the increase in forest cover alone, under potential 2050 conditions. Which would be seen in simulations using other years of meteorological data. It is for this reason that only 1 year of output was examined in this study.

Referee #2

Comment 2.1

The paper by Mooney et al. attempts to quantify future BVOC emissions from different afforestation pathways in the UK. The paper is within the scope of the journal and presents interesting results in terms of air quality implications. However, a number of technical issues need to be addressed prior to potential publication.

Author response to comment 2.1

We thank the referees for their comments and for taking the time to carefully review the work submitted. We thank the editor for the opportunity to respond to these comments, which enables us add necessary details to justify the approach taken and how it relates to the intention and scope of this manuscript. We have done our best to address the concerns below.

Where we are unable to address the comments directly in our revisions, we note our intentions for responding to the recommendations through ongoing and future work that follows.

Comment 2.2

Uncertainty analysis. The authors discuss the effect of CO_2 in inhibiting isoprene emissions in the future, but completely lack a proper sensitivity study to account for projected heat and drought waves on future BVOC emissions, which in my opinion is a much more relevant factor for future emission scenarios. It has been shown in many recent studies that the peak of isoprene (and possibly other light-dependent emissions) is not correctly represented with the standard CLM parameterisations based on Megan v2.1 (e.g. Jiang et al., 2018: doi: 10.1016/j.atmosenv.2018.01.026, Seco et al., 2015, doi: 10.1111/gcb.12980, Potosnak et al., 2014: doi: 10.1016/j.atmosenv.2013.11.055; Kaser et al, 2022: doi: 10.5194/acp-22-5603-2022; Otu-Larbi et al., 2019: doi: 10.1111/gcb.14963; Wang et al., 2024: doi: 10.1038/s41467-024-49960-0). In particular, heat waves can increase (or decrease) BVOC emissions, depending on their duration, and are an important factor not considered in this study. Failure to account for this effect is a major shortcoming and makes future BVOC projections particularly questionable. The authors should provide an uncertainty assessment by using different parameterisations in their sensitivity runs to estimate the effect on their future projections.

Author response to comment 2.2

Thank you for raising this, we ourselves had recognised the need to consider the sensitivity of these estimates to the range of conditions which can impact BVOC emission rates. Namely, we recognise the particular sensitivity to drought and heatwaves as an area requiring further research. We mention in the manuscript our interest in the year 2003 due to the overlap with projected temperatures for 2050, as well as being interesting from the perspective of the historically significant heatwaves experienced in this year. In order to deal with this aspect with an appropriate degree of detail, we have a companion manuscript underway which investigates sensitivities to such variables before, during and after heatwave episodes. This is based on the experiments detailed in the submitted manuscript. Further, it is our intention to evaluate how simulated atmospheric concentrations of isoprene, resulting from our modelled emissions, compare to observational data; this will provide opportunity to comment on how well MEGAN is capturing emissions from UK trees during these episodes.

We appreciate your suggestion to provide an assessment of the impact that different parameterisations of the influence of drought on BVOCs could have for our estimates of total emissions. Given our study is considering the difference in BVOC emissions for a 2050 world based on changes in levels of tree cover, whist modifications to the drought sensitive algorithm in MEGAN would bring changes to the estimates of absolute emissions (e.g. Potosnak et al., 2014; Seco et al., 2015 and Jiang et al., 2018), the relative change in emissions between afforestation experiments is unlikely to change as much, with meteorology constant between scenarios.

To acknowledge the absence of detail regarding sensitivities, as well as limitations regarding the drought algorithm in the submitted abstract, we have added the following in Section 3.3 at lines 440-455: ‘Future work should examine the sensitivity of these projections to extremes such as heatwave and drought episodes, which are expected to increase in frequency in future. Comparing simulated concentrations from our emissions to observations would help to understand the ability of the model to capture these sensitivities. This would aid our understanding of the uncertainty in changes in emissions and how this may vary with climate futures. Studies have demonstrated MEGAN to be unable to reproduce observed emissions of isoprene during episodes of drought, with MEGAN both underestimating and over-estimating isoprene depending on the severity and longevity of drought episodes (e.g. Potosnak et al., 2014; Seco et al., 2015, Jiang et al., 2018; Otu-Larbi et al., 2020). Modifications to account for drought have been found to reduce residuals between simulated and observed emissions of BVOCs when estimated using MEGAN. For example, Jiang et al., (2018) found isoprene emissions could be as much as 17% lower when MEGAN was modified to better capture the physiological effects of drought on emissions. However, Otu-Larbi et al., (2020) demonstrated isoprene emissions could be underestimated by as much as 40% during the drought episode. Whilst changing the drought parameterisation used here would impact the absolute emissions of BVOCs estimated, the change in emissions associated with afforestation should be less sensitive to this.

Comment 2.3

Line 127cc: To quantify emissions a number of datasets are used including ambient concentration data. It is not explained further how, and to what extent these observations are used to validate and/or test the model results.

Author response to comment 2.3

Apologies that our description of use of these datasets was not clear. Datasets of meteorological data and atmospheric CO_2 are used as driving inputs into the CLM model and MEGAN BVOC emission algorithms. We provide more detail on this in our response to Referee comment 1.3. The meteorological dataset is based on reanalysis data (GSWPv3, Dirmeyer et al., 2006), which incorporates measurements to produce an observationally-constrained estimate of the meteorology for the modelled period. CO_2 concentration data is also derived from observational data, produced as part of the CMIP6 for the years 1750-2014.

Comment 2.4

Model setup: Can the authors be more concrete on the methodology to attribute species-specific emission potentials to PFTs for estimating the average emission potential using tree inventories for actual present day scenarios? The assumptions themselves may be valid, but they are simplifications with associated uncertainties. Quantifying these uncertainties is important to understand how much confidence to place in the conclusions.

Author response to comment 2.4

In order to estimate average emissions for present day scenarios, we searched for species-specific emissions potential data for tree species that make up a large proportion of present-day tree cover in the UK.

Information about the proportion of tree species in the UK was obtained from the Forest Research forestry statistics report referenced in line 205 (Forest Research, 2023). Based on this, we sought emissions potential data for 25 tree species from studies where emissions potentials were estimated for the UK, or Europe more generally. Our search returned emissions potential data for 10 broadleaf species and 6 needleleaf trees. For each species a varying number of data points were available, but for each species the mean value was calculated. The error bars shown in Figure 3 and Figure 4 capture the uncertainty of emissions potentials for the different tree species, displaying the minimum and maximum values obtained from the literature. The captions of Figure 3 and Figure 4 have been modified to clarify this. To then apply emissions potentials to the corresponding PFTs, a weighted mean was calculated. Specifically, data for the relative distribution of each of those species at present was used to calculate an average emissions potential for needleleaf and broadleaf PFTs for the UK. The tree species underpinning each are detailed in Table 3.

The application of UK-bespoke estimates for emissions potentials per PFT category are combined with improvements to land surface representation. We detail in section 2.1 the work undertaken to improve representation of UK land cover by regridding the 1 km x 1 km resolution UKCEH land cover map to the 0.47 ° x 0.63 ° resolution of our CLM configuration. This improved the distribution of the Broadleaf Deciduous and Needleleaf Evergreen trees in both boreal and temperate regions. This enables our quantification of the present-day emissions of BVOCs from the land surface. However, we do acknowledge in lines 390-394 the limitation of not also preparing UK-bespoke emissions potentials for non-tree PFTs.

Summary of changes:

The following changes to the manuscript have been made to address some of the comments above:

- Lines 128-131 (to address comment 1.3 and comment 1.4) - *'To quantify the emissions of BVOCs from a range of afforestation experiments, we use the Community Land Model v4.5 (CLM) (Oleson et al., 2013), which has the algorithms of the Model of Emissions of Gases and Aerosols from Nature v2.1 (MEGAN) embedded to estimate emissions of BVOCs from the land surface as categorised by the PFT scheme of the CLM (Guenther et al., 1993, 2012)'*.
- Lines 131-140 (to address comment 1.2 and 1.3) - *'When operating inside the CLM, MEGAN takes information about vegetation type and fraction (PFT), LAI and meteorological variables from the CLM. These are provided as input data when the CLM is operating offline. Within the CLM, these input variables are used to calculate leaf temperature, soil moisture, soil temperature and humidity. The CLM also calculates canopy variables, including the fraction of sunlit vs shaded leaves and the canopy environment coefficient. To calculate BVOC emissions, MEGAN uses leaf temperature, soil moisture, soil temperature, solar radiation and CO_2 concentrations (which are used to estimate CO_2 inhibition in isoprene) as well as the canopy environment coefficient provided by the CLM. Further, European, compound class specific BVOC emissions potential data and tree species distribution data were required.'*

Caption of Figure 3 and Figure 4 – added *'Error bars indicate the minimum and maximum values obtained from the literature.'*

- Lines 276-279 (to address comment 1.4) - ' Emission factors are combined with information on vegetation type and distribution (represented by PFTs), LAI, solar radiation and atmospheric CO_2 concentration and (calculated by the CLM) soil moisture, leaf age, leaf temperature and the canopy environment coefficient for calculating emissions in MEGAN'

- Lines 440-455 (to address comment 2.2) - ' Future work should examine the sensitivity of these projections to extremes such as heatwave and drought episodes, which are expected to increase in frequency in future. Comparing simulated concentrations from our emissions to observations would help to understand the ability of the model to capture these sensitivities. This would aid our understanding of the uncertainty in changes in emissions and how this may vary with climate futures. Studies have demonstrated MEGAN to be unable to reproduce observed emissions of isoprene during episodes of drought, with MEGAN both underestimating and over-estimating isoprene depending on the severity and longevity of drought episodes (e.g. Potosnak et al., 2014; Seco et al., 2015, Jiang et al., 2018; Otu-Larbi et al., 2020). Modifications to account for drought have been found to reduce residuals between simulated and observed emissions of BVOCs when estimated using MEGAN. For example, Jiang et al., (2018) found isoprene emissions could be as much as 17% lower when MEGAN was modified to better capture the physiological effects of drought on emissions. However, Otu-Larbi et al., (2020) demonstrated isoprene emissions could be underestimated by as much as 40% during the drought episode. Whilst changing the drought parameterisation used here would impact the absolute emissions of BVOCs estimated, the change in emissions associated with afforestation should be less sensitive to this.'.
- References have been added to reflect these additions, including Jiang et al., (2018 at lines 606-608, Otu-Larbti et al., (2020) at lines 652-655 and Seco et l., (2015) at lines 677-680.

In addition to changes made in response to reviewer comments, there are a number of changes made to the manuscript in response to one particular issue identified by the authors.

During the discussion phase for the submitted manuscript, we identified a mistake in how coastal grid cells were being dealt with by the land mask in our code. This had implications for our estimates of total emissions from each experiment. Emissions totals have been recalculated to account for the appropriate number of grid cells, and the correct fraction of land in these grid cells. The changes to values are minor (<5%) and do not impact the magnitude or direction of the changes reported. There is no impact on the messages presented in this manuscript. We have updated the following figures and lines of text to reflect the corrections detailed above:

- Lines 21-25 – '*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%. 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%.*'
- Figure 1 updated
- Line 328-329- *'We present an estimate of present-day UK annual isoprene emission of 39 kt yr^{-1} and total monoterpene emission of 46 kt yr^{-1}'*
- Figure 6 updated
- Lines 346-350 - *'Experiment Present_day_Current_UK_mix simulates isoprene emissions lower than our Baseline experiment, at 33 kt yr^{-1}, whilst emissions of total monoterpene are increased marginally, at 47 kt yr^{-1}. The decline of 10% in isoprene emissions can be attributed to the CO_2 inhibition effect on the rate of isoprene emission from trees.'*
- Lines 361-365 - *'Combined, these variations result in the small decrease of 5% in isoprene overall in our experiment (to 33 kt yr^{-1}) when emissions data is adapted to reflect UK tree species (Fig. 7).'*
- Figure 7 updated
- Figure 8 updated
- Line 387 - *'total emissions increased by 123%.'*
- Lines 387– 390 - *'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 -3%, and as much as -50% on an individual grid cell level.'*
- Lines 397-399 - *'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 86%.'*
- Lines 399 – 403 - *'Experiments Afforested_NL_highMono_highIso, Afforested_BL_highMono_lowIso and Afforested_Current_UK_mix demonstrate moderate increases in monoterpene emissions, between 42 and 60%. The smallest change in monoterpene emissions is observed in our Afforested_BL_lowMono_highIso experiment, where a 5% increase is simulated.'*
- Lines 405-407 - *'Our modelled estimates of isoprene emission for the UK with 19% woodland coverage vary between 32 kt yr^{-1} and 74 kt yr^{-1} across the experiments; modelled estimates of total monoterpene emission are between 49 kt yr^{-1} and 87 kt yr^{-1}.'*
- Table 5 values updated

- Lines 417-418 - *'However, in experiments where isoprene is reduced (by as much as -3%), monoterpenes increase by at least 47%.'*
- Lines 418-421 - *'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%.'*
- Figure 9 updated
- Lines 466-468 - *'We present a new estimate for present-day emissions of isoprene at 39 kt yr^{-1}, and 46 kt yr^{-1} for monoterpenes'*
- Lines 474-476 - *'Our experiments show that 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.'*
- Supplementary figure S3 and S4 updated.

Secondly, we have added a sentence to methods section 2.7 regarding the resultant level of afforestation delivered by our experiments, which is equivalent to 18.65% at the resolution presented in this work.

- Lines 317-320 - *'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.'*
- Table 4 has been updated to reflect this, with the 'Land data' column now specifying 18.65% afforestation, rather than 19%.