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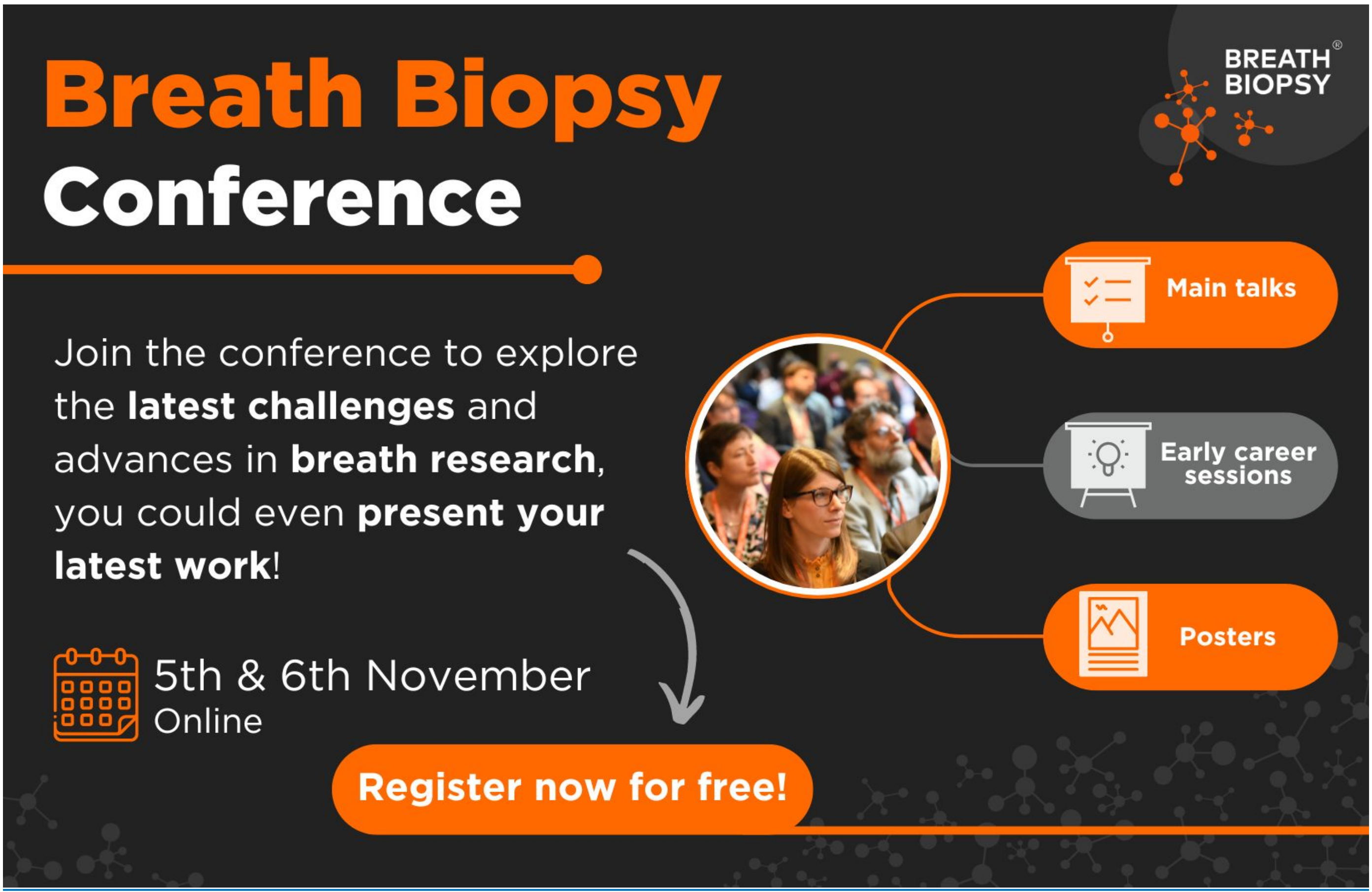

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LETTER

Hydrometeorological response to afforestation in the UK: findings from a kilometer-scale climate model

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Supplementary material for this article is available online

Abstract

Afforestation is of international interest for its positive benefits on carbon storage, ecology, and society, but its impacts on terrestrial and atmospheric processes are still poorly understood. This study presents the first use of a coupled land surface and convection permitting atmospheric model (CPM) to quantify hydrometeorological effects of afforestation across the United Kingdom, focusing on atmospheric processes often missing in hydrological models. Generating a scenario of 93 000 km^2 (40%) additional woodland across the UK, the periods of 2042–2052 and 2062–2072 are analysed. Simulated afforestation alters seasonal and regional UK hydrometeorology. Countrywide runoff increases in all seasons (between 5.4–11 mm and 4.3–8.6% per season) due to elevated subsurface flows from greater soil moisture. Evaporation decreases in summer (−20.6 mm, −10%) but increases in winter (8.1 mm, 15%) whereas rainfall increases throughout all seasons (between 2.2–6.86 mm and 0.9%–2.2% per season). Greater winter rainfall is detected along Great Britain's west coastline as increased surface roughness produces prolonged and heavier rainfall. In the summer, lower albedo increases potential evapotranspiration and reduces near surface specific humidity: water is locked in deeper soil layers as transpiration diminishes and the topsoil dries out. However, the magnitude of hydrometeorological change due to altered land cover is smaller than the uncertainty in local climate change projections. This work sets a precedent in illustrating the impacts of afforestation on hydrology using a high-resolution CPM and highlights the importance of coupled hydrometeorological processes when investigating land cover impacts on hydrological processes.

1. Introduction

Widespread afforestation is receiving growing international interest and could substantially change global land cover (Griscom *et al* 2017, Hawes 2018). Its proposed societal benefits include reducing atmospheric CO_2 and pollution (Bonan 2008, Forster *et al* 2021), improving biodiversity (Vanessa *et al* 2018), and mitigating floods (Carrick *et al* 2019). However, the ramifications of afforestation on the Earth system at large spatial scales are not entirely known related to their magnitude and direction of change.

It is not fully understood how afforestation influences the water cycle (Wang-Erlandsson *et al* 2018). Gaps exist between modelled and observed terrestrial impacts of afforestation (Andréassian 2004), especially when considering the hydrological consequences of using afforestation as natural flood management (NFM) (Dadson *et al* 2017, Lane 2017). Whether the benefits of NFM outweigh the water resource demand of widespread afforestation is undetermined (David *et al* 2012). Direct measurements of woodland on land surface processes (e.g. evaporative fluxes and streamflow) continue to educate us on how afforestation could influence energy

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and water fluxes (Marc and Robinson 2007, Osborne and Weedon 2021, Monger *et al* 2022). However, studies often take place over relatively small spatial scales (<50 km^2) using a paired catchment approach which compares process differences between afforested and unaltered land cover in similar catchments (Bosch and Hewlett 1982, Bathurst *et al* 2018). Many observational studies suggest afforestation reduces overall runoff, although its effects are more complex at the highest flows (Do *et al* 2017, Bathurst *et al* 2020). However, data driven analysis of afforestation consequences are difficult to extrapolate both in time and space due to the number of interacting dependent processes with nonstationary forcing, such as climate change (Slater *et al* 2021, Anderson *et al* 2022).

Conceptual and simple process-based models, used to explore larger spatial scales, broadly agree that afforestation reduces overall and peak streamflow (Bulygina *et al* 2013, Stratford *et al* 2017). These results however do not necessarily provide a full physically-based understanding of afforestation on hydrology, as observed (Soulsby *et al* 2017, Cooper *et al* 2021). Recently, process-based land surface models have been used to explore terrestrial consequences of countrywide land cover change (Blyth *et al* 2019, Ritchie *et al* 2019), and show afforestation generates complex hydrological responses (Buechel *et al* 2022, Zhang *et al* 2022). Those studies only consider terrestrial hydrology and thus intra-catchment afforestation impacts, consequently neglecting significant atmospheric feedbacks (Lacombe *et al* 2016, Meier *et al* 2021, Cui *et al* 2022). Therefore, it is essential to look beyond individual catchment boundaries to fully comprehend afforestation's impact on the water cycle.

Earth system models (ESMs) have illustrated the far reaching consequences of afforestation on atmospheric and ocean circulation (Breil *et al* 2020, Davin *et al* 2020, De Hertog *et al* 2022) but are limited by their coarse grid spacing and provision of continental-scale information, such as orography. These studies have shown widespread afforestation could alter precipitation patterns and energy partitioning at the Earth's surface. This work is the first to use a high spatial resolution (2.2 km) regional convection-permitting model (CPM), coupling the land and atmosphere, to assess the potential hydrometeorological consequences of widespread afforestation at a countrywide scale. We focus on the United Kingdom, which plans widespread afforestation and is considered an ideal location for European afforestation (Bastin *et al* 2019, Committee on Climate Change 2019). We focus on three main questions. Firstly, do the most extreme plausible afforestation scenarios significantly change hydrometeorological processes: rainfall, evaporation, and runoff? Existing work suggests significant changes in hydrology with widespread afforestation (e.g. Hoek van Dijke *et al* 2022), however further work is required to determine if this is reasonable. Secondly, we question whether significant regional patterns in hydrometeorological processes occur with afforestation, and whether terrestrial properties mediate this response. Previous work has shown afforestation impacts on meteorological processes over continental scales (e.g. Teuling *et al* 2017, Cerasoli *et al* 2021) but greater spatial granularity and model diversity is needed. Finally, we assess whether afforestation generates significant seasonal differences in hydrometeorological processes with increased woodland. This study will assess the hydrometeorological consequences of widespread afforestation within the UK and model sensitivity to land cover changes, whilst providing a base understanding of afforestation on the formation of convective rainfall, something previously parameterized in models (Fisher and Koven 2020, Blyth *et al* 2021).

2. Methods

2.1. Model

A CPM is run at a 2.2 km grid spacing and 60 s timestep for a model domain centred over the UK. The configuration is the same one used for the local CPM projections in the UK Climate Projections (UKCP18). Full details are provided by Kendon *et al* (2019), Keat *et al* (2021). Two model ensembles are used from the 12-model ensemble of UKCP18 in this study. Running at kilometer-scale enables a more detailed representation of the land surface than typically resolved in climate models, and convection is explicitly simulated rather than parameterized, which leads to significantly improved physical representation of precipitation extremes at an hourly scale (Kendon *et al* 2014, Prein *et al* 2015). No prior work investigating afforestation impact has used this model type. Lateral boundaries are forced by a regional climate model (RCM; 12 km spatial resolution) which is driven by a global climate model (GCM; 60 km spatial resolution) (Murphy *et al* 2019). Both the RCM and GCM are perturbed in their physical parameters. A variable resolution grid allows showers to grow before entering the CPM (Yongming *et al* 2013) and nesting in the RCM reduces precipitation biases compared to directly coupling with the GCM (Murphy *et al* 2019). The model is run with a 360 d calendar for the periods 2040–2060 and 2060–2080 using the RCP 8.5 transient projection. Although this scenario is potentially beyond what is considered plausible (Hausfather and Peters 2020), it allows identification of hydrological response to extreme climatological conditions.

The land surface scheme is JULES, the Joint UK Land Environment Simulator (Best *et al* 2011, Clark *et al* 2011a), in its regional land and atmospheric science configuration (detailed in Bush *et al* (2020), (2023)), but with three significant hydrological differences. One, Brooks and Corey (1964) soil hydraulics

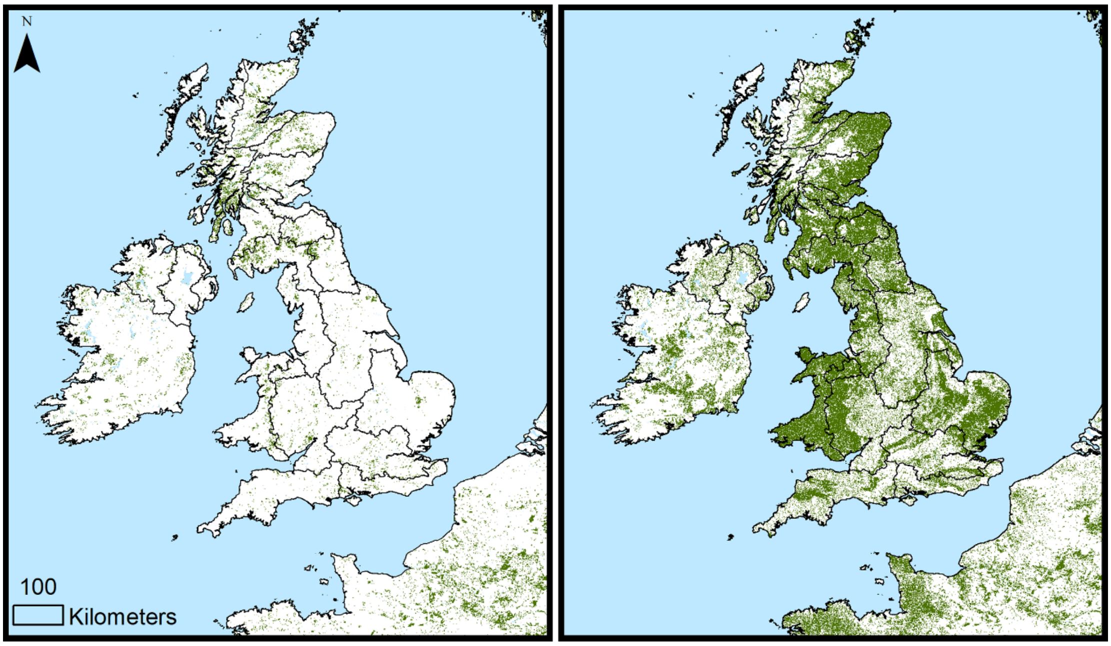

Figure 1. Maps illustrating the amount of land cover before (left) and after (right) afforestation. For the periods simulated, forest cover is the only variable that changes between the model runs. Green represents both broadleaf and needleleaf woodland. Disaggregation between the two species can be found in supplementary figure 1 and the areal increase in woodland in for each region in supplementary table 1.

are used, two, excess moisture is moved downwards in soil layers and finally, the rainfall-runoff model TOPMODEL is used (Clark and Gedney 2008). Soil hydraulic conductivity is derived from the fraction of silt, sand and clay. Landscape heterogeneity is represented using a surface tiling scheme within each grid box and independent water and energy fluxes are calculated for each tile, or land cover type. There are five plant functional types (PFTs): broadleaf and needleleaf trees, C3 and C4 grasses and shrubs; and four non-PFTs: urban, lake, bare soil, and ice. The Met Office Reading Urban Surface Exchange Scheme represents roofs and street canyons as two separate tiles (Porson *et al* 2010). Stomatal conductance is dependent on the humidity deficit and CO_2 concentration, which is related to plant type, and the availability of soil moisture (Cox *et al* 1998). If net photosynthesis is less than zero, or stomatal conductance is below a defined threshold, stomata close and conductance is set to the threshold. The two-stream radiation approach calculates direct and diffuse Photosynthetically Available Radiation at each of the ten layers specified within the canopy (Sellers 1985). Albedo is calculated for each PFT by using transmission and reflection coefficients in the visible and near-infrared regions for individual leaves and the leaf area index (LAI). LAI for each month and PFT is based on climatology between 2005–2009 and the MODIS LAI product (Murphy *et al* 2019, Wiltshire *et al* 2020). Although LAI is kept constant, stomatal conductance varies according to atmospheric and surface conditions. The surface has a sensible heat capacity and evaporation from the soil, water and transpiration combine to generate the surface latent heat fluxes. Energy and water fluxes are calculated in four soil layers with depths of 0.1, 0.25, 0.65 and 2 m. Underneath, there is a layer where drainage slows to form groundwater. Information on precipitation interaction with the canopy and soils is found in Buechel *et al* (2022).

2.2. Land cover scenarios

Three approaches have been taken to predict afforestation influence: model all available land as afforested (e.g. De Hertog *et al* 2022), use scenario-driven afforestation with models (e.g. Hoek van Dijke *et al* 2022), or extrapolate woodland observations (e.g. Schwaab *et al* 2020). To maximize the likelihood of detecting a signal, we use maximal proposed afforestation scenarios determined by the United Kingdom's individual nations: in England, the working with natural processes Environment Agency afforestation scenario (2018); in Wales, the woodland opportunity map created by the Welsh Government (2021); in Scotland, the land suitability map for woodland expansion (Sing and Aitkenhead 2020); and for Northern Ireland, afforestation extent is created using the method of Buechel *et al* (2024) (figure 1). Landcover fractions are constant for the baseline and afforestation scenarios.

Afforestation scenarios for continental Europe and Ireland in the model domain are also created. 50% of the afforestation area proposed by Bastin *et al* (2019) is randomly wooded for continental

Europe, acknowledging its potential over-ambition. In Ireland, an afforestation scenario is created based on Farrelly and Gallagher (2015). In reality, tree species planting is due to socio-economic, political and landowner choices (Sing *et al* 2018, Sutherland and Huttunen 2018, Brown 2020). Accurately modelling these factors is impossible considering the large uncertainty in future environmental and societal conditions. Only broadleaf and needleleaf woodland vegetation classifications are used and so nearest neighbour interpolation is utilized to expand similar species to those nearby, working on the principle woodland is locally similar which is preferable for ecological functioning (e.g. Hughes *et al* 2023). Seventeen land cover types from the Climate Change Initiative 2020 land cover map (ESA 2017) are converted to the nine modelled, and each land cover type is calculated as a fraction of each grid cell (Bush *et al* 2020). A total of 93 290 km^2 (c. 40%) additional woodland is generated across the UK (figure 1 and supplementary table 1). To note, this is an unrealistically large afforestation extent and ignores the hydrological effect of growing vegetation as all additional woodland is mature within the model domain.

2.3. Analysis

Analysis is disaggregated into the 23 UKCP18 hydro-regions and individual nations (figure 1) for two time periods, 2042–2052 and 2062–2072, to identify the response of individual hydrologically distinct areas to afforestation (Murphy *et al* 2019). The period chosen ensures water stores are equilibrated at the start of the period and there is a long enough period for analysis given computational resources. Each CPM period is driven by the same perturbed climatology RCM providing data for 40 years (two model ensembles of 20 years of data each).

Quantile regression (Koenker and Bassett 1978) is used to ascertain direction and magnitude of rainfall, evaporation and runoff changes across regions and countrywide for the overall time period, and seasonally. Quantile regression is nonparametric and minimally influenced by extreme outliers. Spearman's rank correlation coefficient quantifies the strength of association between afforestation extent and hydrometeorological variable changes. Weaker correlations (−0.5–0.5) indicate that regional properties have a greater influence than afforestation extent on simulated changes in hydrometeorology. A full set of the quantile regression and Spearman correlations can be found in supplementary tables 2 and 3. To determine if hydrometeorological alterations due to afforestation are statistically significant in time and space a Shapiro–Wilk test (Shapiro and Wilk 1965) is applied; if the data are normally distributed, a two-sided Student's t test is used, and if not, a Wilcoxon test.

3. Results

Afforesting the UK increases average rainfall between 2.19 and 6.86 mm (0.88%–2.24%) more per season (supplementary table 4). Comparing across regions the maximum average absolute rainfall increases by approximately 7 mm in winter and fall (figure 2). Rainfall increases along the west coast of Great Britain, particularly in winter (figure 3). In spring and winter, statistically significant increases in rainfall occur ($p < 0.025$, over 0.2 mm d^{-1} | 0.9%), but not for the rest of the year across the whole of the UK (figure 3). Decreases in precipitation are simulated in the east of Great Britain but are not statistically significant ($p > 0.025$). An insignificant correlation between afforestation and precipitation changes over the period, and for seasons, suggests that precipitation response to afforestation is not exactly co-located ($\rho = 0.15, p > 0.1$). Heavier rainfall occurs with afforestation as the western coastline of Great Britain has over 3 d of additional heavy rain days over a 10 year period (figure 4).

Afforestation substantially influences seasonal evaporative processes (figure 2). In the winter and fall, overall evaporation increases in the UK per season on average by 8.1 mm (15.6%) and 5.6 mm (6.5%) respectively, however in summer and spring it dramatically reduces by 20.6 mm (10%) and 4.9 mm (3.2%) (supplementary table 4). Soil evaporation, which includes transpiration, is the predominant driver of seasonal changes in overall evaporation (figure 5). Soil evaporation reduces by 0.11% for each PPI of woodland and the pattern is strong ($\rho = -0.75$, $p < 0.001$) across regions. Soil evaporation significantly increases in almost all regions across the UK in winter ($\rho = 0.91, p < 0.001$, 0.53% PPI), but decreases in summer ($\rho = -0.94$, $p < 0.001$, −0.28% PPI). Afforestation broadly increases overall canopy evaporation over the period with a 0.08% increase with each percentage point increase (PPI) of woodland ($\rho = 0.48, p < 0.025$). Winter has the largest increase in canopy evaporation of 0.13% ($\rho = 0.65, p < 0.01$), whereas spring has the least discernible trend with afforestation. Potential evapotranspiration effectively doubles with afforestation across all regions, all year ($\rho = 0.85$, $p < 0.001$, 2.44% PPI), with the largest absolute increase in summer (supplementary table 2). Soil moisture changes are predominantly driven by evaporation alterations with afforestation: decreased summer and spring evaporation increases absolute soil moisture, while winter and fall increases lead to a reduction.

Surface runoff has a strong seasonal directional change with afforestation (figure 5) but there are no significant regional changes across regions (figure 3). Surface runoff slightly increases in winter due to rainfall, but not significantly ($\rho = 0.4$, $p > 0.5$,

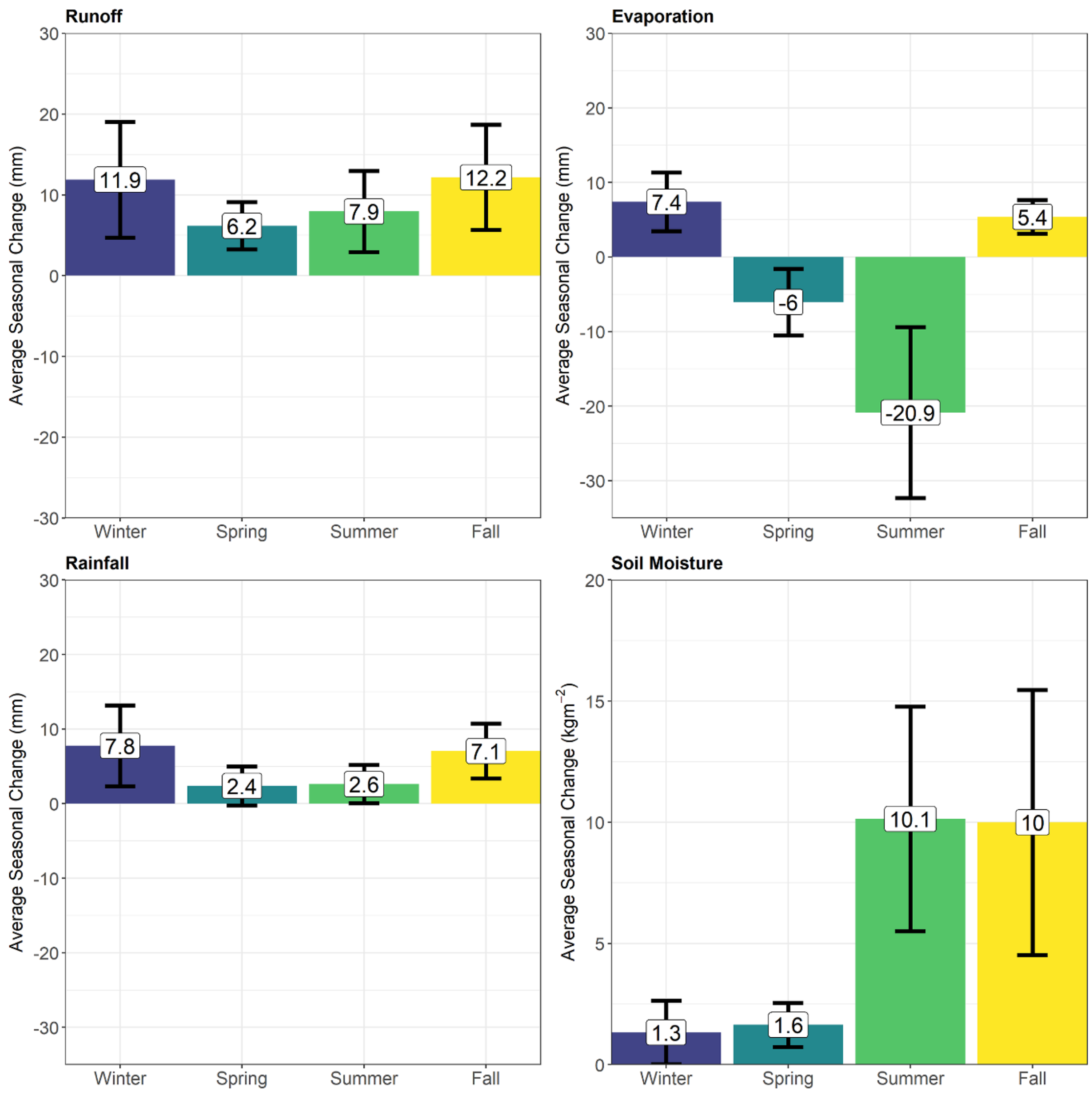

Figure 2. Average absolute change in rainfall, evaporation, runoff, and soil moisture following afforestation across the 23 regions for each season. Error bars represent one standard deviation from the mean. A corresponding plot as percentage change can be found as supplementary figure. These values are different to the averages reported for just the UK which can be found in supplementary table 4.

0.05% PPI), indicating strong regional variation in the increase. In summer, a clear reduction in surface runoff is attributable to afforestation with a drying of the topsoil ($\rho = -0.74$, $p < 0.001$, -0.14% PPI), however, changes are insignificant across regions. Subsurface runoff increases across the entire period and all regions with the most statistically significant increases observed on the western side of Great Britain and in Anglia for all seasons (figure 3). Overall, subsurface runoff increases by 0.15% PPI of afforestation ($\rho = 0.75$, $p < 0.001$) with the largest increases observed in summer months ($\rho = 0.87$, $p < 0.001$, 0.31% PPI) and the smallest in winter ($\rho = 0.5$, $p < 0.025$, 0.08% PPI) due to soil moisture.

4. Discussion

Widespread afforestation alters hydrometeorological processes across the UK. However, changes are strongly regional with noteworthy nearfield effects as a result of afforestation, unlike previous studies (e.g. Yue *et al* 2018, Teuling *et al* 2019). Greater winter rainfall in the west of Great Britain is simulated with afforestation (figure 4), due to increased roughness length, humidity, and temperature (figure 6). Indeed, wind speeds predominantly decrease up to the first 3 km of the atmosphere with additional woodland (supplementary figure 5). Winter fronts and convective showers advect inland from the sea, and the orography and roughness of the western coastline stalls their progress travelling along the westerlies within the CPM (Berthou *et al* 2020, Kendon *et al* 2020). Woodland enhances the sea-land roughness contrast further, likely slowing the progressing systems (Belušić *et al* 2019). Additional woodland also decreases the land snow-free albedo, increasing surface temperatures and potential evapotranspiration (supplementary figures 6 and 7) (*cf* Quentin

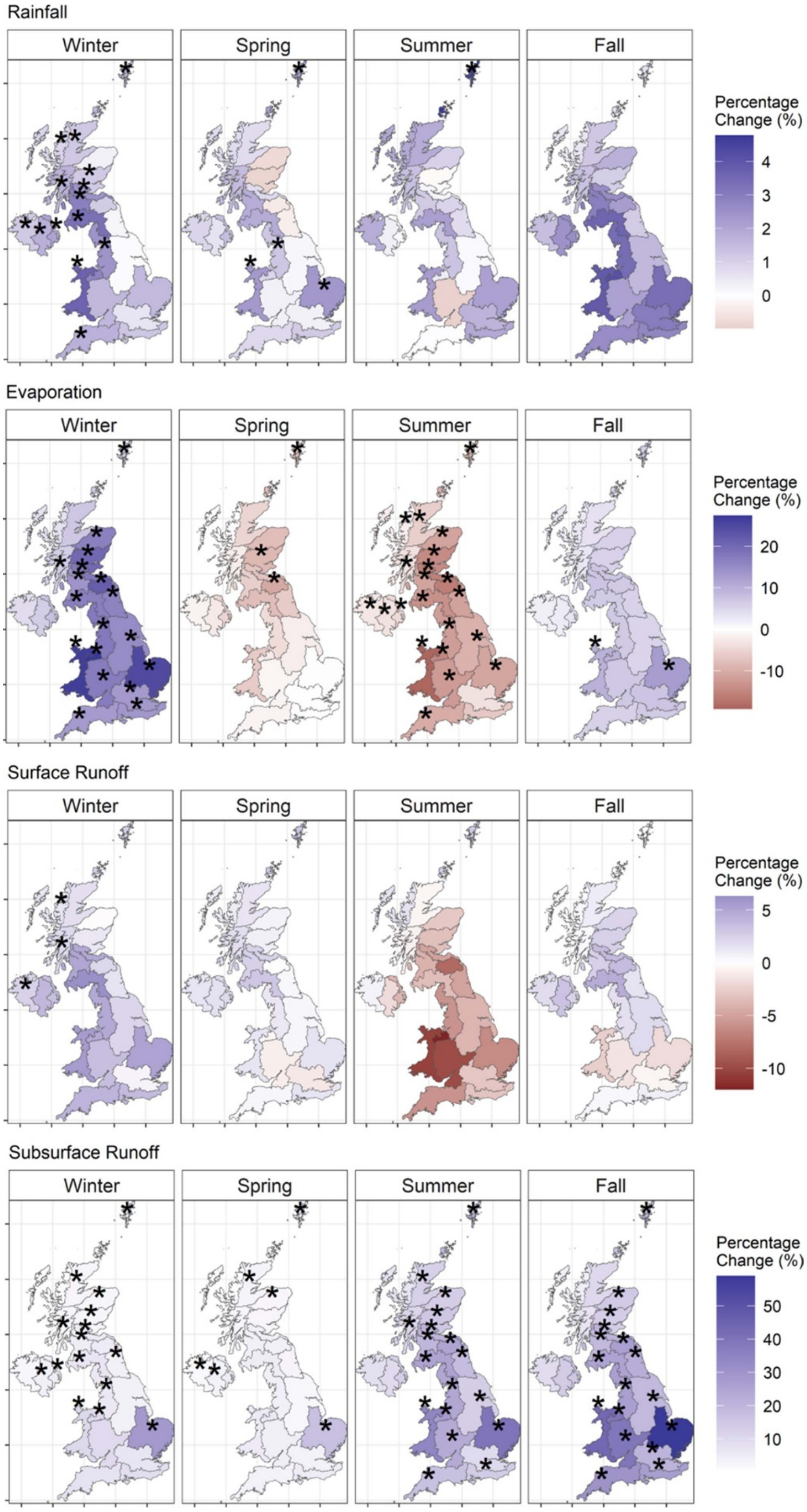

Figure 3. Percentage change in rainfall, evaporation, surface and subsurface runoff following afforestation for each season. The stars represent regions where the change is significant ($p < 0.025$). Supplementary figure 3 shows this as absolute changes. To note, hydrometeorological changes at a gridcell level are more complex than illustrated above and can be seen with the online repository and supplementary figures 16–18.

et al 2017, Cerasoli *et al* 2021). Transpiration and soil evaporation rise, enhancing atmospheric moisture as tree roots access deeper soil moisture stores compared to shorter vegetation. Larger soil moisture stores are available from summer and fall periods (discussed later) (figure 2). Canopy evaporation continues to be elevated providing further atmospheric moisture (figure 5). Higher temperatures and humidity provide conditions more favourable to intense and larger rainfall events with increased air buoyancy and

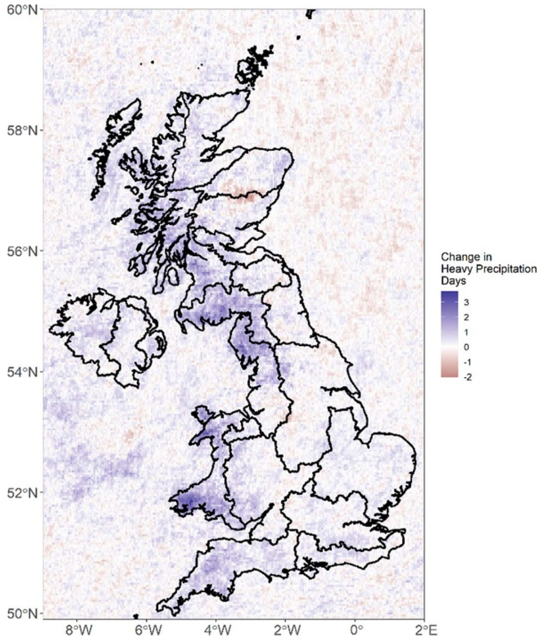

Figure 4. Average increase in the number of days where precipitation is greater than 20 mm for the 20 year period across all run scenarios. Supplementary figure 4 indicates the average number of days with heavy precipitation disaggregated across regions.

instability (illustrated by moist static energy (supplementary figure 8)). Higher winter humidity promotes increased transpiration due to the reduced humidity deficit (Cox *et al* 1998). These factors combine to increase cloud cover (and total overall cloud liquid volume) over afforested regions for the first few kilometres (supplementary figure 9). A slight rain shadow effect is detectable on the northeast side of the UK, although not significant (figure 3), and so precipitation does not significantly increase downstream of westerlies. Increases in winter turnover rate suggest hydrological cycle intensification in afforested regions (supplementary figure 10). Thus, although afforestation is being used as a measure to mitigate climate extremes, it could make rainfall-driven climate change impacts worse with increased flooding events. Enhanced rainfall and antecedent soil moisture (from the summer) elevates surface and subsurface runoff, which would increase streamflow. During winter, absolute soil moisture reduces with increased evaporation and runoff, providing the conditions for hydrometeorological process changes which occur in the summer (figure 2).

In summer, rainfall, evaporation, and runoff function differently with afforestation compared to winter (figure 6). Topsoil moisture decreases, whereas the lower soil column becomes increasingly saturated (aided by reduced drainage promoted to form groundwater table) (supplementary figure 11). Reduced topsoil moisture is likely due to over-drying, caused by the large increase in potential evapotranspiration. An increase in the 1.5 m temperature decreases relative humidity (supplementary figure 12), and combined with lowered soil evaporation, reinforces the transpiration reduction by increasing the humidity deficit (−1.64% in specific humidity across the UK in summer) (Cox *et al* 1998). As topsoil moisture decreases, surface runoff and soil evaporation reduce. Reduced topsoil moisture further decreases transpiration due to the soil root mechanisms in JULES (Best *et al* 2011), particularly with grass roots accessing any available moisture in the topsoil. As summer continues, subsurface runoff gradually increases with rising absolute soil moisture lower in the column (figure 5). In winter, overall soil moisture stores are diminished as additional precipitation saturates the soil which increases runoff (figure 5). However, this UKCP18 RCP 8.5 scenario is at the upper limit of temperature plausibility (Hausfather and Peters 2020) and thus feedbacks may be over-exaggerated. The distribution of soil moisture within the soil column aids an increase in the Bowen Ratio (supplementary figure 12). If this is the case, the hydrological implementation is directly influencing energy balances meaning greater attention is needed to ensure accurate hydrological results (Clark *et al* 2011b, 2016). To note, the increase in soil moisture could be due to the configuration of soil moisture routing implemented in this model configuration (Bush *et al* 2020, 2023). Formation of lower-level clouds (supplementary figure 9) do not appear to counteract the influence of decreased albedo with afforestation on temperatures (e.g. Cerasoli *et al* 2021). In summer, RCMs exhibit divergent temperature and evaporative fraction changes with afforestation, which has been attributed to land surface model parameterizations (Quentin *et al* 2017, Davin *et al* 2020), such as root distributions and soil water uptake

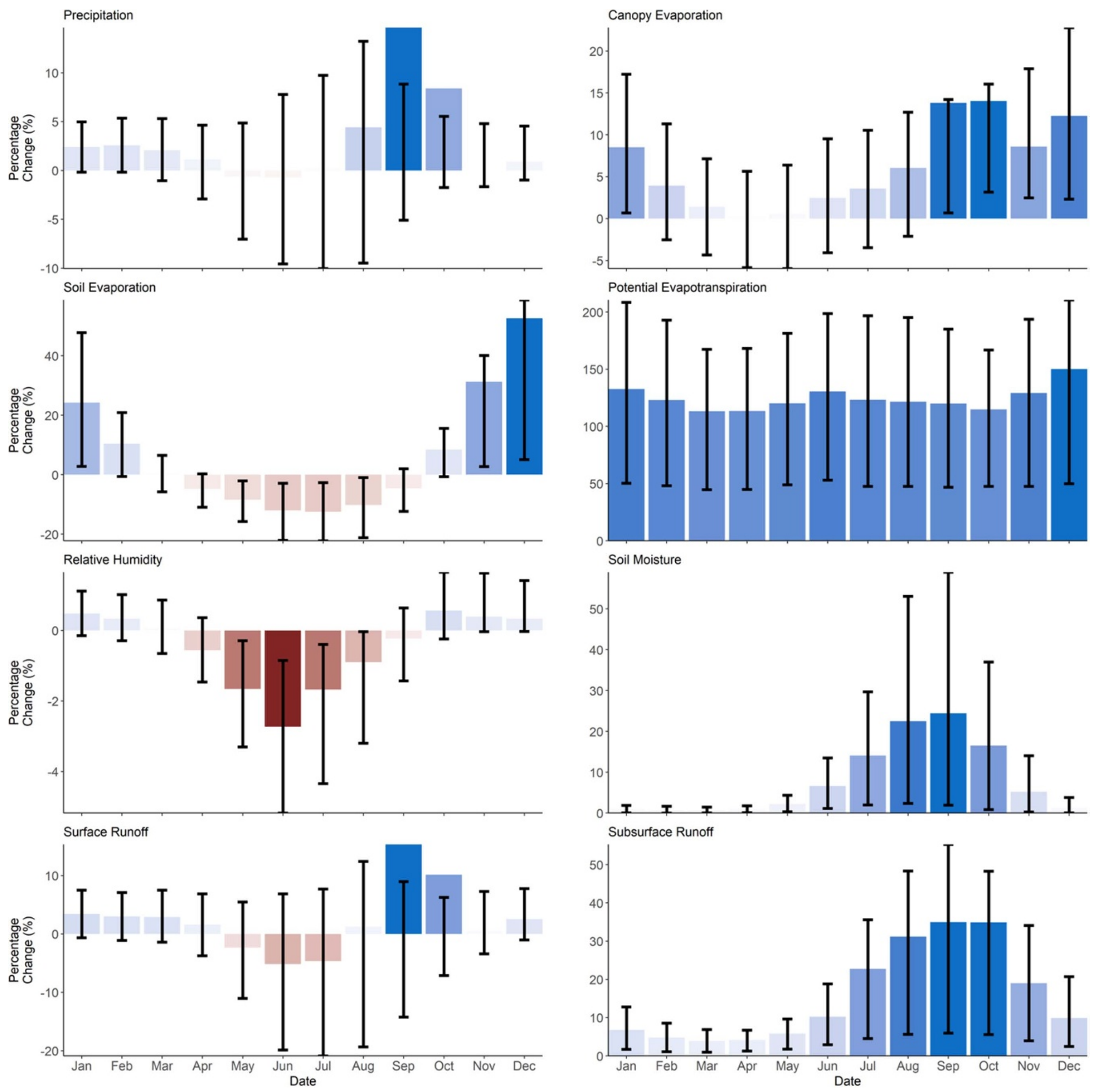

Figure 5. Percentage changes in hydrometeorological processes (precipitation, canopy and soil evaporation, potential evapotranspiration, relative humidity, soil moisture, surface, and subsurface runoff) for the 20 year period for all regions with afforestation. Error bars represent the 10th and 90th percentiles for the 23 regions. Supplementary figure 13 provides the figure as absolute changes.

formulas (Meier *et al* 2018). In this setup, stomatal conductance is the primary driver of transpiration change. Changing the root depth, and including lateral subsurface flows, or including more accurate plant hydraulics would enable more accurate calculation of evaporation (Chang *et al* 2018, Harper *et al* 2021, Picourlat *et al* 2022) and may alter our results by enabling plants to access deeper and locally adjacent soil moisture.

Compared to winter, there is not a similar summer precipitation increase, and regional differences occur. Woodland reduces wind speed, however, humidity, soil evaporation and transpiration decreases. The lessened atmospheric moisture contributes to the reduced rainfall in summer and exemplified by the turnover ratio decline (supplementary figure 10). Decreases in relative humidity are driven by summer increases in temperature and reductions in soil evaporation due to the reduced albedo and greater sensible heat fluxes (supplementary figures 7 and 14). These temperature increases would also be detrimental to human life, particularly in a climate scenario where temperatures are expected to be elevated. Summer temperatures increases are not seen in winter due to larger latent and reduced sensible heat fluxes. Some inland regions receive intense summer precipitation, and this leads to the divergence in the mean precipitation across regions observed in figure 5.

Despite the large areal coverage of afforestation undertaken here, not all hydrometeorological processes changed comparatively. For example, surface runoff changes were minimal compared to land cover changes. However, there were significant changes in radiative fluxes, demonstrated by the significant decrease in albedo (supplementary figure 7)

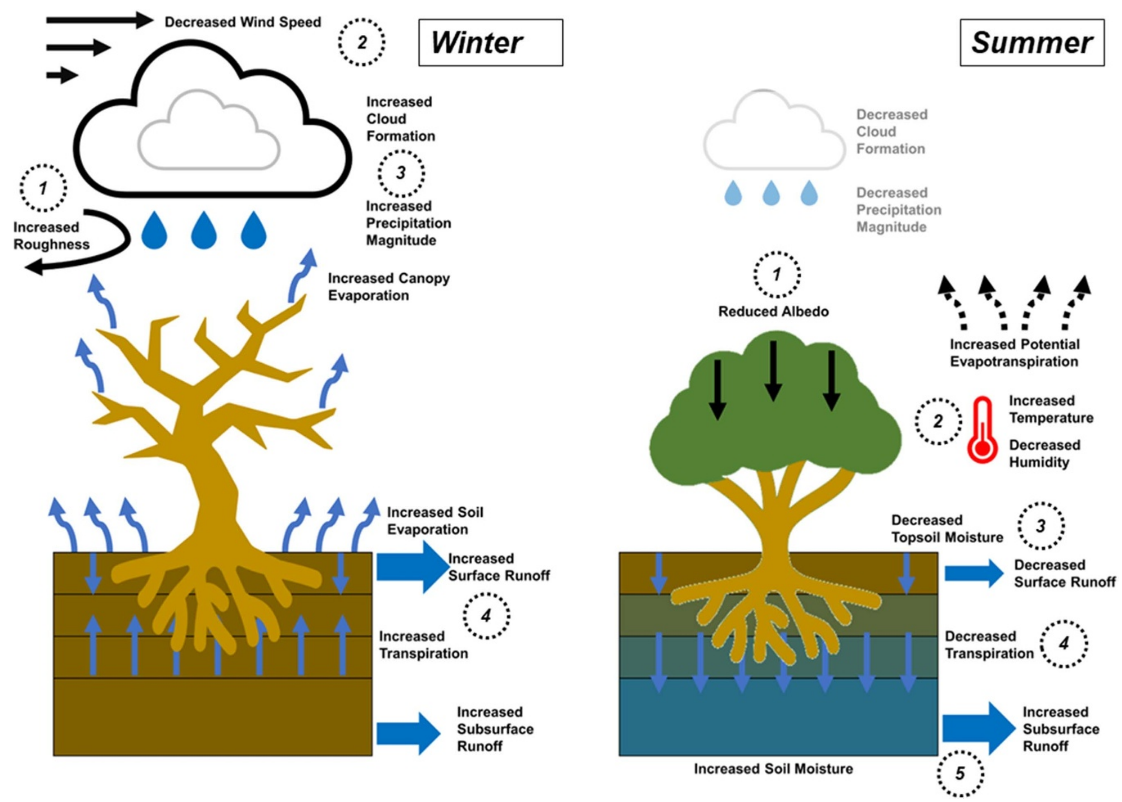

Figure 6. Conceptual diagram of the hydrometeorological changes that occur on average with afforestation in winter and summer. In winter, (1) the increased roughness length of woodland (2) decreases wind speed, which (3) stalls convective cells and leads to increased precipitation and (4) generates increased surface runoff. In summer, woodland (1) decreases albedo that (2) increases temperatures, reduces relative humidity, and increases potential evapotranspiration. This (4) over-dries the topsoil and results in (4) reduced transpiration and stomatal closure (along with reduced humidity). The root profile parameterizations (5) increase soil moisture deeper in the column and enhance subsurface runoff. In some regions, summer precipitation decreases, but it is not significant and thus is shown muted.

and increase in potential evapotranspiration for the entire period (figure 5). When compared to projected changes in climate, afforestation is of minor importance. For the period 2060–2080 compared to 1981–2000, precipitation is projected to decrease over the entire UK between 46% and 16% in summer, whilst increasing between 16% and 43% in winter across the UKCP18 model ensemble. The relatively small range of rainfall changes induced by widespread afforestation in this study (−1%–4% across regions) indicate the relatively minor role of significant land cover changes in altering predominant climate atmospheric signals. This emphasizes the potential difficulty in attributing hydrometeorological changes to land cover in a nonstationary climate. However weak the signal may be, the afforestation response of rainfall, runoff and evaporation is the same across different model ensembles and periods (i.e. no statistical difference based on ANOVA tests; $p > 0.1$), further emphasizing these results are not an artefact of model internal variability. While an estimate of the model internal variability could better quantify this, estimating it would require additional CPM simulations given part of the variability in the UKC18 ensemble arises from perturbed parameters in its driving models.

A coupled land-atmosphere model reveals the noticeable feedback between vegetation and the atmosphere. This approach dynamically calculates evaporation and rainfall according to land surface processes. Previous hydrological work evaluating afforestation impacts on terrestrial hydrology with fixed forcing indicated that vegetation parameterization generates similar responses where increased LAI reduces throughfall, increases the canopy store, and increased transpiration, reduces streamflow (Stratford *et al* 2017, Buechel *et al* 2022). However, in this study, afforestation, particularly in western regions, increases throughfall because of more intense winter precipitation. Thus, epistemic uncertainty caused by not including relevant processes within hydrological models completely reverses intended benefits, particularly as increased precipitation with afforestation (and decrease with deforestation) has been observed before (Staal *et al* 2020, Cerasoli *et al* 2021). Furthermore, although canopy evaporation was relatively heightened, with increased surface temperatures and canopy store, the magnitude of change is so minimal it cannot counteract precipitation and soil evaporation changes. The clear impact on hydrological and atmospheric processes with afforestation means continued effort is required to improve ESM representation to ensure hydrometeorological outputs are given for the right reasons (Beven 2007).

This work has shown the novel application of a CPM to determine the impact of afforestation on hydrometeorological processes. However, future work should explore and compare these results to other CPMs to determine how land surface components, such as the hydrological parameterizations, alter hydrometeorology, similar to CMIP5 (Quentin *et al* 2017). Radiative balance changes with afforestation are due to tree parameterizations and so need to be accurate for predicting climate. Caveats to note are excessive evaporation generated by JULES (Blyth *et al* 2019), inaccurate rooting profile representation (Harper *et al* 2021), and the lack of an accurate representation of groundwater (Vine *et al* 2016). The limited number of tree species and stand age would also significantly impact calculated evapotranspiration (Bentley and Coomes 2020). Using this model from a hydrological perspective illustrates the epistemic uncertainty of determining the impacts of largescale land cover change when using simple terrestrial hydrological models which lack critical biophysical parameterizations. It also reveals that the current practice of driving hydrological models with atmospheric outputs is a somewhat circular endeavour, as the hydrological models originally embedded within RCMs will have left their mark by imprinting processes into the energy and water fluxes.

5. Conclusion

This work demonstrates the impacts afforestation could have on hydrometeorology by using a novel regional convective-permitting model. Seasonal and regional differences exist in how afforestation alters hydrometeorology within the UK, particularly in western regions of Great Britain. In winter, the increased roughness length of woodland stalls convective cells and fronts from the sea, which are then very slightly enhanced by increased moisture and temperature inland (e.g. Belušić *et al* 2019). In summer, changes in precipitation are not significant but reduced albedo diminishes transpiration and elevates soil moisture in deeper soil layers. Greater soil moisture produces larger subsurface runoff. Soil evaporation greatly varies with season and is the predominant driver of hydrometeorological changes. Broad increases in evaporation align with other research investigating the hydrometeorological impact of afforestation in Europe (Meier *et al* 2021, van Dijke *et al* 2022) but contrast in spring and summer. Despite vast increases in woodland, the impacts on hydrometeorology are insignificant when compared to uncertainties in climate projections. This work illustrates that although coupled systems are not as sensitive to land cover changes as to driving atmospheric forces in this geographical setting, they can produce very different results to uncoupled systems. The partitioning of energy influences evaporative and precipitation rates induced by land cover changes, and thus alternative model setups are likely to produce differing results (Quentin *et al* 2017). Our afforestation scenarios suggest the UK would become a slightly wetter place and further work should compare results with other modelling approaches.

Data availability statement

Due to model output size, requests must be made to the Met Office to determine appropriate methods of data sharing. Data can be accessed on the JASMIN CEDA service from Met Office MASS archive: https://help.jasmin.ac.uk/article/228-how-to-apply-for-mass-access. Suite numbers for afforestation scenarios are mi-bd601, mi-bd602, mi-bd603 and mi-bd604. Unprocessed base gridcell maps of the simulated hydrometeorological response can be found at: https://doi.org/10.5281/zenodo.8402609 and some are included as supplementary figures 16–18.

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Author contributions

MB generated afforestation scenarios (with help from SB), analyzed model output, and wrote the manuscript. M B, S D, H L and S B conceived the project. WK ran the model simulations. S B, L S, S D, H L and W K all edited the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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