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Terrestrial carbon sequestration under future climate, nutrient and land use change and management scenarios: a national-scale UK case study

Dmitry Yumashev[1], Victoria Janes-Bassett[1,2], John W Redhead[3], Ed C Rowe[4] and Jessica Davies[1,*]

[1] Lancaster Environment Centre, Lancaster University, Lancaster, United Kingdom
[2] Department of Geography and Planning, University of Liverpool, Liverpool, United Kingdom
[3] UK Centre for Ecology and Hydrology, Wallingford, United Kingdom
[4] UK Centre for Ecology and Hydrology, Bangor, United Kingdom
[*] Author to whom any correspondence should be addressed.

E-mail: jess.davies@lancaster.ac.uk

Abstract

Carbon sequestration (C_{seq}) in soils and plant biomass is viewed as an important means of mitigating climate change. Recent global assessments have estimated considerable potential for terrestrial C_{seq}, but generally lack sensitivity to climate warming, nutrient limitations and perspective on local land use. These are important factors since higher temperatures can accelerate the decomposition of soil organic matter, nutrient availability affects plant productivity, while land use pressures put broader constraints on terrestrial organic matter inputs and storage. Here, we explore the potential for C_{seq} under changing land use, climate and nutrient conditions in a UK-based national scale case study. We apply an integrated terrestrial C–N–P cycle model with representative ranges of high-resolution climate and land use scenarios to estimate C_{seq} potential across the UK. If realistic UK targets for grassland restoration and afforestation over the next 30 years are met, we estimate that an additional 120 TgC could be sequestered by 2100 (similar to current annual UK greenhouse gas emissions or roughly 7% of net emission cuts needed in meeting net zero), conditional on climate change of <2 °C. Conversely, we estimate that UK arable expansion would reduce terrestrial carbon storage by a similar magnitude. The most pessimistic climate trajectories are predicted to cause net losses in UK soil carbon storage under all land use scenarios. Warmer climates substantially reduce the potential total terrestrial carbon storage gains offered by afforestation and grassland restoration. We conclude that although concerted land use change could make an important moderate contribution to national level C_{seq} for countries like the UK, soil C_{seq} only provides a contribution if we are on a low emission pathway, and is therefore conditional on deep global cuts to emissions from fossil fuels, deforestation and soil degradation.

1. Introduction

Growing evidence and understanding of the adverse impacts of climate change [1–6] have intensified calls for ambitious global climate mitigation efforts across all sectors, in line with the Paris Agreement [7, 8]. Whilst deep decarbonisation across many sectors, including energy and transport, is critical [9–16], limiting global warming to the 1.5 °C or even the 2 °C Paris Agreement target also requires the deployment of negative emissions technologies and strategies [9, 17–19].

Anthropogenic land use change and management are responsible for around a quarter of global annual green house gas (GHG) emissions [1, 20]. Growing populations and wealth per capita are driving up demand for food, clothes and other land-based commodities, leading to widespread conversions of natural lands to croplands and pastures [21, 22], the intensification of agriculture [23, 24] and large

associated emissions of CO_2, methane and N_2O. The same land use pressures are also driving major biodiversity losses, which are, in turn, exacerbated by climate change [4]. Ecosystems that provide multiple essential services to humanity are now in danger of being irreversibly damaged by the joint impacts of land use and climate change [25, 26].

Nature-based climate solutions have received much attention in the literature [27–32] because of their potential to remove carbon from the atmosphere and their ability to reduce or even reverse major adverse impacts of our intensive use of land, including deforestation, peatland degradation, soil erosion, depletion and pollution of water resources, and biodiversity losses [4, 21, 33]. The most prominent nature-based negative emission solutions on land are afforestation/reforestation, soil carbon sequestration, and biomass for energy with carbon capture and storage. Multiple national and global assessments of the feasibility and theoretical limits of such solutions have been carried out recently [28, 31, 34–39].

However, concerns have been raised regarding the practical limits of terrestrial carbon sequestration and potential negative impacts [16, 40–49]. The feasibility of carbon sequestration in soils in particular has been questioned following the announcement of the 4 per 1000 initiative during United National Famework Convention on Climate Change Conference of the Parties (COP21), and the subsequent technical potential assessments for multiple countries [36]. Soils are thought to have finite additional carbon storage capacity, and increments can be reversed due to changes in land use and climate [31, 40, 50–54]. Similar concerns apply to biomass accumulation through afforestation [32]. This means that land cover (LC) conversions and management practices known to increase soil and biomass carbon need to be analysed carefully for each location and consider antecedent conditions [43, 55].

Estimates of potential carbon uptake by soils and biomass on land have mainly been scaled-up to global levels based on empirical site-specific evaluations for each action, coupled with geospatial data on applicability. Antecedent conditions, and the future impacts of climate change and other changing environmental drivers cannot be considered in this kind of approach. Dynamic, process-based modelling can help address these shortcomings. Process-based biogeochemical models, when combined with climate and land use change scenarios, can help explore the potential for land-based carbon sequestration or losses, considering past conditions and the multiple drivers of future change.

Here, we take a process-based modelling approach to exploring carbon sequestration potential in plant biomass and soils under joint future pressures from climate, land use and nutrient change, using the UK as a national-scale case study. To achieve this, we use the integrated terrestrial biogeochemical cycle model, N14CP [56–58], which has been previously tested and applied across the UK using historic climate and land use data [59], and add spatially explicit high-resolution United Kingdom Climate Projections (UKCP18) climate scenarios [60], ASSET land use change scenarios [61, 62], and atmospheric N deposition (NDep) scenarios [63].

This national-scale process-based modelling approach to exploring terrestrial carbon sequestration potential has three main merits. Firstly, it aligns with climate commitments, environmental policies and technical feasibility studies that are frequently made at the national-level [30, 64–69]. Secondly, national-scale analyses can make use of finer spatial resolution, place-specific scenario data. National-scale climate projections, like UKCP18, provide potential changes in temperature and precipitation at a finer scale of resolution in comparison to global scenarios, and are more in line with the scale of spatial heterogeneity in land use and management. The ASSIST Scenario Exporation Tool (ASSET) land use and management scenarios used here were developed with stakeholders to reflect national priorities, as well as local biogeochemical, ecological and socio-economic land use change constraints. Thirdly, process-based modelling at this scale allows for the consideration of how climate and land use drivers interact with other drivers of nutrient change [70]. The N14CP model integrates carbon, nitrogen and phosphorus cycles across natural and agricultural land uses [59, 69], allowing the effects of atmospheric NDep, fertilizer additions and N or P limitations on carbon stores to be considered [63]. While perturbations to both N and P cycles are known to affect net primary productivity and plant-soil processes in both natural and agricultural environments [56, 58, 71–78], these important factors are not included in most published global assessments of both historic and future changes in terrestrial carbon [21, 38, 39, 45, 46, 78–81]. Such assessments tend to be based on dynamic global vegetation models (DGVMs). These models do not currently include the P cycle, and the N cycle has been added to a subset of DGVMs only recently [82, 83]. Hence, this study provides novel integrated insights into the potential effects of climate change, land use and management, and nutrient cycles on terrestrial carbon sequestration at a scale suitable for informing national and sub-national decision making on climate change mitigation, land use, agriculture and environment.

2. Data and methods

2.1. The N14CP plant-soil biogeochemical model
The N14CP model is a state-of-the-art dynamic process-based soil biogeochemistry model which integrates C, N and P cycles [61–63; supplementary methods]. N14CP enables long-term coupled simulations of soil and biomass using widely available

data, and has been robustly tested using soil data from 150 sites with varied land use history across Northern Europe, including several long-term agricultural experiments. It has been blind-tested spatially against UK plant biomass and soil carbon survey data [56–59]. The model includes all major UK LC types and transitions between them and allows for the simulation of agricultural land management practices, atmospheric deposition of N driven by human activities, and temperature and precipitation conditions. It simulates a range of C, N, and P plant and soil stocks and flows. Here, we focus on those outputs that form the terrestrial organic carbon (OC) storage: total biomass (both above- and below-ground), topsoil (upper 15 cm of soil); and subsoil (below 15 cm).

N14CP uses a quarterly timestep (Q1 = January; February; March, etc.), providing a compromise between capturing seasonal biogeochemical process variation and allowing long-term simulations. Plant net primary productivity is based on a combination of temperature, water, N and P limitations, while organic matter inputs from plants into soil are modelled using measured characteristic carbon residence times for a range of plant types [56]. The model does not account for plant response to increased atmospheric CO_2 concentrations. While several modelling studies have estimated that rising CO_2 has substantially altered global carbon cycling in recent decades (e.g. [84–86].), these analyses often neglect nutrient constraints and drivers. Other studies suggest that CO_2 fertilisation may have a more limited effect in the long run due to nutrient constraints in many regions including the UK [75, 82, 83], in addition to increasing prevalence of temperature stresses and droughts [87, 88]. Climate-driven changes in photosynthetically active radiation (PAR) are also excluded from N14CP due to high uncertainties in future cloud cover [1].

For the purposes of this study, N14CP has been adapted to run with the ASSET land use change scenarios and UKCP18 climate scenarios (below). An historic model run for the period from the start of the Holocene interglacial (−12 kyr Before Present) to 2015 (as described in [59]) is used to provide an initial condition for the scenario runs, which span 2016–2100 (supplementary methods). The model is run on a regular 5 km Ordnance Survey National Grid for the UK, with a further division into sub-grid fractions according to both historic, present-day and projected future LC and management types (see supplementary methods for more detail). There is a total of ∼80 000 fractions at present, based on the 25 m raster from the 2007 CEH Land Cover map [89] and other historic records such as the Dudley Stamp 1 km land use inventory from 1930s [63]. The number of fractions increases to ∼100 000 under some land use change scenarios.

2.2. Scenarios

We employ four broad types of scenarios (table 1): LC, arable management (MNG), climate Representative Concentration Pathways (RCP), and atmospheric NDep. These are assumed to be independent from one another, which is supported by pan-European studies indicating that local socio-economic drivers in the individual countries have a bigger impact on their land use change [90–92] and atmospheric NDep [93] than global climate and socio-economic pathways. Using land use and climate scenarios as separate independent inputs, however, neglects biophysical feedbacks that occur between land and the climate system, for example changes to albedo as a results of LC change.

LC and arable management scenarios adopted here are based on the ASSET 2.0 tool with a 1 km resolution [61, 62]. They are constructed using a multi-objective optimisation algorithm from the InVEST scenario generator tool [94], and account for historic land conversion patterns in the UK, potential directions of travel in terms of land use change, as well as spatial distributions of biogeochemical, ecological and socio-economic constraints to land use change. The afforestation pathways from ASSET 2.0 focus on creation of forests for climatic and wider environmental benefits (e.g. landscape connectivity, biodiversity), and exclude expansion of forestry solely for commercial, bioenergy and agroforestry purposes. We do not consider scenarios involving restoration of damaged peatland soils [34] and exclude urban expansion [95]. Consideration of the former would require detailed hydrological process representation that is difficult to achieve at this spatiotemporal scale. While urban expansion in the UK is likely over the time period considered, the effects of urbanisation on terrestrial carbon stores and cycles are currently uncertain [96] and likely highly heterogeneous, depending on development and management practices at much smaller scales. Although ASSET 2.0 scenarios include grassland management pathways, we use constant stocking densities in line with present-day conditions for improved grassland areas and assume that biomass removal and redistribution effects of animals on rough grasslands with low stocking densities are negligible.

The UKCP18 probabilistic monthly temperature and precipitation projections [60] are derived for a 25 km UK grid using 100+ perturbed parameter ensemble simulations of the HadGEM3-GC3.05 global climate model, combined with an ensemble of other (structurally different) CMIP5 climate models and the latest observational data. We use UKCP18 ensemble means and introduce additional bias-corrections for quarterly mean temperature and precipitation in each 5 km N14CP grid cell based on the CRU TS4.00 reanalysis dataset [97]. Although

Table 1. Scenario names and brief descriptions. For further details see supplementary methods. GMST stands for global mean surface temperature. CMIP5 is climate model inter-comparison project, phase 5.

| Scenario Name	Description
Land Cover (LC) change scenarios, ASSET 2.0	
LC_+Ara	Further arable expansion
LC_+Ara_Aff	Arable expansion coupled with afforestation
LC_Aff	Afforestation on its own
LC_+Gra_Aff	Semi-natural grassland restoration coupled with afforestation
LC_+Gra	Semi-natural grassland restoration on its own
Arable Management (MNG) scenarios, ASSET 2.0	
MNG_Ara_Cereal+	Switching to cereal-dominated cropping patterns
MNG_Ara_Diversify	Diverse cropping patterns with longer rotations
MNG_Ara_Extensify	Extensive cropping patterns with grass leys and fallow years
MNG_Ara_Extensify+	Extensive cropping plus organic fertilisers and no tillage
Climate (RCP) scenarios, UKCP18	
RCP2.6	GMST anomaly of ~1.6 °C in 2081–2100 (Coupled Model Intercomparison Project 5 (CMIP5) ensemble mean)
RCP4.5	GMST anomaly of ~2.4 °C in 2081–2100 (CMIP5 ensemble mean)
RCP6.0	GMST anomaly of ~2.8 °C in 2081–2100 (CMIP5 ensemble mean)
RCP8.5	GMST anomaly of ~4.3 °C in 2081–2100 (CMIP5 ensemble mean)
Atmospheric N deposition (NDep) scenarios, relative to recent trend [63]	
NDep_Medium	Linear extrapolation of current decline trend out to 2100
NDep_High	Current decline trend until 2030, constant level afterwards
NDep_Low	Current decline trend until 2030, double the rate of decline afterwards

bias-corrected on the same 5 km grid as N14CP, it should be noted that the use of a 25 km climate product neglects climatic changes that occur on a more localised scale, and this, in turn, could lead to some flattening of the simulated spatiotemporal variability in terrestrial carbon simulation results. Atmospheric NDep scenarios out to 2100 are defined relative to the declining trends from the past decade, which were calculated individually for each 5 km grid cell [63].

3. Results

Timeseries estimates of UK-wide topsoil, subsoil and biomass OC pools out to 2100 under the LC, MNG, and NDep scenarios, assuming a RCP2.6 climate, are illustrated in figure 1. For reference, baseline simulations where the present-day LC and MNG conditions are held constant and the medium NDep scenario is used are also provided (grey lines), along with the effect of climate scenarios other than RCP2.6 on this baseline (thin dashed lines, with bigger deviations from the grey lines corresponding to progressively warmer climates). The LC scenarios have the biggest effect on national topsoil and biomass carbon stocks (figure 1(a)), with the highest levels of carbon accumulation achieved through grassland restoration coupled with afforestation. Arable expansion, in contrast, leads to considerable declines in topsoil and biomass carbon. As expected, topsoil and biomass carbon pools respond differently to various combinations of afforestation with arable

expansion or grassland restoration. Subsoil shows a slower response to LC changes. In comparison, arable management changes (MNG) affect topsoil and subsoil, but have negligible effect on total UK biomass (figure 1(b)). The magnitude of the topsoil effects from the MNG scenarios is several times lower than that for the LC scenarios considered. Variations in future NDep (figure 1(c)), in turn, affect topsoil and biomass carbon accumulation at the national scale, but have a smaller effect on subsoil carbon over the timescale examined. This behaviour is similar to LC scenarios, although the magnitude of the effect is several times smaller. For the range of scenarios considered, the effect of NDep changes on topsoil carbon is smaller than that of climate change and arable management changes. Higher NDep levels lead to larger carbon accumulations, in line with earlier studies that focus on historic responses to N pollution [59, 63, 98].

Figure 2 illustrates the spatial variations in total (topsoil + subsoil) soil carbon stocks per unit area under contrasting climate scenarios (RCP2.6 vs. RCP8.5) and contrasting LC pathways (baseline vs. grassland restoration with afforestation vs. arable expansion), assuming present-day arable management baseline. Present-day soil carbon stock per unit area is given in figure 2(a) for reference, while maps (b) to (g) in figure 2 show changes between present-day conditions and 2100 under different scenario combinations. In the +2 °C world scenario (RCP2.6), grassland restoration with afforestation (figure 2(d)) leads to soil carbon accumulations
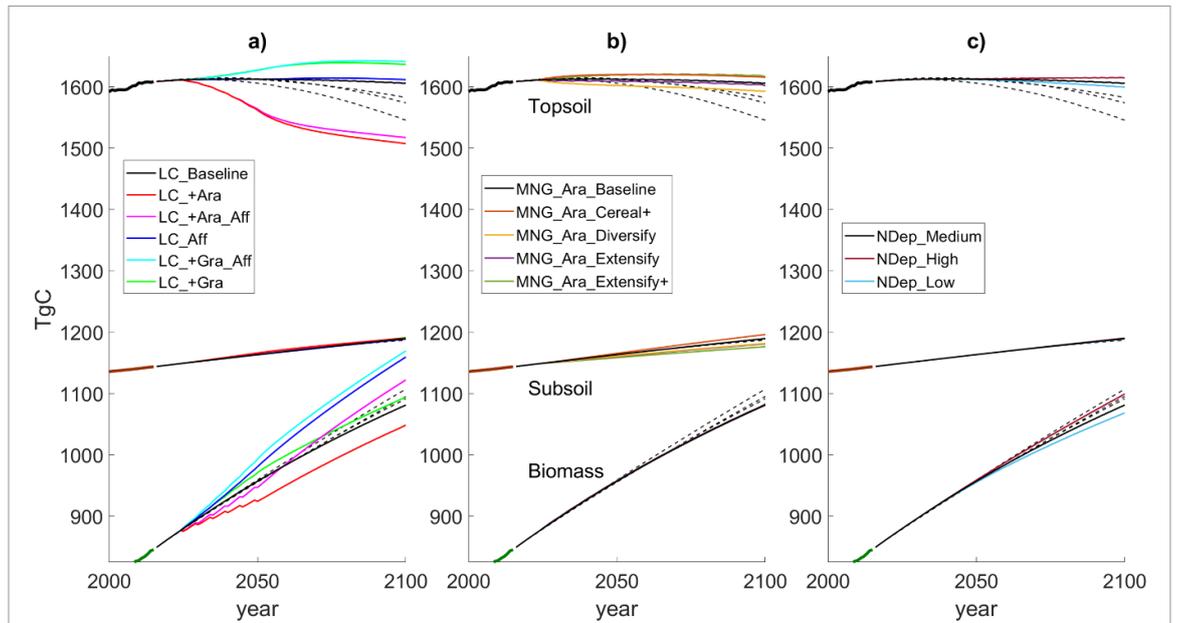
Figure 1. Modelled changes in UK topsoil, subsoil and biomass carbon under land cover change (LC), arable management (MNG) and atmospheric N deposition (NDep) scenarios, assuming RCP2.6 climate. Individual panels represent (a) LC scenarios, (b) MNG scenarios, and (c) NDep scenarios. RCP scenarios other than RCP2.6 are shown for reference using thin dashed lines (assuming baseline LC & MNG, and medium NDep). Note the long-term trends in biomass and subsoil OC present in all simulations. The *Y*-axis range represents present-day OC stocks in the three pools and does not include zero.
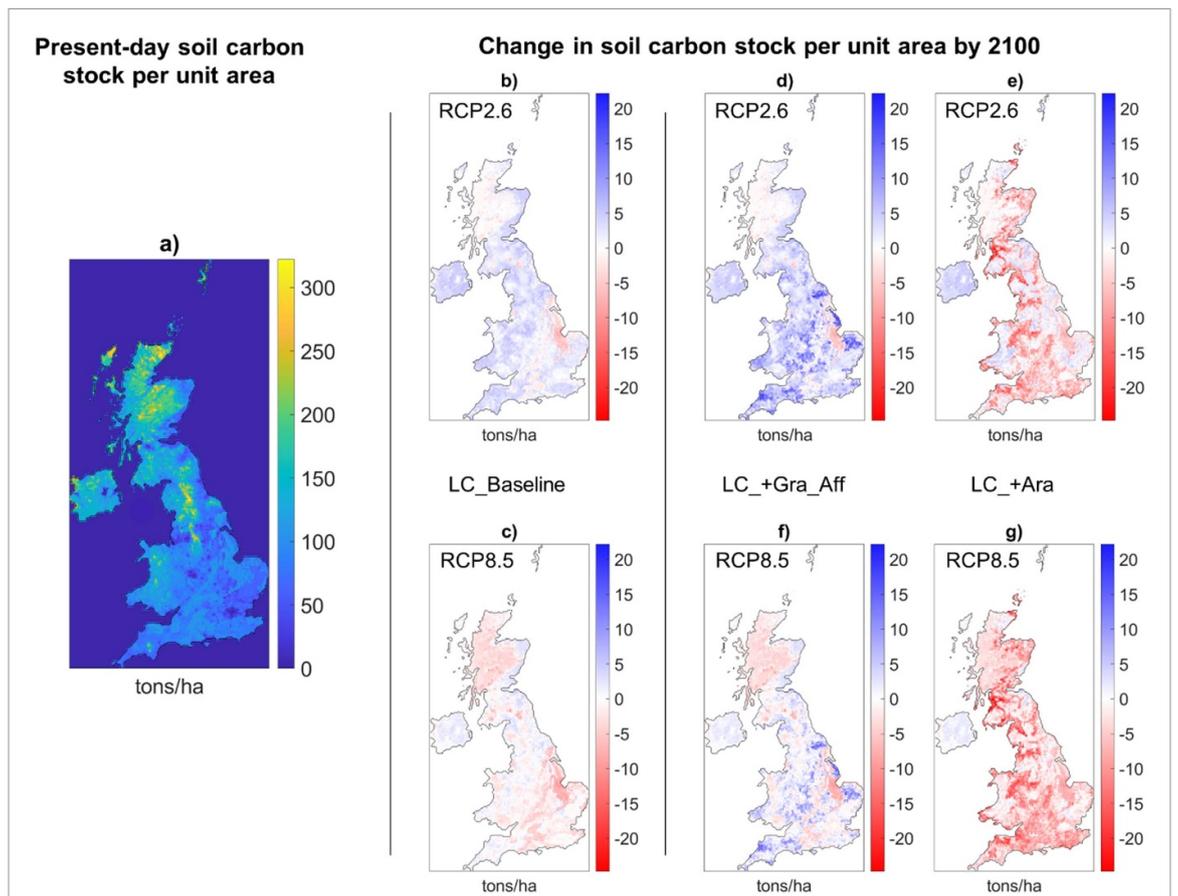
Figure 2. Simulated changes in spatial distribution of UK soil organic carbon stocks per unit area (topsoil + subsoil) under contrasting climate and LC change scenarios between now and 2100, assuming medium N deposition. Modelled present-day stocks are shown in panel (a) for reference. Top row of maps: soil carbon changes by 2100 in a +2 °C world (RCP2.6). Bottom row of maps: soil carbon changes by 2100 in a +4 °C world (RCP8.5) (different land uses). Middle column: soil carbon changes under (b) RCP2.6 and (c) RCP8.5 assuming present-day land use patterns do not change. Right column, top section: soil carbon changes under RCP2.6 and either (d) grassland restoration with afforestation or (e) arable expansion. Right column, bottom section: soil carbon changes under RCP8.5 and either (f) grassland restoration with afforestation or (g) arable expansion. Units: ton C per ha. *Note:* LC scenarios are not extended to Northern Ireland.

Figure 3. Changes in UK topsoil OC and total terrestrial OC by 2090–2100, calculated relative to baseline LC and MNG scenarios, medium N deposition scenario and RCP2.6 climate scenario (combined reference pathway). Top row shows the effect of the LC, NDep and climate scenarios on changes in (a) topsoil and (b) total terrestrial carbon, assuming baseline MNG. The effects of arable expansion or grassland restoration and afforestation are not additive since land conversions happen in different parts of the country depending on the pathway (supplementary methods). Bottom row shows the effect of the MNG, NDep and climate scenarios on changes in (c) topsoil and (d) total terrestrial carbon, assuming baseline LC. Climate scenarios are represented by individual clusters on bar graphs (along horizontal axis). Atmospheric N deposition scenarios are represented by error bars (high-low range), with medium N deposition shown using dots at the ends of the bars. All the values are provided in supplementary results.

in most parts of the country, with localised losses predominantly in arable areas. Conversely, arable expansion (figure 2(e)) causes widespread losses in soil carbon. In the +4 °C world scenario (RCP8.5), higher levels of warming exacerbate the losses in arable areas and drive widespread losses (or reductions in gains) in other land uses across the country. This is the case both under the grassland restoration with afforestation (figure 2(f)) and arable expansion (figure 2(g)) pathways. The effects of climate change alone are shown in figures 2(b) and (c), assuming no changes to present-day LC baseline.

The UK-wide effects of future LC, MNG, climate and NDep changes on the topsoil and total terrestrial OC (topsoil, subsoil and biomass) pools in 2090–2100 are shown in figure 3. Climate scenarios are represented by individual clusters on the bar graphs, and variation in atmospheric NDep are shown using error bars. In figure 3, the changes are measured exclusively in 2090–2100 relative to a combined reference pathway, which consists of maintaining present-day LC and MNG baselines, and following medium NDep

and RCP2.6 climate scenarios. Using the reference pathway as a comparator for all other scenario combinations allows us to eliminate the long-term trends associated with the history of land use specific to the UK (e.g. biomass accumulation in the woodlands planted in the 20th century; figure 1), and isolate the effect of future land use/management changes.

The UK-wide effect of LC changes on the topsoil and total terrestrial carbon pools in 2090–2100 is highlighted in figures 3(a) and (b), assuming present-day baseline arable management throughout. Warmer climates lead to topsoil carbon losses across most LC scenarios (figure 3(a)), with the biggest loss of 144 TgC occurring for a combination of arable expansion with RCP8.5 climate (medium NDep) relative to the reference pathway (for context, current total UK annual GHG emissions from all sectors are around 120 TgCe; [99]). The biggest terrestrial carbon loss occurs under arable expansion and RCP8.5 climate (−155 TgC), while the biggest gain is predicted to take place under grassland restoration with afforestation and RCP2.6 climate

(+119 TgC). Variations in future atmospheric NDep generally have a smaller effect on soil carbon sequestration or loss compared to land use or climate, but the overall effects of NDep on terrestrial carbon, particularly on biomass, are considerable.

The UK-wide effect of arable management changes on the topsoil and total terrestrial carbon pools in 2090–2100 is highlighted in figures 3(c) and (d), assuming present-day baseline LC throughout. The predicted effect of the MNG scenarios on total terrestrial OC is generally smaller than the magnitude of changes simulated under the LC change scenarios. The model predicts national-level topsoil OC stock declines relative to the combined reference pathway for RCP4.5 climates and beyond, regardless of arable management options. Total terrestrial carbon (figure 3(d)) shows a different behaviour due to the way subsoil responds to the management options (figure 1(b)). The biggest terrestrial carbon accumulation occurs under Cereal+ rotations (+16 TgC; medium NDep and RCP2.6 climate), driven by higher residue carbon returns under this management option [58]. Warmer climates lead to carbon losses in the total terrestrial pool for nearly all management options. However, the level of atmospheric NDep can make the difference between a carbon gain or loss under some of the simulated climates and MNG scenarios.

The UK-wide effects of all combinations of the LC and MNG scenarios considered here on the topsoil and total terrestrial carbon pools in 2090–2100, as well as the corresponding differences between the RCP2.6 and RCP8.5 climates, are given in supplementary results.

4. Discussion

Our results suggest that terrestrial carbon sequestration could provide a moderate contribution to reducing net GHG emissions in the UK, and likely in other densely populated temperate regions with a long history of land use change and nutrient limitations. The grassland restoration plus afforestation scenario, coupled with the most ambitious climate pathway, produced the highest estimated sequestration of +119 TgC, which is approximately equivalent to a single year of emissions for the UK or roughly 7% of the total cumulative GHG emission cuts needed to reach net zero climate commitments. This level of sequestration would require widespread land use conversions over the next 30 years that are challenging but, nevertheless, achievable on the required timescales according to a wide body of national-level evidence [62, 100, 101]. The necessary land use conversions are likely to occur only if land managers are provided with sufficient near-term economic incentives that are aligned with long-term environmental goals. Such incentives could be integrated into policies such as the UK's new Environmental Land Management Scheme [102]. Higher levels of ambition, and further options for terrestrial carbon sequestration such as peatland restoration are also possible, though not in scope for this analysis [34, 103].

Our analysis indicates that national terrestrial carbon sequestration potential will decrease considerably under arable expansion. This scenario in the UK may be driven, for example, by aspirations for further food self-sufficiency. The analysis, however, does not consider the land use change and agricultural GHG emissions associated with food grown elsewhere globally and imported to the UK. It should be noted that while gains in total terrestrial OC may be seen at the national level under afforestation and grassland restoration scenarios, losses in soil organic carbon (SOC) are also present at a sub-national level in arable land areas, and the continued loss of SOC in these settings presents other risks beyond GHG emissions, such as loss of soil fertility and water holding potential.

Changes in arable management practices, such as the use of improved grass leys within rotations and organic fertilisers, are estimated to have a smaller effect on national terrestrial carbon storage than the land use change scenarios examined here. This is unsurprising given that management change is only considered in arable lands, and that changes in land use will generally have larger effects on plants and soil carbon stores. Although changing arable management presents a smaller sequestration opportunity at national scale in comparison to afforestation or grassland restoration, employing sustainable arable management practices may produce multiple benefits other than carbon sequestration, including improving soil health and biodiversity [28, 32]. Increasing carbon storage cannot be the sole goal of ecosystem management [11].

Our results strongly indicate that non-negligible long-term gains in terrestrial carbon are conditional on the best-case future climate scenarios. Otherwise, carbon sequestration efficiency is expected to be reduced despite our best efforts, including carbon losses from soils. Net carbon losses are predicted with large-scale expansion of arable even under the best-case climate, but gains are possible under grassland restoration and forestation pathways, in line with other assessments [30, 65, 67, 68, 104, 105]. Hence, this scenario analysis suggests that to achieve sustained negative emissions through the land use and management pathway, it is necessary to actively and urgently pursue emissions reductions in other parts of the economy and society and limit climate change in line with the Paris Agreement targets [3, 10, 12–14, 29, 48].

While we have addressed a number of major land use and management changes in this study, urban expansion was not included. Although only a

relatively small area of land might undergo urbanisation during the examined period compared to the areas considered for afforestation and grassland restoration here, it should be noted that urban development likely has large effects on local terrestrial carbon storage, due to large changes in plant cover and dramatic disturbance of soils. Demographic projections and urban planning maps could be used to develop urban expansion scenarios (e.g. [106]). However, predicting terrestrial carbon change caused by urban development is highly challenging. Since existing soil carbon surveys neglect urban areas, the current carbon storage in urban ecosystems is not well understood [96]. A number of recent studies have shown that urban greenspaces and soils under sealed surfaces can store large amounts of carbon, comparable to carbon concentrations found in semi-natural ecosystems and improved grasslands [107, 108]. However, the effects of compaction, excavation, soil redistribution, and sealing, the fate of carbon and nutrients following soil removal, and the variety of anthropogenic nutrient sources that occur in urban areas are all highly uncertain [109]. New research combining empirical and modelling approaches is needed to address the uncertain effects of urbanisation on terrestrial biogeochemical cycles.

The mechanism underpinning predicted reductions in sequestration potential in topsoils under RCPs 4.5, 6.0 and 8.5 is increased decomposition rates. The increased availability of N and P as a result, in addition to temperature rises leads to an increase in net primary productivity in the simulations and increased biomass pools. While this analysis considers the integrated effects of temperature and water changes, changing nitrogen and phosphorus availability, changing plant functional type, atmospheric deposition of nutrients and agricultural land practices, similar to all modelling analyses, there are limitations. As mentioned in the methods, other aspects relating to climate change such as increased CO_2 concentrations and PAR are not considered here. A recent compilation of experimental studies suggests that elevated CO_2 levels may lead to a trade-off between carbon storage in plants and soils, and that this may be related to plant nitrogen acquisition [110]. However, the combined effects of elevated CO_2 with temperature change are not examined in this study. Incorporation of CO_2 fertilisation and effects on plant nutrient acquisition strategies would make a valuable direction for future model development, and further empirical studies where multiple drivers (e.g. temperature, CO_2, nutrient additions) are combined would help support this [111]. Other climate change-related drivers, too, are neglected, such as the effects of increasing intensity of rainfall events or frequency of acute temperature variations as these occur on a finer temporal scale and require more in-depth hydrological and plant physiological processes. Further omissions include biophysical land-climate feedbacks, soil erosion and redistribution; compaction; crop pests and diseases; changes in crop varieties; woodland management; and wildfires or purposeful burning of land.

5. Conclusions

Here, we presented a national-scale scenario analysis of terrestrial carbon sequestration using process-based modelling that includes four major large-scale drivers of plant and soil carbon change, namely: climate; land use change; agricultural management practices and atmospheric nitrogen pollution. This is the only study to our knowledge that considers the integrated effects of these four major drivers.

Our results suggest that meeting realistic UK national targets for grassland restoration and forestation over the next 30 years [100, 101] could help sequester an additional 120 TgC in soils and biomass by 2100, assuming climate change is limited to 2 °C (RCP2.6). This could account for around 7% of the cumulative emission cuts in the UK required to meet the 2050 Net Zero target [1]. We find that arable expansion could lead to reductions in soil carbon storage of around 100 TgC by 2100 in a +2 °C world (RCP2.6). Total terrestrial carbon sequestration potential is reduced under less optimistic climate scenarios, with gains in soil carbon turning to losses in a +4 °C world (RCP8.5).

Compared to LC change and climate change, alternative UK-wide arable management practices such as rotations with grass leys, and reduced use of inorganic fertilisers, as well as variations in future atmospheric NDep levels, are predicted to have a moderate effect on total soil carbon sequestration of the order of ±20 TgC by 2100.

While cutting emissions from fossil fuels, soil degradation and deforestation remain top priorities for climate mitigation globally, the results suggest that concerted land use change can make a moderate contribution to the negative emissions needed at this national level. If designed and implemented appropriately, landscape interventions could also deliver co-benefits such as improved biodiversity, air and water quality, and soil health.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Code Availability

The N14CP model and all the pre- and post-processing algorithms will be made available upon reasonable request from the authors.

Author contributions

Yumashev: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing - Original Draft, Review & Editing, Visualisation, Project Administration. **Janes-Bassett:** Conceptualization, Methodology, Software, Resources, Data Curation, Writing – Review & Editing. **Redhead:** Methodology, Resources, Writing – Review & Editing, Funding Acquisition. **Rowe:** Methodology, Writing – Review & Editing. **Davies:** Conceptualization, Methodology, Software, Writing – Review & Editing, Supervision, Project Administration, Funding Acquisition.

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