Pathways for achieving climate and biodiversity targets through sustainable land-use and food systems in the UK

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This thesis is submitted for the degree of *Doctor of Philosophy*

July 2024

Lancaster University

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Abstract

There is significant global awareness of the core challenges of climate change and biodiversity loss associated with land-use, with increased international commitment to reduce greenhouse gas emissions and restore nature. Land-use has a critical role to play in overcoming these challenges. In the UK, current land-use is unsustainable, and will be unable to achieve national and international agreements for net-zero greenhouse gas emissions and biodiversity conservation. Business-as-usual is not sufficient, and the UK requires urgent and decisive action to mitigate climate change, reverse biodiversity decline whilst ensuring food security for future generations. Furthermore, the numerous alternative land-use configurations, and the complexity of governance and land-use in the UK, highlight the need for comprehensive and effective policy strategies for transforming land-use to achieve net-zero and biodiversity conservation.

This thesis examined alternative pathways for land-use and food systems in the UK and devolved nations to achieve national and international climate and biodiversity agreements. Using a modified version of the FABLE Calculator (a simple integrated land-use model), alternative policy pathways were developed and modelled, and their feasibility assessed through spatialisation. Trade-offs and synergies within the pathways were analysed, and the implications of the policy pathways were evaluated. The results showed that current policies are inadequate for achieving net-zero or conserving biodiversity, highlighting the urgent need for transformational change. Alternative configurations of land-use, resulting from different policy combinations, indicate that whilst some pathways generated similar outcomes for achieving net-zero, there were greater gains for biodiversity in pathways that embed a multifunctional approach to land-use compared to those that do not. Integrating non-spatial FABLE projections with a downscaling algorithm enhanced the realism and applicability of the pathways, showing that the policy changes within the pathways are theoretically feasible given spatial environmental constraints. This is critical in moving from theoretical, high-level objectives to more localised and practical solutions.

Overall, this thesis demonstrated the need for significant changes in policy, with increased ambitions across afforestation, crop and livestock productivity, stocking densities, biodiversity conservation, peatland restoration, dietary change and food waste. The findings underscore the urgent need for innovative, coordinated policy measures for supporting and incentivising transformative land-use changes. Through embracing these strategies, policy and decision-makers can pave the way towards a sustainable future that successfully balances climate change and biodiversity goals while maintaining a thriving agricultural sector.

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Acknowledgements

Firstly, I would like to thank my supervisory team Pete Atkinson, Paula Harrison and Pete Henrys for their invaluable support, encouragement and guidance throughout this PhD. The insightful feedback and advice they provided me was crucial for me completing the thesis and making the most out of opportunities within the PhD over the last four years.

Secondly, being funded by the DSNE project was a fantastic opportunity to work closely with those working on very different topics within data science and the environment, and I am grateful for all the additional learning from those seminars, coffee breaks and informal conversations. A particular thank you to Rachael and Kate, for being so welcoming and for all the supportive writing group mornings. I am also grateful for my UK CEH office mates, who have kept me sane during these last few months, particularly George who was always ready to listen to my dramatics!

The UK-FABLE team has played an integral role in my thesis, so in particular I would like to thank Alison Smith and Nicholas Leach for showing me the complicated ways of the FABLE Calculator, and for answering any queries I had. I would also like to thank the wider consortium and FABLE Secretariat for being so welcoming and encouraging when I wished to pursue using the calculator in my thesis.

This thesis would not be possible without the support of my family and friends. My Mum and Dad always made me believe I could do anything I put my mind to, and this thesis was no different. So, thank you Mum and Dad, I could not have done it without you. To my siblings, Rachel and Daniel, your support, distractions and encouragement were always there when I needed it, even when I didn’t know I needed it!

And finally, perhaps the biggest thank you goes to Joshua. Thank you for providing all the sweet treats and cups of tea I needed, pretending to listen when I got excited about my research, and for wiping away all the tears. I am so grateful for your love and support, and for believing in me when I did not believe in myself. We did it!!

Declaration

I declare that other than where the contribution of others is specified, this thesis is my entirely my own work and has not been submitted for another degree at this or any other university.

S M JONES

26.07.24

Statement of Authorship

Chapter 3 has been published in Regional Environmental Change, alongside colleagues at the University of Oxford:

Jones, S.M., Smith, A.C., Leach, N., Henrys, P., Atkinson, P.M., and Harrison, P.A. (2023) Pathways to achieving nature-positive and carbon–neutral land-use and food systems in Wales. Reg Environ Change 23, 37. https://doi.org/10.1007/s10113-023-02041-2

Chapter 4 is under review in Environmental Science and Policy (at the time of writing the thesis) and Chapter 5 is under review in the Journal of Land-use Science (at the time of writing the thesis).

1. Introduction

Land is an integral part of life, supporting the provision of food, freshwater, biodiversity and many other beneficial services (IPCC, 2019), and is a limited and valuable resource. Changes in land-use can have detrimental impacts on the environment, potentially leading to reductions in biodiversity, degradation of soil, or pollution through use of fertiliser or pesticides (van Asselen and Verburg, 2013). Changes in land-use can release greenhouse gas (GHG) emissions and are estimated to have contributed approximately a quarter of cumulative carbon emissions since industrialisation (Le Quere et al., 2016). In contrast, land-use changes can also have positive implications, through creating and restoring natural habitats, or improving carbon storage through woodland creation and carbon sequestration (Roe et al., 2019). Unprecedented rates of past and current land-use change, thus, provide a major challenge and potential opportunity for policymakers (Verburg and Lesschen, 2006).

There has become significant global awareness of the challenges associated with land-use, unsustainable agricultural production and depletion of nature over recent years, with increased international commitment to reducing the impacts of climate change and reversing biodiversity decline. One of the most notable is the Paris Agreement, which was adopted at the UN climate talks in Paris in December 2015, aims to hold the rise of global temperatures to below 2°C (UNFCCC, 2015). As well as this, in 2022, the Convention on Biological Diversity (CBD) adopted the Kunming-Montreal Global Biodiversity Framework (GBF), which aims to “catalyze, enable and galvanise” transformative action by Governments to halt and reverse biodiversity decline (CBD, 2022). Land-use is deemed critical to achieving both net-zero and reversing biodiversity loss (CCC, 2020). In the UK, current land-use and agricultural production are unsustainable, with land-use practices damaging natural assets, and will be unable to achieve national and international targets for net-zero emissions (CCC, 2019a). The UK has also been described as one of the most nature depleted countries in the world, with a historic decline in species over the last 50 years (Hayhow et al., 2019). As a signatory to the international agreements, as well as legally binding national policy such as *The Climate Change Act 2008* to reach net-zero by 2050, action is required from national and sub-national policy to reduce GHG emissions and restore nature.

The land-use sector faces a fundamental challenge in translating policy aspirations for climate into actionable and realisable targets and pathways to decarbonisation. This must be done alongside other sustainable land-use objectives, such as maintaining sufficient food production and reversing biodiversity loss (IPCC, 2019). The increasing demands on land to fulfil a variety of policy objectives necessitate clear, concise and ambitious national-level commitments (Burchardt, 2020). However, numerous alternative configurations of land-use exist, each presenting different and distinct trade-offs and synergies for agricultural production, biodiversity and GHG emissions. Consequently, achieving transformation of land requires stringent policy regimes to drive the necessary changes.

Given the combination of limited natural resources, a growing population and the pressures to meet international and national agreements, achieving sustainable land-use is becoming an increasingly critical issue (Franco et al., 2020). Business-as-usual is insufficient; without immediate and decisive action, the opportunity to mitigate climate change, reverse biodiversity decline, and ensure food security will be irrevocably lost, with profound consequences for future generations. In the UK, the numerous alternative configurations of land-use, coupled with the complexity of land-use and governance structures, highlight the urgent need for comprehensive and effective policy strategies for transforming land-use to achieve net-zero and biodiversity conservation targets. Policymakers must understand what policy actions support these alternative configurations, how feasible they would be within the UK and devolved nations, and the wider implications of these changes.

For the Agriculture, Forestry, and Other Land-use (AFOLU) sector, this thesis aims to examine alternative pathways for land-use and food systems in the UK and devolved nations to achieve national and international climate and biodiversity targets, providing evidence for decision-makers to develop effective policy measures. To achieve this, the following objectives were set:

- To develop **alternative pathways** for sustainably transforming land-use and food production in the UK for climate and biodiversity.
- To assess the **feasibility** of these pathways at the UK and devolved levels through spatialising pathway outputs.
- To analyse the **challenges, opportunities, trade-offs, and synergies** within the pathways for achieving climate change mitigation, biodiversity and food production policy goals within the land-use sector.
- To evaluate the **policy implications** of the pathways across national and sub-national scales and their influence on meeting the UK's international environmental commitments.

To address these objectives, the thesis employed a mixed-methods approach. This approach combined qualitative stakeholder engagement and policy review to develop pathways for effective policy measures aimed at transforming land-use in the UK and the devolved nations, with quantitative land-use modelling and spatial analysis to explore the success in achieving climate and biodiversity targets and the feasibility of the pathways in the UK.

The thesis begins with an overview of the challenges and opportunities surrounding land-use and food systems, and the different approaches for investigating and exploring future land-use change (Chapter 2). The analytical chapters (Chapters 3-5) explore national scale pathways towards sustainable land-use and food systems in the UK and its devolved nations, examining the challenges and interactions between competing and complementary demands on land for achieving global and national climate and environmental targets and policy. Chapter 6 presents an overarching discussion on the alternative pathways, the trade-offs and synergies explored in the chapters and provides some limitations of the thesis.

In more detail, Chapter 3 presents the co-creation of pathways to sustainable land-use and food systems in Wales, which were simulated using a national integrated food and land-use model (the FABLE calculator). Through extensive engagement with officials from the Welsh Government, four pathways were developed to 2050, encompassing current and aspirational polices related to agricultural production, climate mitigation and biodiversity. Chapter 4 builds on Chapter 3, by developing additional models for the devolved administrations of Scotland, England and Northern Ireland, and aggregating their outputs to explore the policy implications of the regional autonomy of the nations and their contributions to the UK's climate and biodiversity policy targets. The final analytical chapter, Chapter 5, develops spatially-explicit outputs from the FABLE Calculators developed in Chapter 4, using a downscaling algorithm. The chapter investigates the feasibility and spatial implications of the pathways by testing whether they are feasible spatially within the UK and identifying areas that are consistently simulated as changing land-use and hence are likely to be important for achieving the UK's policy targets. An overall reference list, which has collated all the references from each chapter, is provided at the end of this thesis (Chapter 8), and the supplementary material from each chapter is presented in the appendices (Chapter 9).

2. Literature review

2.1. What are land-use and food systems?

Previously considered a local environmental issue, land-use has now become a topic of global importance (Foley et al., 2005). Land provides the principal basis for human livelihoods, through its critical role in supplying food and supporting the provision of freshwater, biodiversity and many other ecosystem services (IPCC, 2019). This supply of ecosystem goods and services are essential to economic activity and societal wellbeing (CCC, 2018), as well as providing intangible benefits to humans, such as cognitive and spiritual enrichment and recreational values (Arneth et al., 2019).

Land systems encompass the terrestrial component of the Earth system; involving all processes and activities related to the human use of land (Verburg et al., 2013). Changes in land systems have large consequences for the environment and human well-being (Verburg et al., 2015). Land-use change is often a result of human activities transforming the natural landscape for immediate human needs (Paul and Rashid, 2017), often at the expense of degrading the environment (Foley et al., 2005). Land-use change is complex due to the interactions between changes in social and economic opportunities, the biophysical environment and decision-making at different scales (Verburg and Lesschen, 2006). The rate of land-use change globally has increased over much of the last century, with approximately 32% of global land area being affected in the last six decades (1960-2019), which is approximately four times greater than previous long-term assessments of land-use change have calculated (Winkler et al, 2021).

Changes in land-use are driven by a variety of factors, environmental, economic and societal, that are scale- and location-dependent (Heistermann et al., 2011). In the literature, drivers of land-use change are often categorised as direct or indirect causes (Lambin et al., 2003, Mora et al., 2020). Direct (or proximate) causes of land-use change consist of human activities, or immediate actions (Lambin et al., 2003). Indirect (or underlying) causes of land-use change are typically the foundational forces that drive change, often influencing change from a far (Lambin et al., 2003). Generally, these indirect causes are formed by complex interactions among social, political, economic, demographic, technological, cultural and biophysical variables (Lambin et al., 2003), and tend to occur at the national, continental or global level. In contrast, direct causes of land-use change usually operate at the local level, involving a physical action on the land.

Agricultural expansion is considered one of the most widespread forms of direct land-use change, with over one third of the terrestrial land surface being used for cropping or animal husbandry (IPBES, 2019). Population growth and changing diets have increased the demands on agriculture to supply sufficient food, fuel and feed (Alexander et al., 2015), leading to increased demand for agricultural land that has put pressure on available land resources (Brouwer and McCarl, 2006).

Whilst land-use for food production is a key component of land systems, it is also a central part of food systems (Meyfroidt et al., 2019). Food systems consist of all the people, institutions, environments, activities and infrastructure that relate to the production, processing, distribution, preparation and consumption of food (Fanzo et al., 2020). They exist at different scales (global, regional, national and local), are very diverse and location-specific (von Braun et al., 2023), and are intrinsically linked to health, environment, culture, politics and the economy (Fanzo et al., 2020). A systems approach to food recognises that the food system involves interactions that work together to influence multiple outcomes (Parsons and Hawkes, 2018), as well as highlighting the complexity of producing, processing, distributing and attaining food.

2.2. Why are land-use and food systems important?

Land-use and food systems are integral parts of life, and the complex interlinkages between the two are significant to many global environmental change challenges and sustainability issues relating to land degradation, biodiversity loss and climate change (Meyfroidt et al., 2019). Additionally, there are many opportunities for land-use and food systems to transform to address some of these challenges and contribute to global sustainability goals and international agreements.

2.2.1. The challenges of land-use and food systems

There is a growing strain on land due to over-pollution of natural resources, inefficient farming processes and increasing stresses from a rising population (Arcanjo, 2020). Data starting in 1961, based on national statistics from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) show that global population growth and changes in per capita consumption of food, fibre, timber and energy have caused unprecedented rates of land and freshwater use (IPCC, 2019). There are continuing significant external pressures on land and food systems to adequately provide for increasing global populations.

In the IPCC's *Special Report on Climate Change and Land* (2019), land is described as having an important role in the climate system, playing a key part in the exchange of energy, water and aerosols between the land surface and the atmosphere. Land can also act as both a source of GHGs, releasing CO_2 into the atmosphere through, for instance, deforestation, and a carbon sink, absorbing more carbon from the atmosphere than it emits, for example with plants and soil (European Commission, 2021). Land-use change contributed 12% of total anthropogenic emissions in the most recent Global Carbon Budget (2013-2022) (Friedlingstein et al., 2023), with deforestation being the main driver of gross sources.

The global food system uses 40% of global land and 70% of global freshwater and is considered a major contributor to both climate change and biodiversity loss (Clapp, Newell, and Brent 2018, cited in Selwynn, 2021). Current intensive agricultural practices have led to the high use of fertilisers and pesticides, GHG emissions, soil erosion and land degradation, all of which are causing significant environmental harm (Bullock et al., 2023). This presents many challenges for land managers and farmers to continue to produce adequate food, whilst reducing the impact of their activities.

In addition, land-use change has been cited as one of the greatest threats to biodiversity, with the effects manifesting primarily at local scales (Hoskins et al., 2016). Land conversion for agriculture and inappropriate land management has caused losses in species (Godfray et al., 2010), and how rising agricultural demand is managed will be pivotal for the future of biodiversity (Balmford et al., 2018).

2.2.2. Climate change and the net-zero challenge

Human activities, principally through GHG emissions, have unequivocally caused anthropogenic global warming, with the global surface temperature increasing by 1.1°C in 2010-2020 from 1850-1900 levels (IPCC, 2023). Unsustainable fossil-fuel based energy use, land-use, land-use change, lifestyles and consumption patterns continue to contribute to GHG emissions (IPCC, 2023). Limiting global warming requires net-zero CO_2 emissions (IPCC, 2023), which at the global level, refers to a global balance between anthropogenic emissions and removals over a given time period (Correa and Voight, 2021). Climate ambition is now increasingly expressed as a specific target date of reaching net-zero emissions (Fankhauser et al, 2022), and governments across the world are increasingly setting net-zero emissions targets (Booth, 2021). These targets are typically linked to international agreements such as the Paris Agreement.

The Paris Agreement is a legally binding international treaty on climate change that sets long-term temperature goals to limit global warming and reduce GHG emissions (UNFCCC, 2015). Its long-term temperature goal is to hold the global average temperature increase to "*well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels*". The Paris Agreement was adopted at COP21 in Paris in 2015, to strengthen the global response to the threat of climate change (Correa and Voight, 2021). It has near universal participation, with 197 countries signing the pledge (Fankhauser et al., 2022) and is supporting rising levels of national ambition (IPCC, 2023). It has led to policy development and target-setting at national and sub-national levels in relation to mitigation, as well as enhanced transparency of climate action (IPCC, 2023). However, the Paris Agreement does not formulate interim policy goals or a roadmap for action, and only offers limited policy guidance on how to meet the global temperature goals (Streck, 2023). Countries' actions under the Agreement are specified in Nationally Determined Contributions (NDCs), which are elaborations of national mitigation targets, plans and measures for their contribution to the global goal (den Elzen et al., 2023). There has been criticism that the NDCs won't be enough to adequately keep warming below 1.5°C (Roe et al., 2019), with the IPCC noting that the GHG emissions implied by the NDCs in 2030 make it likely that warming will exceed 1.5°C during the 21st century (2023). The current implementation gap, defined as the difference between projected emissions under current policies and projected emissions under full implementation of the NDCs, supports these concerns. Globally, assuming full implementation, the NDCs for 2030 are estimated to reduce global emissions by 9%, compared with current policy projections. To get to levels consistent with pathways limiting global warming to below 1.5°C, global GHG emissions must be reduced 42% (United Nations Environment Programme, 2023).

Climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity and food systems. Warming temperatures, changing precipitation patterns and increases in the frequency and intensity of extreme events impact land in every region globally, as well as affecting food systems and food security (IPCC, 2019, Mbow et al., 2019). Agriculture is amongst the sectors already suffering from the most severe negative impacts of climate change (Correa and Voight, 2022), with the affects felt differently across world regions (Mirzabaev et al., 2023). These climate related disturbances not only have drastic impacts on food distribution patterns, but also on its quality and accessibility (Arora, 2019). Agriculture is therefore often seen as both a villain and a victim of climate change (Reay et al, 2020), through its contribution to GHG emissions, and due to the adverse impacts on it from climate change.

2.2.3. The challenge of biodiversity decline

Biodiversity, described by the IPBES (2019) as the diversity within species, between species and of ecosystems, is declining faster than at any time in human history, and goals to halt biodiversity loss have not been achieved (Henry et al., 2022). Despite 30 years of policy action, downward trends of species abundance are being observed. The Living Planet Index (LPI), which tracks the changes in the relative abundance of species over time, shows an average 69% decline in the relative abundance of monitored wildlife globally between 1970 and 2018 (WWF, 2022). Biodiversity plays a crucial role in maintaining human and planetary health (Benton et al 2021), and losses are damaging ecosystems and harming livelihoods.

Alongside the Paris Agreement for GHG emissions, there are international commitments for protecting and restoring biodiversity. The Convention on Biological Diversity (CBD) has been a pivotal instrument in international biodiversity conservation since 1992 (Li et al, 2023). In 2010, the CBD adopted the Strategic Plan for Biodiversity which presented a set of 20 targets, named the Aichi Biodiversity Targets, for halting biodiversity loss and enhancing benefits (Marques et al., 2014). Similar to the Paris Agreement, the implementation of the strategic plan was at a national and sub-national level (Buchanan et al., 2020), however, despite this, little progress across most of the targets were achieved (Streck, 2023).

Given the shortcomings of previous strategic plans, in 2022 the CBD adopted the Kunming-Montreal Global Biodiversity Framework (GBF). The framework aims to “catalyse, enable and galvanise” transformative action by Governments to halt and reverse biodiversity decline (CBD, 2022), and is expected to guide biodiversity policy globally in the coming years (Streck, 2023). The treaty seeks to harmonise anthropogenic demands with nature conservation, emphasizing the synergies between biodiversity, development and human well-being (Li et al., 2023). One of the key aspects of the Kunming-Montreal GBF relevant for the AFOLU sector in particular, is the target for increasing land and marine areas designated as protected to at least 30% by 2030 (Arneth et al., 2023). This creates an additional pressure on land to support biodiversity conservation.

2.2.4. The opportunities for land-use and food systems

There is a growing global consensus of the need to transform land-use and food systems to achieve the critical global goals that are at the intersection of human and planetary well-being (Herrero et al., 2023). Land is considered vital in combatting climate change, as unlike other sectors where the focus is largely on emission reduction, land provides the possibility to enhance carbon sinks (Arcanjo, 2020). The goals of the Paris Agreement cannot be met without significant contributions from the land-use sector (Roe et al., 2017), and there are many different policy levers that can contribute to net-zero and biodiversity. These levers, which incentivise change primarily through governance approaches and interventions (Chan et al., 2019), are crucial for promoting carbon sequestration and supporting the necessary transformations in the land-use sector. Planned interventions in the land sector, which can be supported through policy, include the prevention of further deforestation, afforestation, reduction in agricultural GHG emissions, and the adoption of bioenergy with carbon capture and storage (Brown et al., 2019). These nature-based solutions (NbS) work with nature to address environmental challenges and are increasingly being incorporated into national governments climate policy (Bradfer-Lawrence, 2021). There is also a need to improve sustainability in food systems, to ensure future populations are adequately fed without compromising the environment (Godfrey et al., 2010).

2.2.4.1. Nature-based solutions

Nature-based solutions (NbS) are actions to simultaneously address environmental, social and economic challenges, by maximising the benefits provided by nature, often inspired by, supported by or copied from nature (Bauduceau et al., 2015). They can aid in climate solutions through sequestering carbon, contributing to net-zero targets, and providing adaptation to climate change effects, such as reducing flooding (Stafford et al., 2021). Research by Griscom et al. (2017) suggests that NbS, such as habitat restoration, improved land management and increases in carbon storage, can provide 37% of cost-effective CO_2 mitigation that is needed between now and 2030 to stabilize warming below 2°C. In addition to contributing to net-zero goals, NbS offer numerous co-benefits for biodiversity, by creating, restoring and improving more resilient ecosystems, benefiting biodiversity, as well as enhancing human well-being (Stafford et al, 2021).

At a global scale, reforestation (the of planting trees on land which was previously forested) and afforestation (the planting of trees on land which was not previously forested) (Andres et al., 2022) are the land-based strategies with the greatest potential for climate change mitigation (Griscom et al., 2017). Afforestation, to capture and store atmospheric carbon, is a prominent part of the public discourse on emissions abatement. It is widely cited as a policy option, with increased forest area or forest as a percentage of land cover as aspirations or targets (Matthews et al., 2020). However, the estimates of afforestation potential vary widely (Doelman et al., 2019). In addition, there are trade-offs between afforestation and other land-uses. For example, large-scale afforestation requires land that is most likely also needed to provide other land-based services such as food production, which could impact food security (Doelman et al., 2019). These trade-offs for large-scale planting require further assessment.

2.2.4.2. Sustainable food systems

Providing a growing population with healthy diets from a more sustainable food system is an immediate global challenge (Willet et al., 2019). Sustainable food systems are defined by the FAO as a food system that delivers food and nutritional security in a way that does not compromise the economic, social, cultural and ecological bases for food production for future generations (FAO, 2018a). One of the prominent responses to reducing the environmental impact of food production is sustainable intensification, which seeks to do more with less through using inputs and resources more efficiently (Poux and Aubert, 2018). Sustainable intensification offers synergistic opportunities for the co-production of agricultural and natural capital outcomes (Pretty et al., 2018). However, large scale coordinated efforts to transform the global food system have been hindered by the absence of scientific targets for achieving healthy diets from a sustainable food system (Willett et al., 2019).

Previous research on livestock consumption impacts on land-use and climate change concluded that action is need on both the supply and demand side to achieve a sustainable food system (Röös et al., 2017). Davis et al. (2016) conducted a multi-metric assessment of agricultural efficiency and diet, concluding that a combination of increased efficiency and changes in diet can increase food supply and minimise environmental impacts, reinforcing the need for change on both fronts. Other studies focused on the production system, for example Poux and Aubert (2018) explored a European-wide transition to agroecology, which is based on phasing out pesticides and synthetic fertilisers and extending natural areas. They found that despite an initial drop in production, enough healthy food could be provided, alongside a 40% reduction in GHG emissions and regains in biodiversity and natural resources (Poux and Aubert, 2018).

Research has also focused on different land-use configurations which target GHG reductions and biodiversity conservation, whilst maintaining agricultural production. A land-sparing configuration, where an intensification of farming practices reduces the farmland area needed to meet food demand and enables the restoration of land for biodiversity conservation and carbon sequestration, has the technical potential to achieve significant reductions in net emissions from agriculture and land-use change (Redhead et al., 2020; Lamb et al., 2016). Contrasting approaches, such as the land-sharing approach, are characterised through integrating food production, carbon sequestration and biodiversity conservation on the same land, increasing the amount of farmed land, but reducing the intensity of agriculture (Redhead et al., 2020). These alternate approaches will have differing consequences for the landscape, as well as different socio-economic impacts and outcomes for GHG emissions or biodiversity.

2.3. Approaches to investigating and exploring future land-use change

Previous research has highlighted that achieving climate stabilisation without compromising food security requires effective policy design of GHG efficient mitigation in the AFOLU sector, whilst supporting equitable growth (Frank et al., 2017). However, when scientists and practitioners seek to provide an evidence-base for decision-making, they are confronted by a variety of challenges (Grove and Pickett, 2019). Not only is this due to the complexity of the problem (described in Section 2.2), but also due to practical challenges, such as incomplete data, varying levels of confidence in the data, uncertainty, or differing policy and societal perspectives. Policymakers require the best available information on the likely consequences, orders of magnitude, and the potential impacts on global environments and society (Hewitt et al., 2020). There are a number of approaches to investigating land-use change, including scenarios and pathways to provide narratives to plausible futures, modelling land-use change both non-spatially and spatially to simulate the possible outcomes from scenarios and pathways, or downscaling outputs from land-use models to analyse the implications of model outcomes at finer resolutions. These are outlined below.

2.3.1. Scenarios and pathways

Scenarios have been widely recognised as a useful tool for planning within climate research in the face of complexity and uncertainty (Kok et al., 2019). Defined by the IPCC as plausible descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (IPCC, 2019), scenarios can provide decision-makers with accessible narratives of potential future changes (Hauck et al., 2019). They describe alternative futures under different sets of assumptions that are based on current understanding of land-use change, its drivers and its interactions with a wide range of other environmental and socio-economic drivers and/or policy interventions (Harrison et al. 2019). Scenarios are often translated into projected outcomes or consequences by land-use models (IPBES, 2016) and can be distinguished into three types, based on their complexity and degree and uncertainty:

- *Predictive* or *prospective* scenarios - those extrapolating current trends, often referred to as business-as-usual scenarios.
- *Exploratory* scenarios – those exploring alternative futures that are plausible, surprising or shocking.

- *Normative* or *target-seeking* scenarios – those describing desired futures, usually goal or target orientated (Perez-Soba and Maas, 2015).

One of the most frequently used set of exploratory scenarios is the Shared Socio-economic Pathways (SSPs), which describe plausible alternative trends in the evolution of civilization and natural systems over the 21st century at the global and large world region level (O'Neill et al., 2014). They consist of two elements, a narrative storyline and a set of quantified measures of development, acting as reference pathways for future research (O'Neill et al., 2014). They are increasingly adopted as a means of providing plausible and credible socioeconomic boundaries to guide the estimation of climate and environmental impacts (O'Neill et al., 2014) and are often integrated with quantitative information and modelling to detail specific impacts (Hewitt et al., 2020).

Closely related to normative scenarios is the concept of pathways. In the context of reaching sustainability goals, pathways consist of different strategies for moving from the current situation towards a desired future vision or set of specified targets, which may be adopted by different actors within the system (Aguiar et al., 2020). Pathways can identify alternative sets or sequences of interventions and potential implications for meeting policy targets (Pérez-Soba and Maas, 2015), having the potential to enhance policy development.

2.3.2. Land-use change modelling

Land-use change modelling is a critical tool used for simulating and exploring the dynamics of land-use change. Model-based projections of future land-use change are frequently used to study the impact of land-use change on environmental systems, as well as providing support for policy and decision-making (Prestele et al., 2016). They aid in understanding the trade-offs between different demands for land-use, as well as complex linkages and feedbacks between different drivers of land-use change (van Soesbergen, 2016).

Land-use models can be static or dynamic, spatial or non-spatial (i.e., focusing on patterns of changes vs. rates of changes), deductive or inductive (i.e., with parameters based on statistical correlations or explicit descriptions of processes), and agent-based or pattern-based (i.e., simulation of individual decision-making agents or inference of underlying behaviour from the observation of land-use change patterns) (Noszczyk, 2019). Land-use models have been categorised as standalone models that focus on the geographical land cover and economic aspects of land-use change, or more integrated models that consider the interrelations between land sectors and environments (Figure 2.1) (Mitchetti and Zamperieri, 2014).

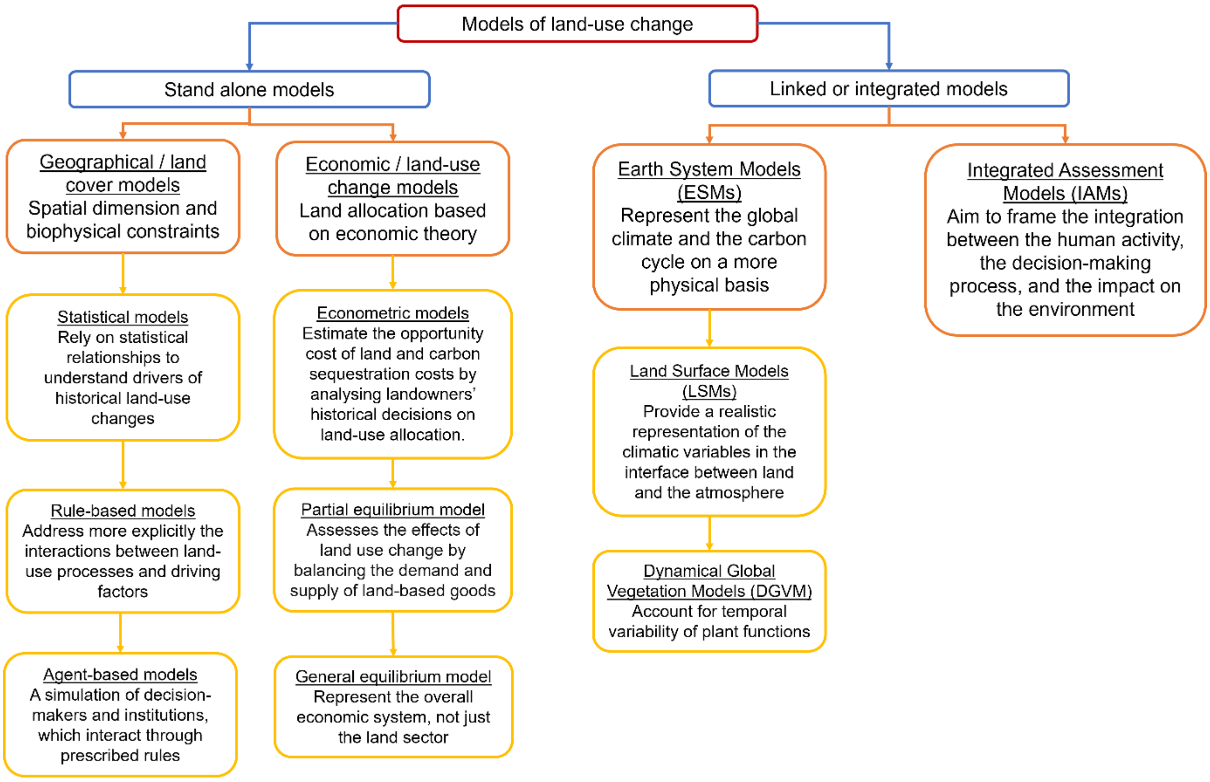

Figure 2.1: Overview of classification of land-use models. Source: Own work based on Michetti and Zampieri (2014), Noszczyk (2019), and van Soesbergen, (2016).

Choosing the most appropriate land-use model can largely depend on the problem at hand; for example, statistical models may not capture decision-making processes well (Sun and Robinson, 2018), which are often better represented by agent-based models (Rounsevell et al., 2014); or when they are integrated with other modelling techniques. Some models focus on simulating the spatial distribution of land-use change, such as the PLUS (Patch-generating land-use simulation) models (Lin and Peng, 2022); or simulating both the land-use change and the consequences of those changes such as the CLUE (Conversion of Land-use and its Effects) model, which has been used widely to better understand the processes that determine land-use change trajectories and their impacts at the regional scale (Verburg and Overmars, 2007). Ultimately, the selection of a land-use model depends on the specific research questions and the desired outcomes, emphasising the importance of aligning model capabilities with research objectives.

2.3.3. Downscaling land-use change models

Outputs from land-use and scenario modelling often lack sufficient spatial resolution for them to be used in effective national or sub-national policy decision-making (Woodman et al., 2023). Information at a coarser scale can be translated to finer scales, effectively increasing the spatial resolution whilst maintaining consistency with the original dataset, through a process called downscaling (van Vuuren et al., 2010; Atkinson, 2013).

Downscaling is beneficial for bridging the gap between the biophysical global processes, and more regional or local impacts (Ermoliev et al., 2017), and testing the feasibility of pathways or scenarios. Downscaled outputs can also support localised impact assessments, which are required for effective decision-making for developing efficient mitigation and adaption strategies (Estoque et al., 2020). In the context of the UK, downscaling global or regional land-use model outputs, or national land-use or commodity data, to a sub-national level is particularly beneficial given the devolution of governance and environmental policy.

A variety of methods for downscaling exist, which range in complexity from simpler arithmetic processes to more complex multi-scale models (van Vuuren et al., 2010). The simpler downscaling methods disaggregate data from different scales; either through assuming elements have the same growth rates (proportional downscaling) or through using an average regional value to disaggregate data (convergence downscaling) (van Vuuren, et al., 2010). More complex algorithms include statistical downscaling, which can derive statistical relationships between observed historic data and climate global model data to produce fine resolution data assessing the local impacts of climate change (Tabari et al., 2021). Models can also be integrated to solve issues relating to different scales, through coupling models. The most complex multi-scale coupled models interactively link different scales, where data at more aggregated levels is downscaled to lower aggregation for more dynamical use as part of the modelling process (van Vuuren et al., 2010). These diverse downscaling methods provide essential tools for translating global data into actionable insights at regional and local levels.

Spatial resolution is a technical challenge for research that is focused on the impacts of land-use change (Le Page et al., 2016). This is of particular concern when wanting to couple climate models and IAMs that are spatially disaggregated into geopolitical regions, with land-use models that typically operate at gridded scales. Previous research has downscaled global climate model simulated precipitation projections to specific catchments for assessing the drought risk on vineyards in Germany (Hofmann et al., 2022); or downscaled global land cover model projections for exploring the effects of different mitigation pathways (West et al., 2014). Finally, integration of methods can include incorporating more qualitative methods to improve downscaling, to ensure the results are representative of local areas. Rickebusch et al. (2011) combined a rule-based downscaling method for downscaling European land-use scenarios with increased thematic resolution of land-use categories for landscape level results through incorporating an element of local decision-making that enabled the projections to be more representative of reality.

2.4. Integrating global and national policy action

There is now international consensus that immediate action is required to limit anthropogenic warming and reverse biodiversity decline, with the adoption of long-term targets such as the Paris Agreement and Kunming-Montreal GBF. However, there is an urgent need to translate these targets into actions (Mosnier et al., 2022). Scenarios designed at a national level are key to ensuring representation of more local priorities, cultures and contexts that are vital for developing national climate and environmental policies for international agreements (Mosnier et al., 2023). In this vein, the SSPs have been increasingly interpreted at a European scale (Kok et al., 2019) and a national scale to inform national level climate policy development (Merkle et al., 2023; Frame et al., 2018; Chen et al., 2020, Lehtonen et al., 2021).

Bridging the gap between global policies and national actions presents numerous challenges, driven by the complexity of different contexts such as economic disparities, political environments and varying institutional capacities. Scenarios and modelling can be used to investigate how national targets and contexts contribute to global goals. However, as countries are connected through international agreements and international trade, it is important to understand and represent these connections in such efforts. One of the largest multidisciplinary collaborations aimed at supporting the development of nationally autonomous yet globally aligned land-use pathways, while maintaining the international balance of trade, is the Food, Agriculture, Biodiversity, Land-Use and Energy (FABLE) consortium (Mosnier et al., 2022; Jones et al., 2023a). A key objective of the FABLE consortium is to build capacity among its members to use multi-objective assessment tools to help understand options and design integrated food and land-use policies. The major innovation of FABLE is that it allows countries to develop their own pathways that meet domestic priorities, and iteratively refine them to collectively meet global sustainability goals. The consortium's efforts are essential in demonstrating how collaborative, well-informed strategies can bridge the global-national policy gap and drive sustainable land-use transformations worldwide.

2.4.1. The FABLE approach

The FABLE consortium consists of 24 country teams, that learn, share, create and apply knowledge and tools to develop bottom–up, mid-century, integrated national pathways, that aim to address local development priorities and international agreements (Jones et al., 2023a). These national pathways are then combined with pathways for six ‘rest of the world’ regions to simulate results at the global level, to solve trade imbalances and determine if global targets are met. This iterative process of aligning the national pathways with global targets and trade is termed a *scenathon*, a 'marathon of scenarios', and is depicted in Figure 2.2 (Mosnier et al., 2023).

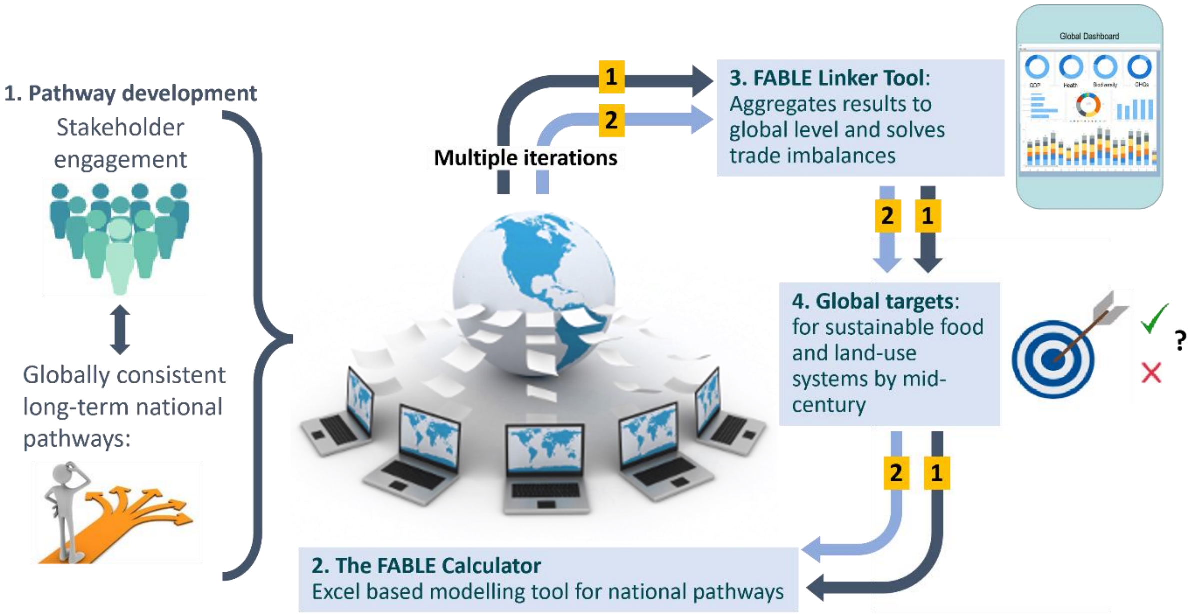

Figure 2.2: the FABLE consortium scenathon process. Source: Smith and Harrison et al., 2022

First, as described by Mosnier et al., (2023), the scenathon process begins with the FABLE consortium members agreeing on global sustainability targets, which contain a mix of science-based and political targets, and broad narratives for the national and regional pathways. The global targets focus on five critical food and land-use system domains: 1) land and biodiversity, 2) climate change and GHG emissions, 3) food and nutritional security, 4) freshwater use, and 5) nitrogen and phosphorus pollution (Mosnier et al., 2022). The targets are regularly revised, alongside the quantifications to monitor the progress. In the 2020 scenathon, each country team developed a "Current Trends" pathway, that corresponds to a low ambition of feasible action, and a "Sustainable" pathway, that corresponds to stronger national political action toward the achievement of global sustainability, matching policy aspirations. National pathways are grounded in local and national stakeholder knowledge, which is used to parameterise the pathways (Jones et al., 2023a).

Second, the pathways are simulated using the FABLE calculator, an open-source tool developed by the consortium (described in section 2.4.2). Third, the outputs of the pathways are then submitted to an online platform, the FABLE linker tool, to allow for comparison of results across countries, and for aggregation of results at the global level. This includes a trade evaluation step, whereby exports are proportionally adjusted to match global imports. This ensures that the evolution of trade is driven by country assumptions about their internal demand. Fourth, the national and regional results are summed and compared to the global sustainability targets. For each indicator that fails to achieve its global target, country teams are invited to strengthen the ambition of their “Sustainability” pathway before resubmitting to the online platform (Mosnier et al., 2022). Finally, the trade evaluation step is repeated and final results for each global target are displayed on an online platform, where participants and those interested can then see whether, given national policy aspirations, global targets are collectively met by 2050.

The FABLE consortium has published two global reports on the country pathways to sustainable land-use and food systems (FABLE, 2019; FABLE, 2020), as well as policy briefs on the impacts of dietary shifts at global and national scales (FABLE, 2021), pathways for land-use and food systems that contribute to biodiversity targets (FABLE, 2022a), and food and land mitigation for net-zero (FABLE, 2022b). The FABLE Consortium also contributed to the Sustainable Development Report 2024 (Sachs, et al., 2024), on transforming land-use and food systems to achieve SDGs, highlighting change levers to guide sustainable development policies to 2030 and to 2050, together with risks of trade-offs and opportunities for synergies (FABLE, 2024). These publications highlight the consortium's vital role in providing evidence-based insights and recommendations across the land-use and food sector internationally.

2.4.2. The FABLE Calculator

The FABLE Calculator is an open-source, Excel-based food and land-use system assessment tool, which is relatively easy to use, yet complex enough to provide reasonable estimates of multi-objective impacts (Jones et al., 2023a). It is designed to work at a national level, supported by data from global datasets such as FAOSTAT, which can be modified with more specific national data where available and appropriate.

As described by Mosnier et al. (2020), the calculator is driven by the demand for 88 agricultural (raw and processed) products from crop and livestock sectors, which are determined by the pathway assumptions on current and future diets, as well as population projections. For each five-year time step over the period 2000 to 2050, the calculator computes the per capita demand for consumption of products, the total demand accounting for food waste, imports and exports, the livestock numbers to meet this demand, and the associated demand for cropland and pasture, considering demand for animal feed crops. The final land-use is calculated, taking into account the competing demands for land for urban expansion, afforestation and protected areas. If there is insufficient land to meet demand, there is a land adjustment step, whereby crop and pasture area is scaled to a ‘feasible’ area, which could lead to food consumption targets not being met. This final ‘feasible’ land-use is used to calculate a range of output indicators, including GHG emissions from agriculture and land-use change, and land supporting biodiversity.

The calculator has several limitations. These include: the use of broad land-use categories (cropland, grassland, urban, forest and other natural land); not accounting for differences in productivity, biodiversity value or carbon storage of agricultural land and forested areas under different management categories (e.g., agroforestry versus monoculture cropland, or extensive versus intensively managed pasture); and it is not spatially explicit (Smith and Harrison et al., 2022). Whilst limitations remain, the collaborative approach focused on the same tool has significantly accelerated the identification and resolution of problems in the model (Mosnier et al., 2022), and these limitations are consistently being updated by the secretariat, as well as country teams through adaptation to their contexts. Furthermore, the limitations do not stop the FABLE calculator being a useful tool across the country teams as evidenced by its recent use in the FAO State of Agriculture report, the current IPBES Nexus assessment, as well as supporting national teams to feed into policy design and development.

2.5. UK context of the thesis

The UK faces challenges surrounding climate change, biodiversity loss and public health, particularly given its relatively large population and small land area. This finite land resource must meet many competing land-use demands and ecosystem services. Additionally, complex land tenure and political governance further complicate these issues (Field et al., 2020). The UK’s Committee on Climate Change (CCC), the independent advisory body to the UK Government, note that the current approaches to land-use in the UK are not sustainable, and should they continue as is, it will not be able to support future demands for settlements, per capita food production, or be prepared for climate change (CCC, 2018).

2.5.1. Food and land-use in the UK

The UK food system includes a wide range of activities, e.g., production, processing, marketing, retail, consumption and disposal, undertaken by a wide range of actors across multiple spatial, temporal and jurisdictional scales (Hasnain et al., 2020). The UK agri-food sector is a major driver of economic growth, contributing 9.4% to GVA in 2018. However, it faces multiple challenges including unhealthy diets contributing to health-related diseases and unsustainable production driving biodiversity loss, soil degradation and pollution (Hasnain et al., 2020). Recent shocks and stresses on the UK food system, such as the COVID-19 pandemic, highlighted vulnerabilities in the UK food system, with the pandemic impacting all four pillars of food security (access, availability, utilisation and stability) at a national, as well as at the global level (Duckett et al., 2021). Recovery from the pandemic presented an opportunity to better align policies to improve the resilience of the UK food system, as well as an opportunity to rebuild it to address the wider threats to the food system and society, such as climate change and biodiversity challenges (Rivington et al., 2021).

Land-use in the UK is diverse, ranging from lowland arable lands in southeast England to upland grasslands in parts of England, Scotland and Wales. Land-use is predominantly used for agriculture, with 42% used for grasslands and 24% for arable land (Rowland et al., 2017a, b). The rest of the UK includes 15% mountainous, heath and bog areas, 8% forested areas, 6% urban and 5% water and coastal ecosystems (Rowland et al. 2017a, b). The pattern of land-use in the UK reflects the geology and soils, as well as reflecting historic national economic development, industrialisation and urbanisation (Burchardt et al 2020). As demonstrated in the *State of Nature Report* (2019), the abundance and distribution of the UK's species has on average declined 13% since 1970, with 15% of species threatened (Hayhow et al, 2019). Agricultural activity has contributed to the net loss of biodiversity, particularly linked to the intensification of land management, which is still increasing in the UK (Hayhow et al., 2019). In addition, thousands of hectares of farmland and woodland are built on each year through urbanisation (Hayhow et al., 2019).

Land-use in the UK has been highly influenced by a complex set of national, EU and international policies (CCC, 2018). Over the last few decades land-use in the UK has undergone significant changes as a result of multiple policy drivers, economic shifts and increasingly environmental impacts (Cole et al., 2022). Direct decisions over rural land-use remain largely in the hands of a small set of private landowners (Burchardt et al., 2020), whose actions whether in relation to access, conservation or community development, have not always been well aligned with wider social and environmental priorities.

2.5.2. Climate and environmental policy in the UK

The UK is at an important juncture in terms of its climate and environmental policy. Following the UK's exit from the EU, there are new opportunities to address climate change and biodiversity loss through the implementation of innovative policies (Stafford et al., 2021). Such policies are important to ensure the UK meets its commitments to the international agreements to which it is a signatory, including the Paris Agreement and the Kunming-Montreal GBF, as well as its own environmental laws, such as the 2019 amendment to the *Climate Change Act 2008* that states that GHG emissions must reach net-zero by 2050 (Booth, 2021).

Agricultural policy in the UK has previously been formulated in relation to globalised agricultural trade and fluctuating commodity prices, something that policymakers and food producers have little or no control over (Burchardt et al., 2020). For over 40 years, the relationship between the UK Government and the farming sector has been dominated by the EU's Common Agricultural Policy (CAP), which has determined the public subsidies paid to farmers (Bateman and Blamford, 2019). Designing a replacement for the CAP provides an opportunity for better alignment of land-use strategies, environmental priorities and local contexts (Reay et al., 2020), that potentially incentivise actions for achieving climate and biodiversity targets.

In the UK, there are separate legislatures and executives in Scotland, Wales and Northern Ireland, each with its own unique devolution settlement. The reallocation of resources between Westminster and the devolved governments is asymmetric and complex, with each of the devolved governments receiving differing degrees of powers and responsibilities (Cowell et al., 2017). The core framework of agricultural policies and rules emanates from central UK Government for reserved matters (such as trade and financial support), and largely from the devolved governments on agriculture and the environment (Petetin, 2022). Different policy contexts of the devolved nations, coupled with their different ecological conditions and histories (Burns et al., 2018) influence new policy design and its potential success. Consequently, the capacity of the UK to deliver on international and domestic environmental agreements is dependent on the actions, policies and land capabilities of the devolved nations, as relevant policy fields for achieving both climate and biodiversity targets in the AFOLU sector fall under the competencies of both Westminster and the devolved governments (Nash, 2021).

Given the complex land-use and political context of the UK and devolved nations, implementing policy uniformly across the regions can be challenging. This diversity presents a unique opportunity to explore alternative policy pathways for achieving international climate and biodiversity agreements at a UK level, whilst accounting for different regional aspirations and contexts. This thesis aims to provide evidence for decision-makers for developing policy measures, through examining alternative pathways for land-use and food systems in the UK and the devolved nations to achieve national and international climate and biodiversity targets. Pathways are developed for the devolved nations, through stakeholder engagement and policy review, combining policies for afforestation, peatland restoration, agricultural productivity, food waste, and areas for biodiversity conservation. This approach allows different policy contexts to be reflected in the pathways. The feasibility of the pathways given land constraints are explored, adding value to the FABLE outputs for decision-makers developing policy. The thesis explores the challenges, trade-offs and synergies for achieving net-zero and reversing biodiversity decline across the national and sub-national scales.

3. Pathways to achieving nature positive and carbon neutral land-use and food systems in Wales

Abstract

Land-use and its management can play a vital role in carbon sequestration, but trade-offs may exist with other objectives including food security and nature recovery. Using an integrated model (the FABLE calculator), four pathways, co-created with colleagues at the Welsh Government, towards achieving climate and biodiversity targets in Wales were explored: Status Quo, Improvements on Current Trends, Land-sparing and Land-sharing. We found that continuing as usual will not be sufficient to meet Wales's climate and biodiversity targets. In contrast, the land-use and agricultural sector became a net carbon sink in both the Land-sparing and Land-sharing pathways, through high afforestation targets, peatland restoration, reducing food waste and moving towards a healthier diet. Whilst both pathways released land for biodiversity, the gains were greater in the Land-sharing pathway, which was also less dependent on optimistic assumptions concerning productivity improvements. The results demonstrate that alternative approaches to achieving nature positive and carbon neutral land-use and food systems may be possible, but they come with stringent and transformative requirements for policy changes, with an integrated approach necessary to maximise benefits for climate, food and nature.

Key Words

Land-Use; Biodiversity; Policy; Diet; Agricultural productivity

3.1. Introduction

Land-use and food systems are prominent in many global environmental change challenges (Meyfroidt et al., 2019). Land provides the principal basis for human livelihoods, by supplying food, freshwater, biodiversity and many other ecosystem services (IPCC, 2019). However, global population growth and changes in per capita consumption of food, fibre, timber and energy have caused unprecedented rates of increase in land and freshwater use (IPCC, 2019). Climate change creates additional stresses on land-use, exacerbating existing risks to livelihoods, human and ecosystem health, biodiversity and food systems (IPCC, 2019). At the same time, land-use can play a vital role in combatting climate change by providing options for enhancing carbon sinks

(Arcanjo, 2020). Land-use change is seen as one of the greatest threats to biodiversity globally through habitat loss, pollution and over-exploitation (Hoskins et al., 2016), and action is needed to reduce the intensity of drivers of biodiversity loss, such as land-use change (IPBES, 2019). Conserving biodiversity and increasing global food security are two of the world's most pressing challenges (Glamann et al., 2017). Therefore, there is an urgent need for decision-making and policy to manage land-use across multiple geographic scales and multiple ecological dimensions (Foley et al, 2005).

Over recent years there has been significant awareness of, and commitment internationally to, reducing the impacts of climate change, reversing biodiversity decline and improving agricultural systems. For example, the Paris Agreement aims to hold the rise in average global temperatures to below 2°C (CCC, 2019). Other agreements include the Convention on Biological Diversity's (CBD) Global Biodiversity Framework (GBF) and the UN Sustainable Development Goals (SDGs). The UK is a signatory to all these international agreements, and the effective use of land will be key if the government is to achieve its long-term policy commitments. However, current food systems in the UK are often deemed unsustainable, with fragmented past policies that favour food production over other services that land can provide. Leaving the European Union (EU) has raised the profile of UK food systems and food security with policymakers (Lang, 2020), and there is recognition that UK policy goals for climate change and biodiversity are unlikely to be met without fundamental land reform (CCC, 2018).

Potential options for achieving targets for sustainable land-use focus primarily on transformations that maintain the functions of land, whilst mitigating climate impacts through emissions reductions (CCC, 2019). A land configuration advocated for by the UK Climate Change Committee (CCC), the independent advisory body for UK and devolved governments, is the land-sparing scenario (CCC, 2018); where an intensification of farming practices reduces the area of farmland needed to meet food demand, and, thus, enables restoration of land for biodiversity conservation and carbon sequestration (Redhead et al., 2020). By contrast, a land-sharing approach is characterised through integrating food production, carbon sequestration and biodiversity conservation on the same land, increasing the amount of farmed land, by reducing the intensity of agriculture (Redhead et al., 2020).

Previous research explored transformations to sustainable land-use and food systems at the global scale, focusing on achieving food security and eradicating hunger and malnutrition (FAO, 2018b), linking food security, land-use, health and nutrition (Mora et al., 2020), modelling agroecological scenarios (Poux and Aubert, 2018), and demonstrating how agroecology can aid in reaching EU policy targets (Röös et al., 2022). Other research focused on the role of livestock production and dietary change on land-use and greenhouse gas (GHG) emissions (Hedenus et al., 2014; Röös et al., 2017), and the potential for a global transition towards organic agriculture (Muller et al., 2017). Some research has also focused on the importance of multiple policy goals to support food systems that benefit all actors in the system (Parsons and Hawkes, 2018). Models that operate at the global scale, like those used in these studies, lack local insights and stakeholder knowledge on the cultural and political contexts that are important for national planning (Smith and Harrison et al., 2022).

Studies on land-use and food system transformations are rarer at the national scale compared to the global scale. Previous research for the UK explored future agricultural land demands, providing perspectives on the main drivers of change (Angus et al., 2009); linked metrics on environmental sustainability and nutrition (de Ruiter et al., 2018); or the literature to highlight how changes in food systems could benefit a population's health (Bash and Donnelly, 2019). Other research modelled the impacts of climate change on agricultural productivity (Fezzi et al., 2014); and the projected changes in GHG emissions due to shifts in agricultural land-use (Abson et al., 2014). Some studies considered the consumer perspective on what the future of the UK food system should look like (Rust et al., 2021; O'Keefe et al., 2016). These studies raised awareness of different aspects of land-use and food system transformations in the UK using a range of qualitative and quantitative methods. Nevertheless, existing models are unable to test the wide range of land-use policy and options of interest to UK policy stakeholders for achieving multiple sustainability targets (Smith and Harrison et al., 2022). Research is needed that explores a range of pathways of land-use and food system transformation using locally-relevant integrated modelling in partnership with those stakeholders directly responsible for the design of more holistic and multi-objective land-use policies (Sharmina et al., 2016; FFCC, 2018).

This research addresses this need through working in close collaboration with national government representatives, through several rounds of iteration, to co-design pathways to achieving nature positive and carbon neutral land-use systems in Wales. Four pathways were co-designed that include a wide range of policy levers relevant to the Welsh context: shifting food consumption patterns, planting trees, establishing new protected areas and land conservation, improving productivity, restoring peatland and reducing food waste. These include two alternative land configuration pathways that were of specific interest to the Welsh Government, land-sparing and land-sharing, given the biophysical constraints for agriculture in Wales and potentially differing views on land-use transformations between Wales and the UK CCC. This is particularly important as agricultural, environmental and land-use policies are devolved in the UK, with the different Devolved Administrations favouring different approaches to land reform. The pathways were simulated by adapting the UK version of the Food, Agriculture, Biodiversity, Land and Energy (FABLE) Calculator (Smith and Harrison et al. 2022) for Wales; an Excel-based integrated model developed by the international FABLE consortium. The co-benefits and trade-offs associated with the different pathways for achieving multiple policy goals were compared and analysed and used to support government planning in response to policy commitments.

3.2. Methodology

3.2.1. Welsh context

The focus of this research was the devolved administration of Wales, which sits to the west of England and covers 2,077,000ha. Land in Wales is mainly grazed grassland (70% of land area), with 25% of this being rough pasture (Rowland et al., 2017), and approximately 15% of land cover being forest (Figure A1). Around a quarter of the land area is designated as National Park or Area of Outstanding National Beauty and is important for biodiversity and recreation. Wales's natural environment is considered one of its most precious resources, being central to the health and wellbeing of the population and economy (Natural Resources Wales, 2020a). The wet climate and mountainous areas of Wales mean that most of the land is better suited to pasture and livestock farming rather than arable cropping, with only a small number of holdings dedicated to crops (Armstrong, 2016).

In 2017 agriculture contributed 0.8% of total GVA for Wales and is a higher percentage of the economy than it is for the UK as a whole (Welsh Government, 2019a). Average Welsh farm holdings are 48ha, smaller than those in England and Scotland, and the relatively low levels of intensive farming result in smaller incomes relative to similar sized farms in England (Armstrong, 2016). The agriculture sector output focuses heavily on livestock (51%) and livestock products (35%), mainly lamb, beef and milk (Armstrong, 2016). Farmers are the largest group of land managers in Wales (Welsh Government, 2019a), and the contribution made by farmers to the appearance of the Welsh landscape is often cited as an indirect and important way in which agriculture contributes to the Welsh economy.

Despite falling 11% since 1990, agricultural emissions have increased since 2016 (CCC, 2020b), with emissions from livestock accounting for 54% of agricultural emissions. Land in Wales acts as a net carbon sink, predominantly due to forested areas sequestrating carbon (CCC, 2020b). The Land-use, Land-use Change and Forestry (LULUCF) sector in Wales comprises of both sources and sinks of carbon. Sources of emissions stem from conversion of land-use from grassland to cropland, existing cropland, grassland conversion to settlements and existing settlements (Welsh Government, 2019a). The largest carbon sinks are existing forest, conversion of land from cropland to grassland and existing grassland (Welsh Government, 2019a).

Wales is subject to the administration of the UK Government in Westminster and the Welsh Parliament in Cardiff (ONS, 2021). The Welsh Parliament has devolved competency for environment and agricultural policy and does not have responsibility for energy policy or trade at a strategic level. Welsh Ministers have made commitments to reach net-zero carbon by 2050 through amendments to *The Environment (Wales) Act 2016* as well as further commitments for maintaining and enhancing a biodiverse natural environment domestically through *The Well-being of Future Generations (Wales) Act* (Welsh Government, 2015), and the Nature Recovery Action Plan 2020-21 (Welsh Government, 2020). Given the departure of the UK from the EU, and the pressure of delivering on Wales's own domestic climate commitments, as well as those of the UK, the Welsh Government is at a significant point in terms of designing future policy.

3.2.2. The FABLE approach

The FABLE consortium aims to understand how countries can transition towards sustainable land-use and food systems and collectively meet associated SDGs, biodiversity targets and the objectives of the Paris Agreement (FABLE, 2020; Jones et al., 2023a). The 20 country teams design bottom-up pathways to address national priorities and collectively achieve global sustainability targets, using the specially developed FABLE Calculator. These national results are then combined with pathways for seven 'rest of the world' regions to simulate results at the global level. Global targets are formulated by the consortium and incorporate objectives on land-use and biodiversity conservation, GHG emissions from agriculture and land-use, food security, freshwater use, and nitrogen and phosphorus use. Once national pathways are developed, the FABLE approach includes an iterative stage where key parameters and results of the pathways from all participating country teams are aggregated to determine if the global targets are met (Mosnier et al., 2020). The FABLE approach is built on extensive stakeholder engagement, and this participatory approach facilitates close links to current and future policy goals during the development of the assumptions underlying the pathways.

The FABLE Calculator is an open-source Excel-based tool used to study the potential evolution of food and land-use systems over the period 2000 to 2050 (Mosnier et al., 2020). It is designed to work at a national level, supported by data from global datasets, such as FAOSTAT (FAO, 2020). For each pathway, the calculator aims to solve the major transformations that are needed to achieve them from the present-day land-use configuration (FABLE, 2020), and test the impact of different policies related to the agriculture and land-use sectors.

The calculator, as described by Mosnier et al (2020), is driven by the demand for 76 agricultural (raw and processed) products from crop and livestock sectors, determined by assumptions concerning current and future diets and population levels. For each five-year time step over 2000 to 2050, the calculator computes the *per capita* demand for consumption of different products, the total demand considering food waste, imports and exports, the livestock numbers needed to meet the demand, and the associated demand for cropland and pasture, considering demand for animal feed crops. The final land-use change is then calculated, taking account of competing demands for land for urban expansion, afforestation and protected areas. If there is insufficient land to meet demand, crop and pasture area is scaled down to the 'feasible' area, which may result in targets for food consumption not being met. The final 'feasible' land-use change is then used to calculate GHG emissions from agriculture and land use change, as well as food security and biodiversity indicators. The calculation steps are shown in Figure A3.

3.2.3. Participatory approach with the Welsh Government

Bohunovsky et al. (2011) argue that participatory approaches to develop scenarios at the regional level can be valuable, and perhaps essential, for deriving solutions that lead to real-world application. As mentioned, the FABLE approach relies extensively on stakeholder engagement, so for this research we devised a participatory approach with colleagues from the Welsh Government for the co-creation of pathways, to ensure precision in how future policy developments were represented in the pathways, and cohesion across different policy areas. The co-creation of the pathways took place through seven meetings between April and September 2021, supplemented by numerous email exchanges. Three Welsh Government representatives participated in the meetings, acting as intermediaries to colleagues in relevant Welsh Government policy departments.

The first meeting focused on defining the overall scope and number of pathways to be co-developed. A template listing the assumptions and data required to parameterise the FABLE calculator for each pathway was created by the project team and shared with the

Welsh Government. Subsequent meetings gradually filled the template with explicit assumptions representing either current policy or policy ambitions. The iterations enabled the project team to explain the precise requirements for the calculator, allowing Welsh Government colleagues to gather input from different policy teams, covering a wider policy context. The iterations also informed adaptations to the calculator to better meet Welsh Government needs, and aided understanding by Welsh Government of the assumptions underlying the calculator, including what could and could not be modelled, to ensure output indicators were not misinterpreted. It should be noted that the timing of the study did not align with submitting Welsh pathways to a global iteration within the wider FABLE consortium, meaning a global trade adjustment was not included for Wales.

3.2.4. Pathway development

Four pathways were co-created with the Welsh Government, two representing current policies or slight improvements in current policies, and two that represent alternative approaches with a higher ambition of realistic action to reach sustainable land-use and food systems.

3.2.4.1. Common assumptions across the pathways

Population estimates, used to calculate future food demand, were taken from the Office for National Statistics (ONS), which forecasts the Welsh population to increase from 3.153 million in 2019 to 3.258 million by 2050 (ONS, 2019). The demand for land for urbanisation was based on the projections of population growth and associated increases in urban area from the Welsh Government's 20-year spatial plan (Welsh Government, 2021b). This results in an estimated 5% increase in urban area for Wales, from 105,773 ha in 2015 to 110,000 ha in 2050, equalling approximately 5% of total land area in 2050.

Whilst the outcomes of leaving the EU remain uncertain, the level of uncertainty is reduced to some extent by the existence of an EU trade deal. However, the impacts of future trade agreements remain unknown, and the Welsh Government has commissioned research to better understand the range of potential outcomes (Harrison et al., 2022). Therefore, in the absence of further information, and on the advice of experts within the Welsh Government, it was assumed that the share of total consumption that is imported and the quantity (in tonnes) of total production exported remain the same up to 2050.

For each pathway it was assumed that any woodland planting would be subject to Glastir Woodland Creation (a Rural Development Programme scheme) constraints (Welsh Government, 2019b), and all planting would be compliant with the UK Forestry Standards (Forestry Commission, 2017). This includes conditions on the minimum area of open ground managed for conservation, and how much of the forest management must be managed for conservation and biodiversity. For Pathways 1 and 2, new forest was assumed to be created in line with the existing split between broadleaved (51%) and coniferous (49%) woodland. For Pathways 3 and 4, 22% of new forest should be aimed at supporting biodiversity, assumed to be seminatural woodland, and the rest assumed to be plantations, which is line with Welsh Government policy.

At this moment, there are no plans for policy to increase the amount of energy derived from biofuels, due to the physical geographical constraints of Wales, so this was not included in the pathways.

3.2.4.2. The pathways

The Status Quo pathway corresponds to the lowest boundary of feasible action, continuing with no changes to current policies. The second pathway represents slight improvements to the current system, in line with current trajectories and reflecting current trends in policy.

The third pathway, and the first representing system change, is the Land-sparing pathway, which represents broadly the UK land-use strategy proposed by the UK CCC in its Land-use report (CCC 2018), and further referenced in *The path to Net-zero: Progress on reducing emissions in Wales* (CCC, 2020b). The pathway focuses on an intensification of agricultural production using sustainable techniques on the most productive land. This, together with reductions in food waste and dietary changes, releases land for biodiversity conservation and afforestation to sequester carbon.

The fourth pathway, the Land-sharing pathway, represents a different approach to system change, and is a consequence of the desire from Welsh Government to develop a different approach that is more closely aligned to Welsh Government policy ambitions. It uses land management techniques to deliver biodiversity restoration, carbon sequestration and food production simultaneously on the same land. It is primarily based on the principles of the *Sustainable Management of Natural Resources strategy* and *The Environment (Wales) Act*, which aim to deliver multiple objectives on the same land (Welsh Government, 2018).

An overview of the differences between the pathways can be seen in Table 3.1, with the underlying assumptions and justifications seen in the Online Resource and Table A1.

Table 3.1: Overview of the key differences in assumptions for the pathways

Characteristics	Pathway 1: Status Quo	Pathway 2: Improvement on Current Trends	Pathway 3: Land-sparing	Pathway 4: Land-sharing
Agricultural expansion	No constraints on agricultural expansion except for protected areas, which does not include National Parks, AONBs and Heritage Coasts.	No constraints on agricultural expansion except for protected areas, including National Parks, AONBs and Heritage Coasts.	No constraints on agricultural expansion except for protected areas, including National Parks, AONBs and heritage coasts.	No agricultural expansion on existing habitats, including all existing semi-natural habitats. Aspirations to create 500,000 ha of additional semi-natural habitat.
Crop productivity	No change to current levels.	No change to current levels.	Increased productivity (+65%).	Increased productivity (+39%).
Livestock productivity	No change to current levels.	No change for beef & poultry. Productivity increases for dairy (+37%) and lamb (+17%).	No change for beef. Productivity increases for poultry (+10%), dairy (+50%) and lamb (+52%) beef and lamb.	As pathway 2, but with additional increases for lambing (+41%).
Stocking density	Current stocking densities of 2.2 livestock units per hectare on	Slight increases in stocking density (132% compared to baseline).	100% of the grazing ruminants on intensive grassland by 2050.	Increase to 50% of grazing ruminants using extensive grassland, from 25% today.

	intensive grassland and 0.92 on extensive grassland.		Stocking density doubles on grassland by 2050.	
Afforestation targets	Current levels.	Slight increases to 20,000 ha planted by 2030, rising to 80,000 ha by 2050.	Increases to 43,000 ha planted by 2030, rising to 180,000 ha by 2050.	Increases to 43,000 ha planted by 2030, rising to 180,000 ha by 2050.
Peatland restoration	Current levels of 600 ha/year.	Slight increases to 800 ha/year.	All peatland (90,000 ha) restored to natural state by 2030.	All peatland (90,000 ha) restored to natural state by 2030.
Food waste and post-harvest losses	No change.	Slight reduction in food waste, no change in post-harvest losses.	Reduction in food waste: • 50% reduction by 2025 • 60% reduction by 2030 • Zero Avoidable food waste by 2050 Post-harvest losses reduced by 50% by 2050.	Reduction in food waste: • 50% reduction by 2025 • 60% reduction by 2030 • Zero Avoidable food waste by 2050 Post-harvest losses reduced by 50% by 2030.
Diet of the population	No change to current diet.	No change to current diet.	Healthier, more plant based EatWell diet.	Healthier, more plant based EatWell diet.

3.2.5. Adapting the FABLE Calculator for Wales

The participatory interaction with Welsh Government highlighted several adaptations that were needed to the UK version of the FABLE Calculator (Smith and Harrison et al., 2022) to better represent land-use and food systems in Wales and the specific parameterisations for the Welsh context.

The UK CEH Land Cover Map (LCM) for Wales was used to represent historic land-use (Fuller et al., 2002, Morton et al., 2011, Rowland et al., 2017). The LCM is more accurate than the dataset used for the UK version of the FABLE model (the European Space Agency CCI dataset) and is also used for other modelling within the Welsh Government. However, LCM data are only available for 2000, 2007 and 2015, so interpolation was used to derive data for the years required by the FABLE calculator (2000, 2005, 2010, 2015). The values used in the calculator and the mapping of LCM land classes to FABLE land classes is shown in Table A2 and Table A3.

An important aspect of land-use in Wales that is key to differentiating between different land configurations, is the difference between management of intensive and extensive grassland. In Wales, large areas of rough grassland exist that are grazed extensively, at low stocking densities and with no inputs of fertilisers. The standard version of the FABLE model treats all grassland the same, therefore the calculator was adapted to include a new ‘Extensive Grassland’ category, allowing the representation of different grazing strategies within the pathways. The current stocking densities were derived by fitting to historic livestock numbers and land areas, with 25% of the cattle and sheep grazing on extensive grassland in the year 2000.

In the standard version of the FABLE calculator all forests are treated the same, but for the Welsh pathways the model was adapted to divide forests into semi-natural and plantation. User-defined parameters were added to specify the proportion of new and existing forest that is semi-natural and, therefore, supports biodiversity, as opposed to low diversity plantations of non-native species. These different types of forest were assumed to have different carbon stocks and sequestration rates (Table A4), as a proportion of the carbon stock within a plantation forest will be lost when it is felled and converted to short-lived products such as paper or furniture. The standard FABLE calculator was also adapted to include a basic model of peatland restoration. Peatland areas were divided into ‘intact’ and ‘degraded’ in the calculator, with each being assigned different emissions factors (Table A5). There is currently no separate treatment of peatland-used for forestry or grazing. Deforestation of existing forest is not allowed in the pathways. Further information on the calculation of GHG emissions in the FABLE calculator can be seen in the Supplementary Material (Chapter 9.A).

FAOSTAT data on consumption, production, imports and exports of each product for the UK were downscaled for Wales using the most appropriate scaling factor for each variable (Table A6). As a consequence of discussions with experts in the Welsh Government, consumption was then subtracted from production to obtain imports or exports to and from Wales. At this stage, the assumptions regarding imports and exports of agricultural commodities were checked for consistency, and discrepancies addressed through iterative refinement of pathways through further discussions and refinement of assumptions with the Welsh Government.

The calculator was calibrated to match historic data for the first three-time steps (2000, 2005 and 2010). From 2015 onwards, the scenario assumptions were used to adjust future evolution of parameters. Therefore, it is possible for projections for 2015 and 2020 to divert from historical data (Smith and Harrison et al., 2022). The next development of the model will update the calibration period to extend to 2020.

The adapted FABLE Calculator was applied to the four pathways. A sensitivity analysis was also conducted to explore the impacts of key drivers of the pathways.

3.3. Results

3.3.1. Land-use change

The Status Quo pathway (no changes to current policies in Wales) results in very little change in land-use up to 2050 (Figure 3.1A). The total areas of cropland and grazing are simulated to increase slightly in line with population growth. The increases in urban area and new forest specified in the pathway result in loss of non-forest natural land ('other natural land', mainly bog, heath and wetland). From 2030 onwards there are land constraints in this pathway, whereby all the unprotected non-forest natural land is converted to other uses and, therefore, this pathway is not able to fully meet the demand for agricultural land as further expansion is not possible. By 2050, 133,000 ha of agricultural land demand will not be met, requiring Wales to either import more food or reduce consumption.

The Improvement on Current Trends pathway includes increases in productivity of livestock, which leads to an overall decrease in grassland area (Figure 3.1B). Diet does not change in this pathway, so these changes are driven by productivity and stocking density increases, and reduction in food waste. There are no land constraints in this scenario.

The Land-sparing pathway specifies a shift towards 100% of the ruminant livestock on intensive grassland, therefore extensive grassland area is simulated to decrease to zero towards 2050 (Figure 3.1C). The decrease in both types of grassland is driven primarily by a shift towards healthier diets, zero food waste, productivity increases and doubling of stocking densities. The pathway successfully frees up land for new forest and ‘other natural land’ for biodiversity. However, the intensification of livestock grazing will likely have implications for the use of agro-chemicals.

The Land-sharing pathway assumes the percentage of ruminant livestock on extensive grassland increases from 25% to 50% by 2050 which, therefore, leads to a large simulated increase in extensive grassland coupled with decreases in intensive grassland (Figure 3.1D). All semi-natural land is protected in this scenario for biodiversity, and ‘other natural land’ is projected to increase as cropland and intensive pasture are freed up due to dietary changes. Although less than the Status Quo pathway, there are some land constraints from 2040 due to the high targets for protected areas and afforestation, with 70,000 ha of agricultural land demand not met, requiring increased imports or reduced consumption.

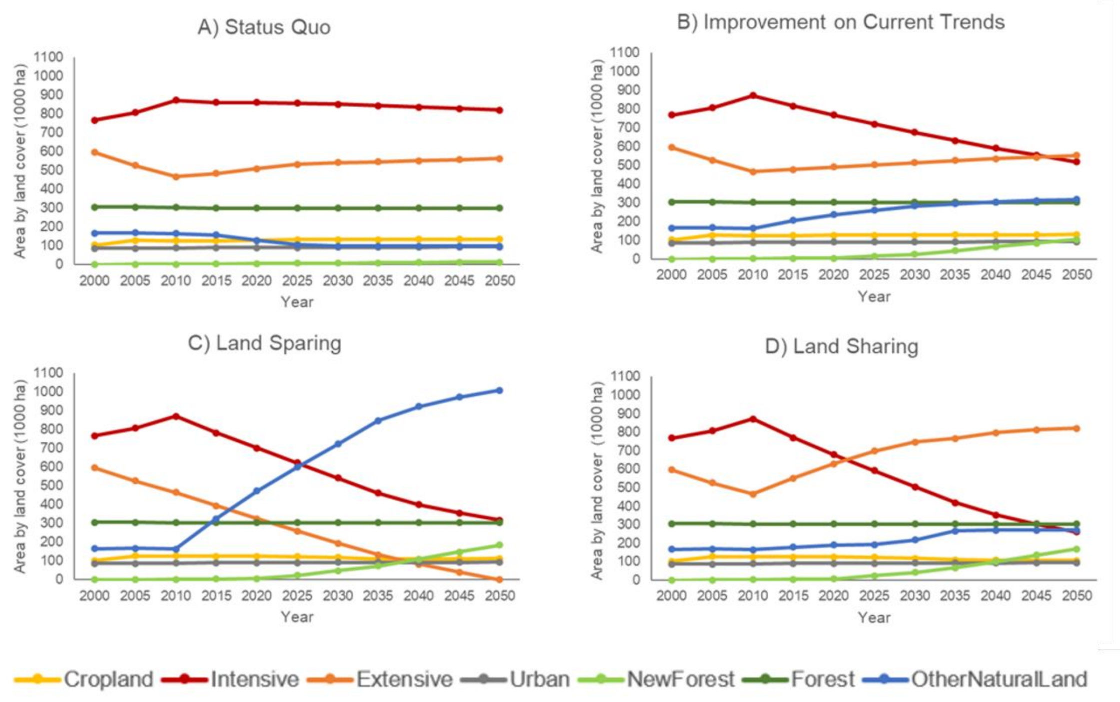

Figure 3.1: Projected land-use change for the four pathways. Note: ‘Intensive’ represents intensively grazed high-input (‘improved’) grassland and ‘Extensive’ represents species-rich semi-natural grassland. “OtherNaturalLand” is defined as mainly peat bog, heath and wetlands. Results are every five-year time step, which are connected by a line to highlight the trends in land-use change up to 2050.

3.3.2. Land that can support biodiversity conservation

The FABLE calculator indicates areas of land that can support biodiversity, composed of species rich semi-natural grassland, ‘other natural land’ comprising mainly peat bog, heath and wetlands, and a user-defined proportion of forested area (i.e. the proportion of new forest area set during pathway development that is semi-natural forest composed of native species to be managed for biodiversity conservation, as opposed to commercial plantations of non-native species).

The Status Quo pathway simulates little change in the availability of ‘other natural land’ for biodiversity, and forest area stays the same due to low afforestation rates (Figure 3.2). The Improvements on Current Trends pathway projects slight increases in ‘other natural land’, and afforestation targets lead to some increases in new forest (Figure 3.2).

The Land-sparing and Land-sharing pathways’ afforestation targets and productivity improvements lead to simulated increases in the availability of land for biodiversity conservation. For Land-sparing this creates 317,000 ha of additional land (a 38% increase) from the 2015 baseline made up predominantly of ‘other natural land’ (Figure 3.2). In comparison, for Land-sharing there is 394,000 ha of additional land (a 45% increase) for biodiversity conservation in 2050, consisting predominantly of extensive grassland, with the assumption that all extensive grassland is managed for biodiversity (Figure 3.2).

The Status Quo and Improvement on Current Trends pathways assume that new woodland planting follows existing splits of about half semi-natural woodland for biodiversity benefit and half for conifer plantation. However, the Land-sparing and Land-sharing pathways assume that only 22% of new woodland supports biodiversity. Hence, although less woodland is planted in the Improvement on Current Trends pathway, it delivers similar biodiversity benefits to the Land-sparing and Land-sharing pathways.

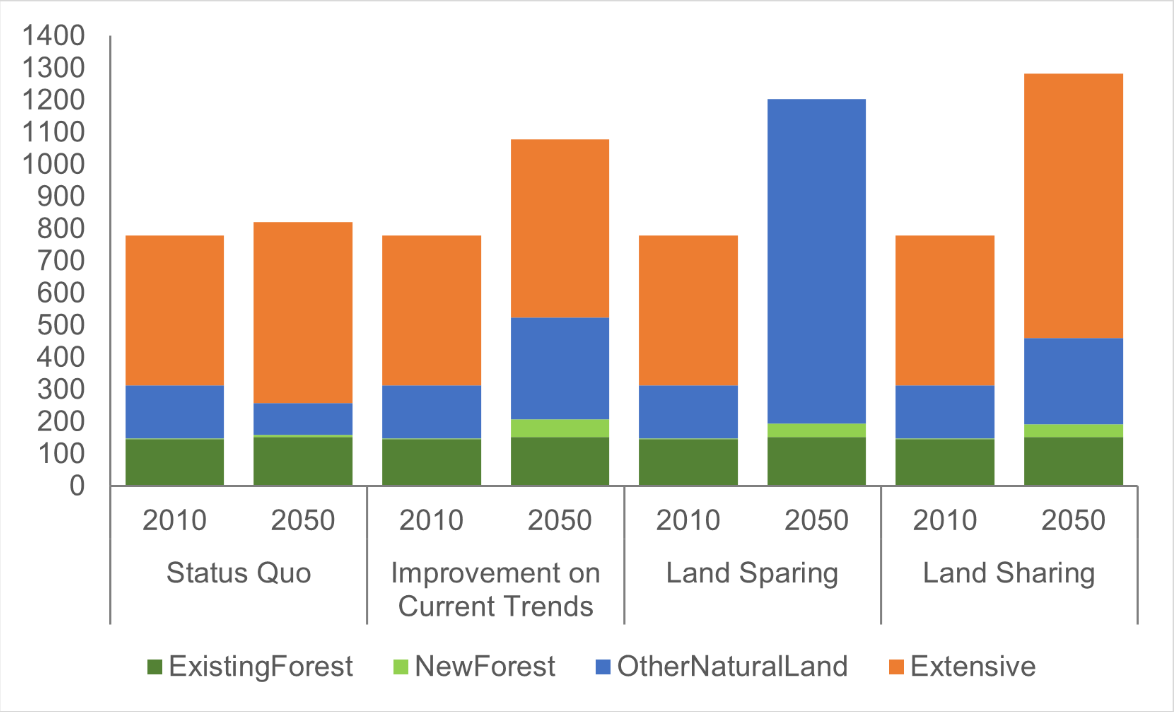

Figure 3.2: Projections of land that can support biodiversity conservation for the four pathways. Note: New Forest only includes the proportion of new forest that is semi-natural and can support biodiversity.

3.3.3. Greenhouse gas emissions

In the Status Quo pathway, the continued gradual loss of natural land due to urbanisation and expansion of farmland to meet the food demand of a growing population results in emissions from land-use change. From 2030 onwards, as all the unprotected natural land has been converted to other uses, emissions from loss of natural land cease and the small sequestration benefit from afforestation is evident (Figure 3.3A). Emissions from peatland reduce slightly due to restoration. Despite the apparent cessation of land-use change emissions after 2030, if imports of food were to increase to make up the shortfall in food production in Wales, this would be expected to cause increased GHG emissions elsewhere.

The Improvements on Current Trends pathway shows that slight increases in productivity reduce the demand for farmland, and restoration of pasture to natural land combined with carbon sequestration from afforestation can shift land-use change emissions to net sequestration (Figure 3.3B). Overall, the total emissions from Agriculture, Forestry and Other Land-use (AFOLU) decrease in this pathway although they remain above zero.

In the Land-sparing pathway GHG emissions from land-use change shift to even higher net sequestration, as large areas of pasture are freed up for restoration to natural land due to healthier diet choices and productivity improvements (Figure 3.3C). Peatland restoration targets are higher in this pathway and, thus, degraded peatland emissions decrease to zero. Emissions from crop and livestock production also decrease due to assumed increases in productivity. However, for this pathway, where intensification of production dominates, the potential impacts of more intensive fertiliser use on GHG emissions are not modelled; emissions per hectare of cropland are assumed to remain constant even as yield increases.

The Land-sharing pathway also leads to a shift in emissions from land-use change to net sequestration due to conversion of intensive to extensive grassland coupled with afforestation (Figure 3.3D). Land constraints from 2045 onwards lead to a slight reversal of this trend. There are decreases in emissions from livestock and cropland due to healthier diets, and emissions from degraded peatland reduce to zero due to restoration. Total AFOLU becomes negative from 2040 onwards, becoming a net carbon sink.

When interpreting GHG emissions results, it should be noted that the land-use change emissions in the initial years of the model output (2000 to 2015) are related mainly to discrepancies in the historic land cover maps, and not as a result of changing parameters, which occur from 2015 onwards.

Figure 3.3: Projected GHG emissions for the four pathways

3.3.4. Sensitivity of impacts to key policy levers

The results show that assumptions related to dietary change and livestock productivity have large impacts on the achievement of multiple policy goals relating to land-use and food production. Thus, we explored the sensitivity of the modelled land-use outcomes to these assumptions.

3.3.4.1. Healthy diets

To understand the magnitude of the impact of moving towards a healthier diet, the Status Quo pathway was re-run assuming the healthier EatWell diet, with other assumptions remaining the same. The results show that switching to the healthier diet reduces meat demand and therefore simulated pasture area, which leads to an increase in 'other natural land' (Figure 3.4B), as land is released from agriculture. This quantifies the extent to which altering diet alone can potentially positively impact land-use change. However, this impact is limited as most meat production in Wales is for export and the pathways assumed no change in exports.

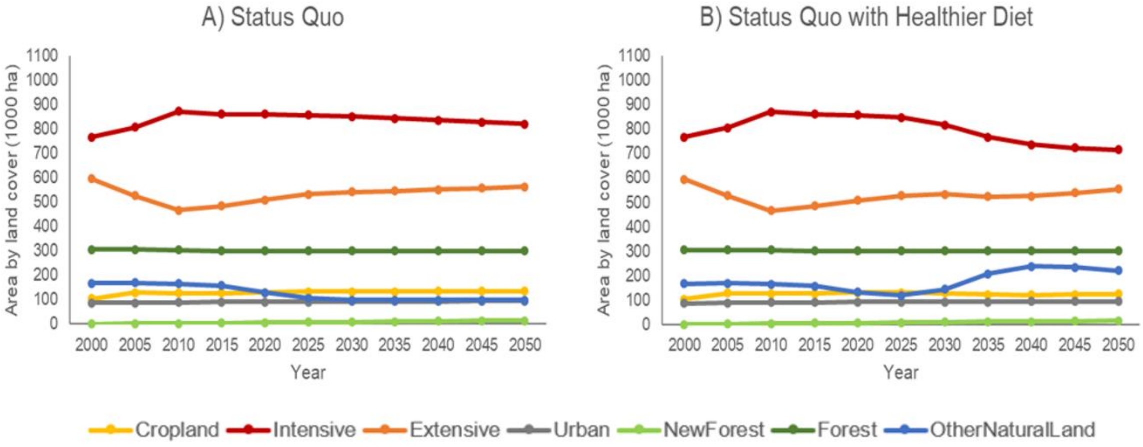

Figure 3.4: Projected land-use change in the Status Quo pathway: A) with all assumptions; and B) including the healthier EatWell diet.

3.3.4.2. Productivity

The large increases in livestock productivity assumed in the Land-sparing scenario could be considered highly optimistic, therefore, the sensitivity of the modelled land-use outcomes to changes in productivity was tested. The livestock productivity and stocking densities for the Land-sparing and Land-sharing pathways were changed to match the Status Quo pathway. This simulated large changes in land-use, with the area of intensive grassland remaining high and leading to much smaller areas of 'other natural land'

(Figure 3.5B). This indicates a high dependence in the Land-sparing scenario on assumptions of increases in productivity and stocking rates.

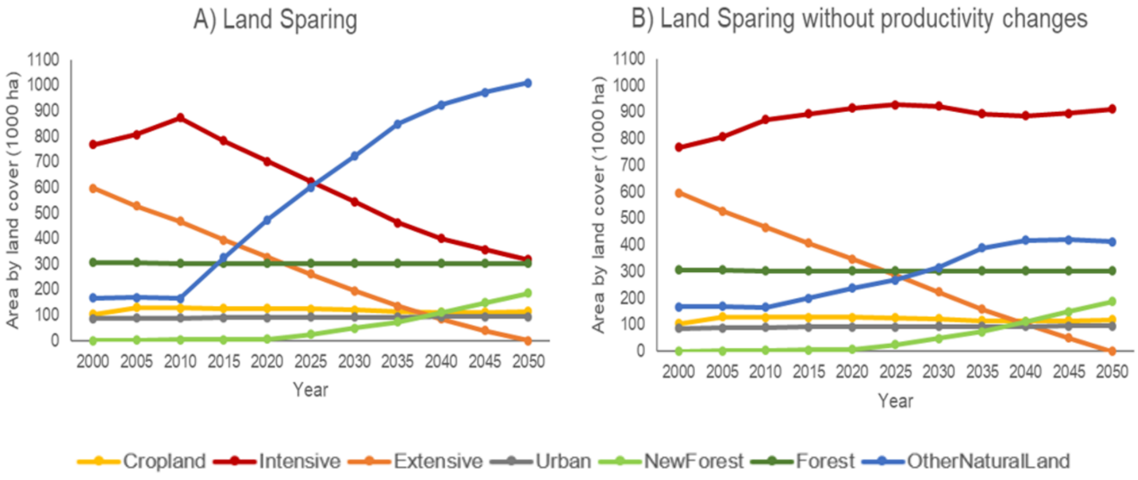

Figure 3.5: Projected land-use change for the Land-sparing pathway: (A) with all assumptions; and (B) without increases in productivity and stocking rate.

The Land-sharing pathway with no change to productivity shows less drastic changes than Land-sparing, largely due to less reliance on the increases in stocking rates and productivity. There still exist decreases in intensive grassland, albeit not as large (Figure A4B).

3.3.4.3. New Forest configuration

The Welsh Government included a target of achieving 500,000 ha of additional land for biodiversity conservation within the Land-sharing pathway, which is not met under the pathway assumptions. Therefore, an additional test was conducted to determine how this target could be achieved for the Land-sharing pathway. This revealed that it could be attained by specifying that 86% of new woodland planting should target biodiversity, which also better aligns with the land-sharing narrative (Figure 3.6).

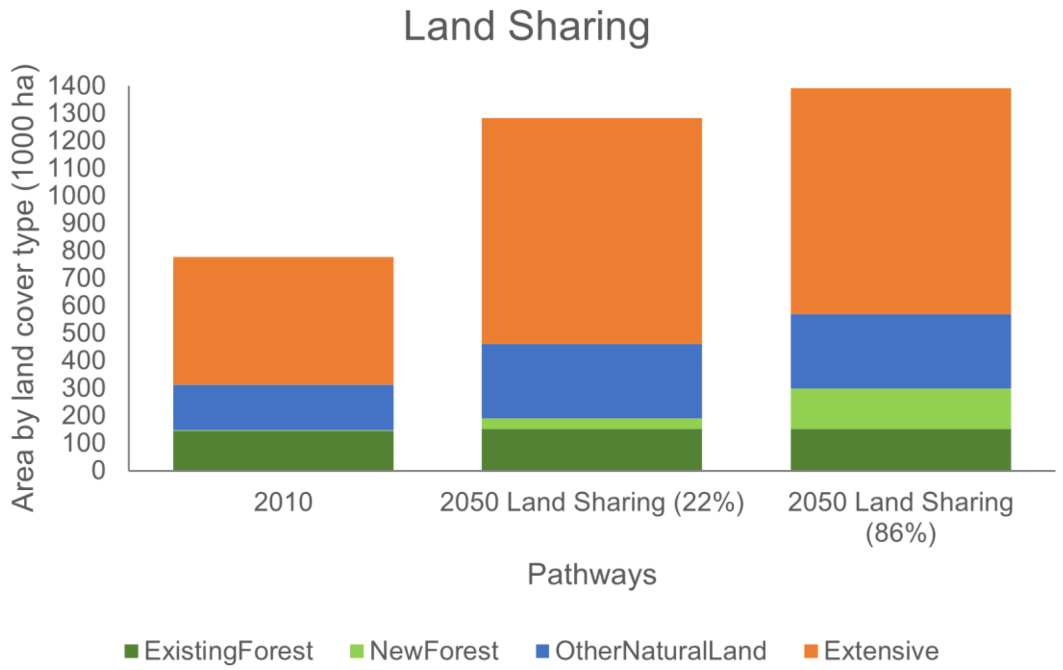

Figure 3.6: Land that can support biodiversity conservation for Land-sharing pathway, achieving the desired 500,000 ha when 86% of new forest is planted for biodiversity.

3.4. Discussion

The purpose of the four pathways, developed in close collaboration with the Welsh Government, presented in this research is to provide an indication of the consequences of policy decisions on land-use and GHG emissions in Wales. The results indicate the level of transformational change that would be required to achieve more nature positive and carbon neutral land-use and food systems in Wales and are directly being used to influence policy discussions.

3.4.1. Greenhouse gas emissions

Achieving net-zero emissions in Wales requires the land-use sector to be a carbon sink, and the results indicate that if Wales were to continue along current trajectories (Pathway 1) or with slight improvements (Pathway 2) net-zero GHG emissions would not be achieved. However, both the Land-sharing and the Land-sparing pathways project that the land-use sector becomes a net carbon sink, aiding in offsetting emissions in other sectors. This is an important requirement of long-term land-use planning in Wales to meet climate targets (Welsh Government, 2019c).

Whilst GHG emission results are similar for the Land-sparing and Land-sharing pathways (-3.5 Mt CO_2-eq^{-yr} for Land-sparing and -2.9 Mt CO_2-eq^{-yr} for Land-sharing), there is less reliance on optimistic assumptions concerning increased crop and livestock productivity in the Land-sharing pathway. Previous research has supported the technical potential of a land-sparing strategy to achieve reductions in net emissions and carbon losses (Lamb et al., 2016, Williams et al., 2018). In contrast, although evidence does suggest that grazing livestock more extensively can be attributed to enhanced sequestration (Chang et al., 2016), there are many factors, including soil type and quality, seasonal variability and vegetation type, that will determine if sequestration actually occurs (Garnett et al., 2017, Conant, 2010).

A frequent component of policy discourse on forestry, land-use and GHG emissions abatement are area-based targets for afforestation (Matthews et al., 2020), which imply an expected contribution to the net reduction of emissions. CO_2 uptake from forests in the past has led to substantial net GHG removal from the atmosphere (Rounsevell and Reay, 2009), the magnitude of which depends on the age and structure of forests. Further ambitions in afforestation for Wales contributed to carbon sequestration in all the pathways. However, there is considerable uncertainty over the eventual GHG reductions, which depend on the nature of afforestation, the geographical distribution and the end use of any harvested wood products (Matthews et al., 2020). Afforestation on peaty soils, which are widespread in Wales, may result in loss of soil carbon that outweighs carbon sequestered as trees grow (Friggens et al., 2020; Sloan et al., 2018). Also, some of the carbon sequestered by a plantation will be emitted back to the atmosphere when it is felled and converted to short-lived products such as paper, pallets, fencing, panels or wood fuel, which currently account for about 84% of harvested wood products in the UK (Forest Research, 2021). While fast growing monoculture plantations may be susceptible to fire, drought, pests and diseases, semi-natural woodland using a diverse mix of suitable native species offers the potential for longer term carbon storage that is more resilient to future environmental change.

3.4.2. Biodiversity

Wales has a wide representation of species across a range of taxonomic groups, and habitats (Natural Resource Wales, 2016). Most habitats have seen a reduction in biodiversity over the last 100 years, with the rate of decline increasing from the 1970s onwards (Natural Resource Wales, 2016), indicating that current ecosystems are not resilient, and species are not recovering. Results from a newly developed indicator for the status of biological diversity in Wales show that between 2011 and 2016, the populations of 35% of species showed an increase and 19% of species showed a decline (Smart et al., 2022). Our simulated results for the pathways indicate that changes in policy and land management can lead to an increase in the availability of land that can support biodiversity in the Land-sparing (predominantly ‘other natural land’) and Land-sharing pathways (semi-natural and species-rich extensive grassland). The actual biodiversity benefits delivered will depend on the success of restoration and subsequent management of the habitats.

Under the initial policy assumptions co-created with Welsh Government, none of the pathways met the target of 500,000 ha of additional land for nature conservation. Additional runs with the FABLE calculator showed that Welsh Government would need to increase the proportion of new forest managed for biodiversity from 22% to 86% to reach the target area. This increase would lead to a greater proportion of new forest being composed of broadleaf woodland and native species, as opposed to commercial plantations, altering the appearance of the forest on the landscape. Broadleaf woodland can also provide a range of ecosystems services (Bullock et al., 2015), having the potential to aid in sequestrating carbon (Fletcher et al., 2016), support increases in biodiversity (Sweeney et al., 2010) and reduce rainfall generated flooding (Monger et al, 2022). However, the FABLE analysis does not consider the additional forest areas spatially, therefore the trade-offs between biodiversity gains through increasing the proportion of native woodland and other policy goals, e.g. climate mitigation, remains unclear.

Another option, that was not explored in this model, would be to include agroforestry into the pathways. Agroforestry is often considered a sustainable form of land management and, relative to conventional agriculture, contributes significantly to carbon sequestration, increases ecosystem services and enhances biodiversity (Kay et al., 2019). This configuration is advocated by the Food Farming and Countryside Commission (2021). An advantage of agroforestry is that it allows agricultural production to continue with little or no loss of yield, while increasing biodiversity and carbon storage on the same land, in line with the Land-sharing narrative. However, there can be financial barriers to implementing it, and practical barriers such as small field sizes in Wales. The inclusion of agroforestry in the pathways could be studied when looking at the pathways spatially, to indicate where forestry and agriculture can feasibly coincide.

3.4.3. Implications for policy

The pathways presented in this research include a vast set of underlying components that would need to be implemented for the pathways to be considered a “success”. First, there are those linked to land becoming a net carbon sink, including higher rates of afforestation and peatland restoration. Second, and perhaps the most important for emissions reduction and biodiversity conservation (with regards to releasing land for biodiversity) are increases in productivity and improvements in agricultural technology. There would also be further policies required to encourage landowners to manage land to benefit biodiversity, and promote reductions in food waste and healthier diets. These ambitions and requirements all come with associated costs and trade-offs, likely requiring high investment and government incentives to encourage relevant actions, as well as adequate education and promotion to link everyday decision-making with achieving climate goals. This is potentially a monumental task for the Welsh Government.

One of the principal strengths of the FABLE approach is the co-design of the pathways involving stakeholders from different policy departments that have tended to work in silos, as this facilitates discussion and agreement of assumptions related to land-use, dietary choices, food waste and afforestation policy in a set of coherent pathways. However, despite seemingly positive outcomes for the Land-sharing and Land-sparing pathways, these both rely heavily on transformative policies with substantial public buy-in, and technological advances that may have other adverse impacts outside the scope of modelling in FABLE.

The Land-sparing pathway relies on the intensification of crop and livestock production through advances in technology and productivity to meet its targets, thus a land-sparing approach in practice would require policies that couple yield increases with habitat restoration on spared land (Lamb et al., 2016). The increased use of chemical inputs and machinery per unit area of land increases nitrous oxide emissions from arable land and grasslands and causes water pollution (Rounsevell and Reay, 2009). Therefore, the Land-sparing pathway carries a higher risk of adverse environmental impacts associated with intensification of production, something that does not necessarily align with policy legislation in Wales. This is particularly relevant for legislation on agricultural pollution designed to reduce losses of pollutants from agriculture to the environment, with the passing of the *Water Resources (Control of Agricultural Pollution) (Wales) Regulations 2021*.

A second policy area that would require large public buy-in and significant change in consumer behaviour is the shift towards healthier diets. Policies to manage the diets of the population often revert away from more mandated polices, as policies that inform rather than restrict the public are often met with less resistance (Gorksi and Roberto, 2015). The results from our sensitivity analysis indicate that improving diet alone can reduce meat demand and pasture area, freeing up land for ‘other natural land’ and biodiversity. Incorporating aspects of diet, environment and economy in one suite of policy goals is imperative for combatting ill-health related to diets, improving environmental sustainability in production and generating equitable wealth across regions (Parsons and Hawkes, 2018). Therefore, policies to address meat consumption and demand should include all aspects of the food system. The results of these pathways also support the notion that altering diet alone will not achieve as much as a combination of policy changes.

3.4.4. Impacts of the research

The participatory approach significantly increased the impacts on policy. It was considered particularly valuable for policymakers in the Welsh Government as it pushed teams to incorporate a longer time horizon into their policy context than normal, and enabled them to discuss the interactions between the policy ambitions. It also prompted discussions around what Wales will be farming in the future (i.e. will the Welsh agricultural sector move away from red meat and milk) and raised challenging questions about the ambition of reversing the decline in biodiversity.

The land-sharing and land-sparing pathways provided compelling evidence for including the policy of seeking a dietary shift in the Welsh population for both health and planetary outcomes, with the inclusion of “Over the next 20 years the ambition is to shift the population’s diet closer to the Eatwell Guide” in the Welsh Government’s *Low Carbon Delivery Plan* (Welsh Government, 2021c, p 22) and the establishment of a new policy group to develop the work programme in this area directly resulting from this study. The research was also welcomed by the Welsh Government as it demonstrated an alternative to the UK CCC Land-sparing pathway, enabling them to chart their own pathways aligned with their differing values and legislative frameworks. This was also welcomed by the UK CCC for the same reason.

‘*Working in partnership with our academic partners really helped us to tailor the model to meet our specific policy needs. As a result of this close collaboration the outputs of the work has had a significant impact on policy thinking in Welsh Government and continues to do so’. - Ann Humble – Head of Strategic Analysis, Welsh Government.*

3.4.5. Limitations

The FABLE calculator encompasses a comprehensive set of assumptions across policy sectors relevant for land-use and food systems, co-created directly with policymakers. However, there are limitations to what the FABLE approach can achieve.

Firstly, the FABLE calculator does not quantify uncertainty in the analysis. Research by Alexander et al. (2017) indicates that understanding uncertainty in land cover projections is critical when investigating climate mitigation policies that are land-based, recommending that a diverse set of models and approaches should be used to assess the potential impacts of future climate on land-use change. Sensitivities exist in the parameters used in the calculator. For example, GHG emissions are calculated based on assumptions on the carbon content of soils and vegetation, and the time taken for land to regenerate. These are based on limited data, for which there is weak evidence. The FABLE calculator is also designed to calculate futures for entire countries that have a full set of FAO statistics for commodity balances. Therefore, assumptions had to be made to downscale these commodity balance statistics from the UK for Wales, increasing uncertainties. A shift towards a healthier diet is also reliant on shifts in consumer behaviour, something which is hard to model with certainty, and exploratory modelling studies indicate substantial shifts are obtained in only a few simulations with optimistic assumptions on dietary changes (Eker et al., 2019).

Secondly, climate policies, particularly relating to GHG emissions targets, are based on CO_2-equivalent emissions formed through the conversion of non-CO_2 gases using Global Warming Potentials. This is the unit used in the FABLE calculator. However, the use of CO_2-equivalents for agricultural emissions has been critiqued due to differences in the dynamics of methane (CH_4) and Carbon Dioxide (CO_2), which mean that conventional reporting of aggregated CO_2-equivalent emission rates are highly ambiguous, and do not straightforwardly reflect historical or anticipated contributions to global temperature change (Lynch et al., 2021). Whilst new metrics are being researched (Allen et al., 2018; Cain et al., 2019), this is not something included in the FABLE calculator currently. In relation to this, whilst the FABLE calculator includes mitigation of GHG emissions through improvements in productivity and dietary choices, Hedunus et al. (2014) highlighted that mitigation of GHG emissions in agricultural production should also include dedicated technical measures, such as methane reduction or other fertiliser use such as manure, something the FABLE Calculator does not currently include. This is a considerable drawback, particularly when calculating impacts of increased productivity through fertiliser use for the Land-sparing pathway, as only one generic type of fertiliser is considered.

Thirdly, the FABLE calculator does not consider the results spatially (apart from modelling the proportion of different land-use types that are within protected areas) or test the plausibility of the pathways given spatially-explicit land constraints. The simulated land-use changes can, therefore, occur anywhere in Wales, which may not be feasible in certain contexts. Further spatial analysis would be greatly beneficial to identify where changes in land-use would be better suited to deliver on national climate and biodiversity targets, whilst maintaining livelihoods of farmers, land managers and rural communities.

Furthermore, given the absence of more detailed information on future trade agreements for Wales, it was assumed in this research that the share of total consumption that is imported and the quantity of total production exported remain the same up to 2050. Imports and exports were based on FAO data that were downscaled, and exports were fixed in tonnes at the 2010 value. Therefore, there is no inclusion of how dietary change in export countries towards 2050 would impact exports and demand. There is potential for future research to test the impacts of varying exports due to changing dietary preferences elsewhere. In addition, the FABLE calculator does not include any economic modelling, so further research should include whether the land configurations are economically viable business models for Welsh farmers. Finally, FABLE does not consider impacts on water use and availability due to land-use change, something explored by Kundu et al. (2017).

3.5. Conclusion

This research showed how a national scale integrated food and land-use model can be downscaled to the sub-national scale to develop sustainable pathways that are tailored to the local policy context through stakeholder engagement. Working closely with Welsh Government policymakers, alternative pathways to nature-positive and carbon-neutral land-use and food systems in Wales that align with policy aspirations, were developed and tested using a modified version of the FABLE Calculator. The results show that transformative changes to current policies are needed to achieve targets for net-zero in the AFOLU sector in Wales. Both the Land-sparing and Land-sharing pathways rely on transformative policy actions that are coordinated across sectors for mutual benefit and illustrate the crucial role of dietary choices in freeing up land for nature restoration and carbon sequestration. They both transformed the AFOLU sector from an emission source to a net carbon sink, but the Land-sharing pathway offered an approach that was less reliant on optimistic assumptions concerning productivity increases, and less likely to result in adverse environmental impacts such as water pollution, as well as being more in line with Welsh policy priorities. The co-creation of pathways with policymakers provides results set within the context of current policy discussions and can provide tailored evidence to directly inform upcoming policy decisions. However, crucially, the pathways show only the likely consequences of a set of certain policy assumptions and, thus, the task ahead for the Welsh Government to achieve the transformational change is significant.

3.6. Acknowledgements

This research was funded the UK EPSRC Data Science of the Natural Environment (DSNE) programme grant (award number EP/R01860X/1) and the Welsh Government (WG) and UK Centre for Ecology & Hydrology (UKCEH), as part of the Environment and Rural Affairs Monitoring & Modelling Programme (ERAMMP) (WG Contract C210/2016/2017 & UKCEH Projects: 06297 & 06810). We thank all of the ERAMMP team, especially Bridget Emmett, Bronwen Williams and Chris Bell (UKCEH), and James Skates, Ann Humble and Ken Stebbings (WG), for their support. The authors also acknowledge the valuable support of the FABLE Secretariat in developing and maintaining the UK and Wales versions of the FABLE calculator and providing technical assistance.

4. The impact of Regional Autonomy over land-use planning for net-zero and biodiversity targets in the UK

Abstract

The UK Government has set legally binding net-zero emissions targets through amendments to the Climate Change Act 2008, and international agreements. The capacity of the UK food and land-use sector to contribute to its climate targets is dependent on the activities of the devolved administrations, who have autonomy over agricultural and environmental policy. Using a regional integrated land-use model, the FABLE calculator, three pathways towards achieving sustainable land-use futures for each devolved administration were explored and compared: a Current Trends (CT) pathway, a pathway based on the recommendations from the UK Government's Climate Change Committee (CCC), and a pathway based on the policies of the Devolved Administrations (DA). The simulated results indicate that the CT pathways lead to a significant shortfall in achieving both net-zero and biodiversity targets. The simulated DA pathways create 11% more land to support biodiversity conservation when aggregated to the UK level than the CCC pathways, ranging from 6%-36% across the four nations. In contrast, the CCC pathways sequester more carbon and see the greater emissions reductions in 2050 in the AFOLU sector, with a 19% greater reduction when aggregated to the UK compared to the DA pathways, ranging from 21%-25% across the four nations. The findings demonstrate potential tensions between managing multiple policy goals within and across devolved governance structures. They highlight the importance of coordination and alignment of emerging policy designs across the UK nations to fulfil international commitments in ways that maximize synergies, minimize trade-offs and avoid unintended consequences.

Keywords

Land-use; Policy; Biodiversity Conservation; Net-zero

4.1. Introduction

Agriculture, Forestry and Other Land-uses (AFOLU) account for 23% of global anthropogenic Greenhouse Gas (GHG) emissions (IPCC, 2019). Reducing emissions from the land-based sector is essential to address commitments to international agreements such as the Paris Agreement (DeFries et al., 2022). Roe et al. (2019) indicated that a transformation of land and deploying reduction measures in agriculture, forestry, wetland and bioenergy could feasibly and sustainably contribute approximately 30% of the global mitigation required to obtain the Paris Agreement's 1.5^{o}C target. There are opportunities for land-use change to sequester carbon to aid achieving net-zero, with many national governments incorporating nature-based solutions in plans to reduce GHG emissions (Bradfer-Lawrence, 2021). However, confusion persists about the specific set of land stewardship options available, and their mitigation potential (Griscom et al., 2017). Moreover, how a country's land is used can be highly political (Lang, 2020), with food production and land-use being deeply embedded in local biophysical, cultural, historical and socio-economic practices (Mosnier et al., 2023). Achieving net-zero GHG emissions using the AFOLU sector, therefore, requires decision-makers to balance wide ranging priorities from a complex evidence base (Sharmina et al., 2016).

As a signatory to the Paris Agreement, the UK Government has set a legally binding target for net-zero emissions by 2050 through amendments to the *Climate Change Act 2008* (Dray 2021). To achieve net-zero, the UKs net emissions must fall by 100% from current levels, with residual emissions offset by carbon removal (CCC, 2020c). Therefore, the transition to net-zero is expected to rely heavily on changes in land-use and agriculture. Major barriers to delivering AFOLU mitigation include political inertia, weak governance, and lack of finance (Roe et al., 2019). Moreover, governance of a net-zero transition must take full account of national and sub-national legislation and powers (Reay, 2020). In the UK, there are separate legislatures and executives in Scotland, Wales and Northern Ireland, each with its own unique devolution settlement. The reallocation of resources between Westminster and the devolved governments is asymmetric and complex, with each of the devolved governments receiving differing degrees of powers and responsibilities (Cowell et al., 2017). When constitutional power was devolved to Scotland, Wales and Northern Ireland in the 1990s, little consideration was given to climate change as a specific area of policy responsibility, resulting in devolved governments having capacity to act in some areas of climate policy, such as environment and agriculture, and not in others, such as energy (Royles and McEwan, 2015). This regional autonomy of the devolved nations, combined with their different land capabilities, suggests each has different capacities to deliver on AFOLU net-zero targets. Consequently, the capacity of the UK to deliver on international and domestic climate agreements is dependent on the actions, policies and land capabilities of the devolved nations, as relevant policy fields for achieving net-zero in the AFOLU sector fall under the competencies of both Westminster and the devolved governments (Nash, 2021).

Previous research has considered climate and land-use policy for achieving net-zero, and the potential for negative emissions technologies at a UK level (Pareliussen et al., 2022, Smith et al., 2016). However, allocation of powers at a sub-national level represents a clear source of decision-making autonomy (Royles and McEwen, 2015), and in the context of the UK reaching net-zero, this is an important consideration. There is a growing body of literature focused on sub-national governance, sustainable development and climate policy (Schreurs, 2008; Happaerts, 2012), highlighting that national governments are no longer the sole actor in climate governance, with sub-national actions vital for keeping global temperatures below 1.5°C as per the Paris Agreement (Hsu et al., 2017). Valenzuela (2014) explored interrelations between national and sub-national governments in relation to climate change policy in Mexico, demonstrating that sub-national governments could effectively develop independent climate change agendas, guided by local electoral concerns. This is supported by similar studies in Norway that found that regional governments can support local implementation of climate adaptation polices (Dannevig and Aall, 2015). Devolution and climate action in the UK was explored by Cowell et al. (2017) who addressed the impacts of devolution and renewable energy development through policy review and semi-structured interviews. Kirsop-Taylor (2020) explored the policy responses of the devolved nations to the Convention for Biological Diversity (CBD) ecosystem approach, similarly through semi-structured interviews and analysis of policy documents. Research on climate action in the devolved nations individually has focused on specific sectors within the nation, such as local governance for heat and energy efficiency in Scotland (Wade et al 2022), good environmental farming practices in Wales (Franklin et al., 2021), or net-zero futures in agriculture in England (Booth, 2021). Kirsop-Taylor (2020) noted that no comparative studies exist addressing how environmental policymaking compares across the devolved nations, with little evidence of whether environmental policies diverge, converge or mirror those of the UK.

This study addresses this by investigating the ability of the UK to meet its international net-zero commitments if the devolved nations follow a pathway based on current trends, a pathway based on the UK Government's Climate Change Committee (CCC) or a pathway based on their own policy aspirations. Differences in the outcomes of the pathways are quantified using a set of linked regional integrated land-use models based on the FABLE calculator (Mosnier et al, 2020). This allows outcomes for both climate and biodiversity targets to be determined that reflect changes in demand management (diets and food waste), land-use management (afforestation, stocking density, biodiversity conservation and peatland restoration), and innovation (crop and livestock productivity). We explore potential synergies and trade-offs that emerge between policy goals for climate and biodiversity and how these are affected by the autonomy the devolved nations exert over their approaches to land-use.

4.2. Study context: policy and land-use

Challenges for the future development of environmental governance in the UK include differing ecological conditions, histories of policies, ambitions, income levels, land-use planning and commitment to environmental policies, and alignment across England, Wales, Scotland and Northern Ireland (Burns et al., 2018). Each of the nations have their own policies and land-use contexts that determine their capabilities to achieve climate targets, with each of them having responsibility for environment and planning, agriculture, and fisheries. Scotland and Wales have sought to develop their own ambitious environmental policy since devolution (Burns et al., 2018), with their own aspirations for the future of environment and land-use policy. As well as this, the UK's exit from the European Union (EU) offered an opportunity to rethink the design and ambitions of future environmental policy, with Scotland, Wales and the UK Government indicating a willingness to think strategically. England, Scotland, Wales and Northern Ireland have their own agricultural ministries that are progressing agricultural and environmental policy in different ways, with these differing approaches to be implemented between 2023 and 2025, which could potentially lead to different changes in food and land-use systems across the UK (Booth, 2021) (see the Supplementary Material (Chapter 9.B) for full policy context).

The CCC, the independent advisory body to the UK and devolved administrations, has established scenarios to cut emissions rapidly across the devolved nations (CCC, 2020c). Their recommended "Balanced Net-Zero Pathway" represents a decisive transition to net-zero, reaching net-zero in 2050 across all GHG emissions, with over 60% of the necessary reduction achieved before 2035 (CCC, 2020c). However, emissions from agriculture do not reach zero, and need to be offset by a carbon sink facilitated through land-use change (CCC, 2020c). The CCC state that UK climate targets cannot be met without strong policy action across Scotland, Wales and Northern Ireland, that is tailored to national, regional and local needs (CCC, 2020c), and they provide a set of recommendations for policy actions for each devolved administration to meet their recommended pathways (CCC, 2021; CCC, 2020b; CCC, 2019).

As well as the different policy contexts, across the UK there exist different ecological conditions and histories (Burns et al., 2018) that influence new policy design and their potential success. The UK landscape is diverse, ranging from lowland arable lands in southeast England, to upland grasslands in various parts of England, Scotland and Wales. Land-use in the UK is predominantly used for agriculture, with 42% used for grassland and 24% for arable land (Rowland et al. 2017a, b). The rest of the UK includes 15% mountainous, heath and bog areas, 8% forested areas, 6% urban and 5% water and coastal ecosystems (Rowland et al. 2017a, b) (Figure B1). Grassland and cropland in the UK have remained relatively stable from 1990 to 2021 (DEFRA, 2021). An overview of land-use in the UK is given in Table 4.1.

The AFOLU sector accounted for 12% of total UK GHG emissions in 2018 (CCC, 2020a), which has increased since 1990. Agriculture in the UK is the main source of both nitrous oxides from soils as a result of nitrogen fertiliser application and methane emissions from enteric fermentation in ruminating animals (DEFRA, 2021). In the UK, 27.8% of land is reported by the UK Government as protected, as National Parks, Areas of Outstanding Natural Beauty (AONB) and other designations (Bailey et al., 2022). However, condition monitoring research by Starnes et al. (2021) indicated that only 11.4% of this land is designated primarily for nature conservation. Furthermore, only 43–51% of protected areas are in favourable condition (Starnes et al. 2021). Hence, the area of land strictly protected for biodiversity and in good condition could be as low as 4.9%.

Table 4.1: Overview of the land-use in the UK for 2015 used in the FABLE calculator.

Country	**Total area (1000 ha)**	**Population (million people)**	**Arable land**	**Area of grassland (1000 ha)**	**Area of forest (1000 ha)**	**Total protected areas (1000 ha)[1]**	**Total protected areas (1000 ha)[2]**
England	13,216	54.79	4,759	4,887	1,270	419	4,021
Scotland	7,769	5.37	661	2,510	1,302	966	2,479
Wales	2,071	3.10	97	1,376	319	291	684
Northern Ireland	1,409	1.85	95	888	120	123	406
UK	24,465	65.11	5,612	9,661	3,011	1,799	7,590

[1] excluding National Parks, AONBs and Heritage Coasts

[2] including National Parks, AONBs and Heritage Coasts

4.3. Methodology

4.3.1. Pathway development

Three pathways for each devolved nation were developed: a Current Trends (CT) pathway, a CCC pathway (CCC) and a Devolved Administrations (DA) pathway to compare the combination of policy actions required to achieve net-zero (Table 4.2). Pathways for Wales were adapted from Jones et al. (2023b).

The CT pathway is a continuation of current policy trends, which includes current diets, stocking densities, and rates of afforestation and peatland restoration. The CT pathways continue to protect current protected areas, excluding National Parks, AONBs and Heritage Coasts.

The CCC's "Balanced Net-zero Pathway" to net-zero, set out in the Sixth Carbon Budget (CCC, 2020a), encompasses targets across all sectors (Waste and F-gases, Agriculture and land-use, Manufacturing, construction and fuel supply, Electricity supply, Buildings and Transport). This research considers only the agriculture and land-use sector. The pathway is characterized by reducing demand for carbon-intensive activities, increasing uptake of low-carbon solutions, expansion of low-carbon energy supplies and removal of CO_2 through land-use. For the AFOLU sector, this requires a transformation of land through increases in crop and livestock productivity which releases agricultural land for afforestation and restoration of national land. The CCC pathway also includes a reduction in the demand for meat and dairy consumption. Nearly 60% of abatement in Scotland, Wales and Northern Ireland is in sectors where powers are partially or mostly devolved, therefore, a detailed set of policy recommendations are made in the accompanying Policy Report (CCC, 2020b). The recommendations across the AFOLU sector form the basis of the CCC pathway for this work.

The Devolved Administrations (DA) pathways were developed by reviewing policy documents of the devolved nations. In general, these differs from the CCC pathway in terms of lower agricultural productivity for both crop and livestock production, a transition to more livestock farmed on extensive grassland, higher aspirations for biodiversity conservation, increased afforestation, slightly lower peatland restoration for Scotland and England, and greater reductions in food waste.

The UK is a signatory to international agreements such as the Paris agreement, which aims to keep global temperatures below 1.5°C, and the Kunming-Montreal Global Biodiversity Framework (GBF) at COP 15 (CBD Secretariat, 2022), which has a target to protect 30% of land in the UK by 2030 (Brader, 2023). The CCC pathways therefore continue to protect current designated protected areas, including those designated as National Parks, AONBs and Heritage Coasts. For the DA Pathways, Wales and Scotland protect all-natural land (excluding forests), England aspire to create an additional 500,000 ha of protected areas by 2030, and Northern Ireland will increase protected areas to reach the 30% target.

The full assumptions underlying the pathways are given in the supplementary material (Table B1).

Table 4.2: Overview of the three sets of pathways

Pathway	**Summary**
Pathway 1: Current Trends	Continuing with no changes to current policies.
Pathway 2: CCC pathways	Transformation of land-use to sequester carbon and restore peatlands combined with ambitious increases in productivity.
Pathway 3: DA pathways	**Wales**: Using land management techniques, the Welsh policy aims to deliver biodiversity restoration, carbon sequestration and production simultaneously on the same land. **Scotland**: The pathway has more ambitious targets for achieving net-zero by 2045, with a focus on multifunctional land-use, reducing food waste and restoring nature. **Northern Ireland:** Given the infancy of climate policy, very similar to current trends, with slight increases in afforestation. **England:** Aspirations to increase areas of land for biodiversity, without compromising productivity**.**

4.3.2. The FABLE Approach

The different pathways for the devolved nations were modelled using the FABLE calculator (Mosnier et al. 2020), developed by the Food Agriculture Biodiversity Land-Use and Energy (FABLE) Consortium. The FABLE Consortium aims to understand how countries can transition towards sustainable land-use and food systems, and collectively meet targets associated with the Paris Agreement, the Kunming-Montreal GBF and the related Sustainable Development Goals (FABLE 2020; Jones et al. 2023a).

The FABLE calculator is an open-source, comprehensive Excel-based tool designed to study the potential evolution of food and land-use systems over the period 2000 to 2050 (Mosnier et al., 2020). The calculator covers the main domains of food and land-use systems: land-use and land cover change, proxy indicators for biodiversity impacts, GHG emissions from agriculture and land-use change, food and nutrition security, and water use (Mosnier et al., 2023). The calculator allows the incorporation of changes in different policy assumptions, which can be adapted by the user to reflect their national contexts.

The FABLE calculator is demand driven, and for each five-year time step between 2000-2050, the calculate computes demand for products when considering food waste, imports and exports, livestock numbers to meet demand, and demand for cropland and grassland associated with demand for animal feed crops. The final land-use change is calculated, considering competing demands for land such as urban expansion, afforestation and protected areas. More information on the calculator can be found in the supplementary material (Figure B3, Figure B4).

The key outputs from the FABLE Calculator used in this paper are changes in land-use, land available to support biodiversity, protected areas, and GHG emissions (CO_2eq) from agriculture and land-use change. The GHG emissions are estimated from crop production, livestock emissions and land-use changes (see the supplementary material for more information). Within the FABLE calculator, land is simulated to become a carbon sink when emissions from land-use change, e.g. when land is converted to a different type (e.g. natural land converted to farmland or urban), is less than the amount of carbon sequestered due to afforestation or regeneration of natural land. The FABLE Calculator simulates the land available to support biodiversity, including ‘other natural land’ (mainly peatland, bog and wetlands), a user-defined proportion of forest area (set in the pathway development composed of native species to be managed for biodiversity) and species-rich semi-natural grasslands (under the assumption it is managed for biodiversity).

4.4. Results

The results of the FABLE modelling offer an indication of how the devolved nations can achieve sustainable land-use and food systems, as well as their contribution to UK climate targets.

4.4.1. Achieving net-zero

4.4.1.1. Land becoming a carbon sink

The CCC state that for their recommended Balanced Pathway, the AFOLU sector does not need to reach net-zero, but land must become a carbon sink (CCC, 2020a). For the devolved nations, land is simulated to become a carbon sink under both the CCC and DA pathways between 2015 and 2050. However, variation exists in the size of the carbon sink throughout the years, related to trends in the composition of land-use over time (Figure 4.1).

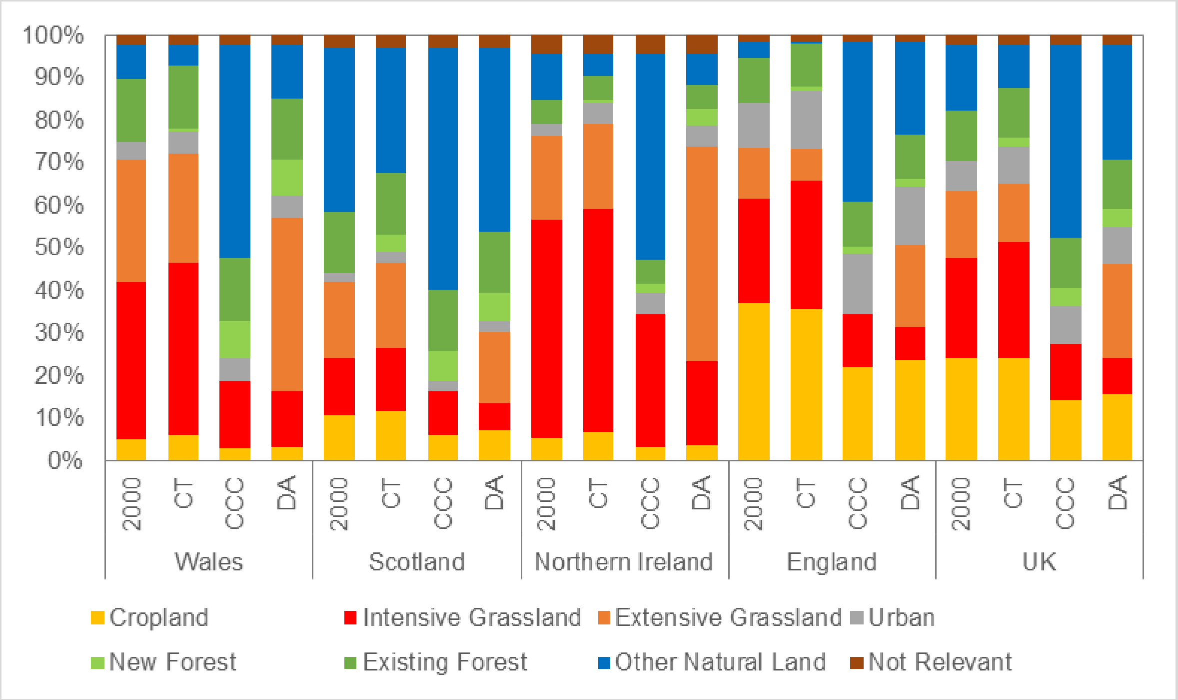

Figure 4.1: Composition of land-use for the baseline (2000) and for the three pathways in 2050 for the four nations: Current Trends (CT), Climate Change Committee (CCC) and Devolved Administrations (DA). Note: 'Other Natural Land' is defined as mainly peat bog, heath and wetlands. Not Relevant includes rocks and bare ground.

Under the CT pathways, land is projected to become a carbon sink for Wales only from 2025 onwards, due to the conversion of land from intensive to extensive grassland, and sequestration from afforestation. For Scotland and Northern Ireland, despite sequestration from afforestation, the decreases in 'other natural land' means emissions from land-use change remain above zero. For England, the CT pathway simulates reductions in 'other natural land' and extensive grassland, coupled with increases in pasture and urban areas, with land remaining a source of GHG emissions throughout the time-period. When aggregated to the UK, land does not become a carbon sink by 2050 under the CT pathways.

For Wales in 2050, the pathway resulting in the greatest carbon sink is the CCC pathway, driven by the conversion of intensive grassland and cropland to 'other natural land' and increased afforestation, with a continuous negative trend until 2050 (-3.92 $MtCO_2eq$ in 2050). The DA pathway simulates a smaller carbon sink in 2050 (-3.10 MtCO2eq), with the sequestration driven by a reduction in intensive grassland, increases in extensive grassland, increases in afforestation and slight increases in 'other natural land'. Over the period from 2000 to 2050, the CCC pathway sequesters 0.24 $MtCO_2eq$ more than the DA pathway (-9.36 $MtCO_2eq$ vs –9.12 $MtCO_2eq$ respectively) (Figure 4.2A).

Similarly for Scotland, the carbon sink is projected to be greater in the CCC pathway, reaching -6.97 $MtCO_2eq$ in 2050, driven primarily by increases in ‘other natural land’ due to the release of cropland because of increases in productivity. The DA pathway reaches -5.19 $MtCO_2eq$ in 2050, driven by the increases in extensive grassland coupled with decreases in intensive grassland, and slight increases in ‘other natural land’. Between 2000 and 2050, the CCC pathway sequesters 5.41 $MtCO_2eq$ more GHG emissions than the DA pathway (-14.43 $MtCO_2eq$ and -9.02 $MtCO_2eq$ respectively) (Figure 4.2B).

In contrast, the greatest carbon sink is simulated for Northern Ireland in 2050 in the DA pathway (-2.48 $MtCO_2eq$), driven by increases in restoration of ‘other natural land’ coupled with decreases in intensive grassland. However, the cumulative sequestration for the DA pathway is lower than the CCC pathway (-4.90 $MtCO_2eq$ compared to -5.30 $MtCO_2eq$ respectively) (Figure 4.2C). The CCC pathway reaches a carbon sink -1.91 $MtCO_2eq$ in 2050, driven by the conversion of intensive grassland and cropland to ‘other natural land’.

For England, increases in productivity in the CCC pathway result in large areas of cropland and intensive grassland being released for conversion to ‘other natural land’ and afforestation, leading to a simulated carbon sink of -15.90 $MtCO_2eq$ in 2050 (Figure 4.2D). Despite having a smaller carbon sink in 2050, -9.58 $MtCO_2eq$, the DA pathway cumulatively sequesters 14.58 $MtCO_2eq$ more carbon than the CCC pathway (-47.92 $MtCO_2eq$ compared to -33.34 $MtCO_2eq$ respectively). These emissions from land-use change are driven by the conversion of intensive grassland and cropland to ‘other natural land’, extensive grassland and afforestation.

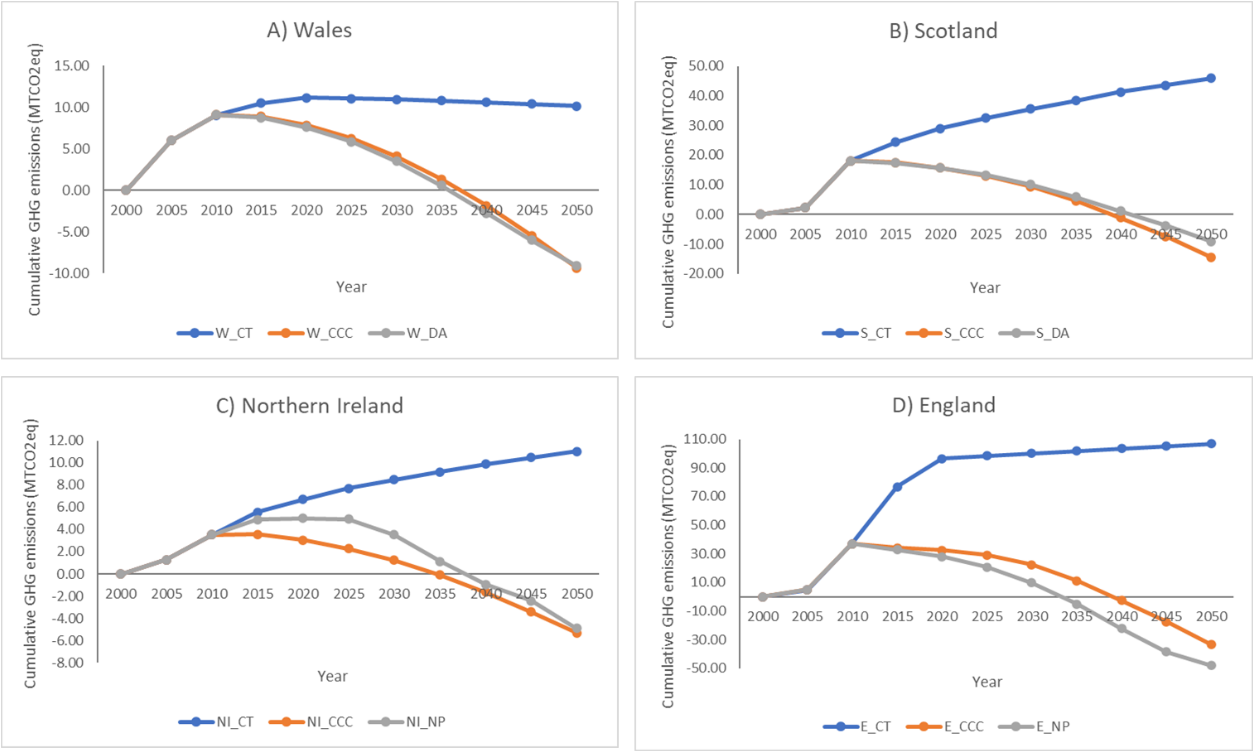

Figure 4.2: Cumulative GHG emissions from Land-use Change between 2000 and 2050 in the devolved nations for the three pathways

When aggregated to the UK level, the DA pathways, despite simulating the smaller carbon sink in 2050 (-20.35 $MtCO_2eq$, compared to -28.71 $MtCO_2eq$ for the CCC pathways) achieves the greater cumulative gains over the time-period, sequestrating -70.95 $MtCO_2eq$. In comparison, the CCC aggregated pathways cumulatively sequester -62.43 $MtCO_2eq$ by 2050 (Figure 4.3).

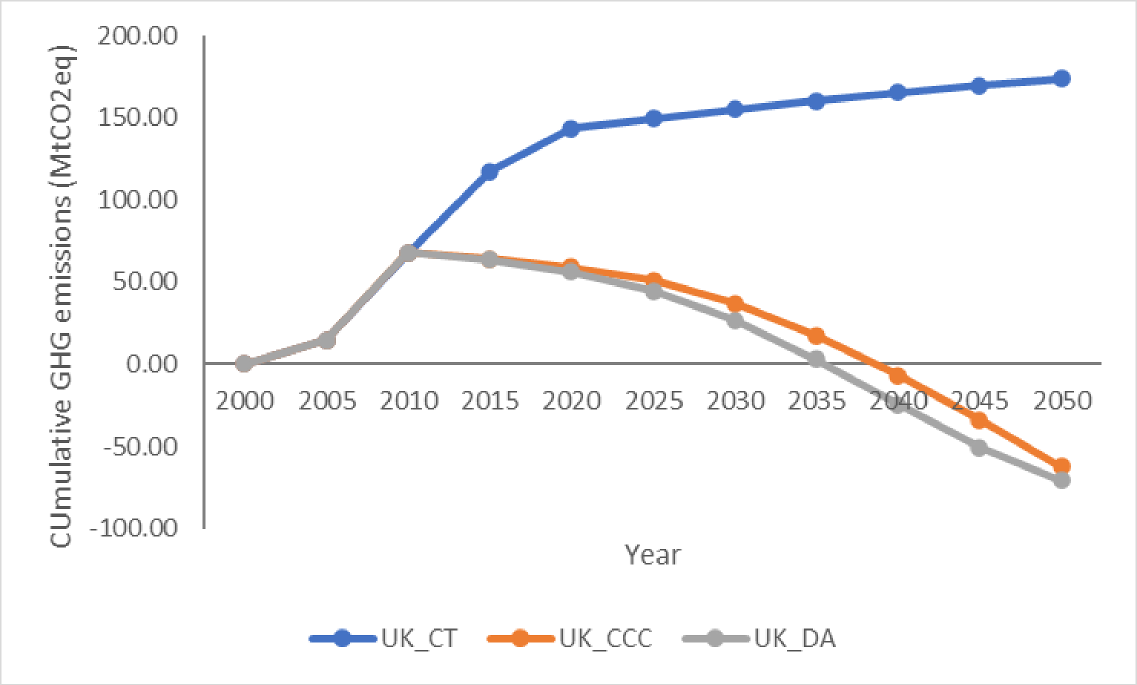

Figure 4.3: Aggregated Cumulative land-use change in the UK under the CCC and DA pathways.

4.4.1.2. Total Emissions from AFOLU

The results in Section 4.1.1.1 form part of the Total Emissions from the AFOLU sector; alongside emissions from agriculture (crop and livestock production) and biofuel savings.

Without any changes to policy in Wales, agriculture in the CT pathway is simulated to be 3.65 $MtCO_2eq$, combined with the small carbon sink leads to total emissions in the CT pathway in 2050 of 3.29 $MtCO_2eq$, cumulatively emitting 50.91 $MtCO_2eq$ across the time-period. For the CCC pathways, agriculture emits 2.22 $MtCO_2eq$ in 2050, with the DA pathways emitting 2.28 $MtCO_2eq$ in 2050. When these emissions are combined with the carbon sink, Wales achieves negative emissions from AFOLU in both the CCC and DA pathways from 2035 onwards, with slightly greater gains in the CCC pathway (-1.73 $MtCO_2eq$ compared to -0.84 $MtCO_2eq$ for DA in 2050). The AFOLU sector under the CCC pathway emits less GHG emissions than the DA pathways between 2000 and 2050, 25.09 $MtCO_2eq$ and 25.97 $MtCO_2eq$ respectively. Wales also has the lowest emissions of the devolved nations through the time-period for both the CCC and DA pathways (Figure 4.4A).

For Scotland, GHG emissions from agriculture in the CT pathway are simulated to reach 7.06 $MtCO_2eq$ in 2050, with the total from AFOLU simulated to be 9.37 $MtCO_2eq$, predominantly from livestock production. For agricultural emissions, the CCC pathway in 2050 is lower than the DA (4.00 $MtCO_2eq$ compared to 4.21 $MtCO_2eq$). Therefore, when combined with the land-use change emissions, the AFOLU sector is a carbon sink for

GHG emissions under the CCC pathway in 2050 (-3.02 $MtCO_2eq$), accumulating 48.42 $MtCO_2eq$ of emissions over the time-period. This is less than the DA pathway for Scotland, which sequesters -1.03 $MtCO_2eq$ emissions in 2050, equating to 55.03 $MtCO_2eq$ over the time-period (Figure 4.4B).

In 2050, with no changes to policy, Northern Ireland's CT pathway simulates 4.24 $MtCO_2eq$ in the AFOLU sector (3.70 $MtCO_2eq$ from agriculture), emitting 51.35 $MtCO_2eq$ over the time-period. Despite both the DA pathways and CCC pathways having carbon sinks due to sequestration from land-use change in 2050, when combined with the emissions from agriculture and biofuel savings, the DA pathway emits lower emissions in 2050 (0.10 $MtCO_2eq$) compared to the CCC pathway (0.65 $MtCO_2eq$). Conversely, when comparing cumulative emissions over the time-period, the DA pathway emits more emissions over the full time-period (30.74 $MtCO_2eq$) compared to the CCC pathway (29.96 $MtCO_2eq$) (Figure 4.4C).

For England, no changes to policy lead to 29.07 $MtCO_2eq$ emitted from the AFOLU sector in 2050 (28.03 $MtCO_2eq$ from agricultural sources), cumulating 417.13 $MtCO_2eq$ across the time- period, more than the other devolved nations combined. In the CCC pathway, increases in crop productivity in the assumptions lead to a decrease in emissions from agriculture (reducing by 18.77 $MtCO_2eq$ to 13.32 $MtCO_2eq$ in 2050), and increases sequestration from land-use change. Therefore, in 2050, AFOLU emissions in the CCC pathway are net-negative, at -3.06 $MtCO_2eq$. This is lower than the DA pathways in 2050 of 3.66 $MtCO_2eq$. Cumulatively however, the DA pathway has lower cumulative emissions over the time-period (197.25 $MtCO_2eq$ compared to 210.60 $MtCO_2eq$ for the CCC pathway) (Figure 4.4D).

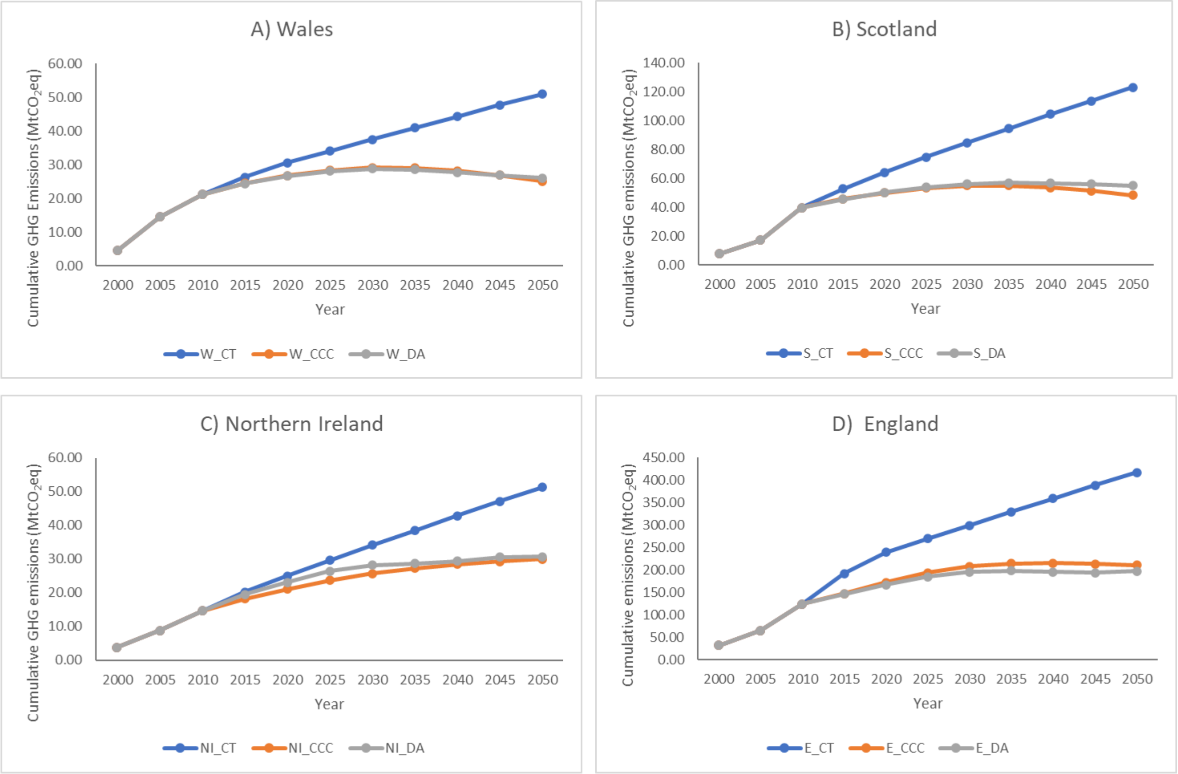

Figure 4.4: Cumulative emissions from the AFOLU sector in the devolved nations. Note: This includes emissions from Croplands, livestock production, land-use change and savings from biofuels.

When aggregated to the UK level, with no changes to policy the AFOLU sector emits 45.97 $MtCO_2eq$ in 2050, cumulating to 642.36 $MtCO_2eq$ over the time-period, 65% of which is from England. Overall, the AFOLU sector sequesters carbon under the aggregated CCC pathways (-7.16 $MtCO_2eq$ in 2050), whilst emissions from the DA pathways remain positive in 2050 (1.89 $MtCO_2eq$). However, the CCC pathway emits more emissions throughout the time-period, 314.07 $MtCO_2eq$, compared to 308.98 $MtCO_2eq$ for the DA pathways (Figure 4.5). This is due to greater carbon sequestration (land-use change emissions) and lower emissions from livestock in the DA pathways.

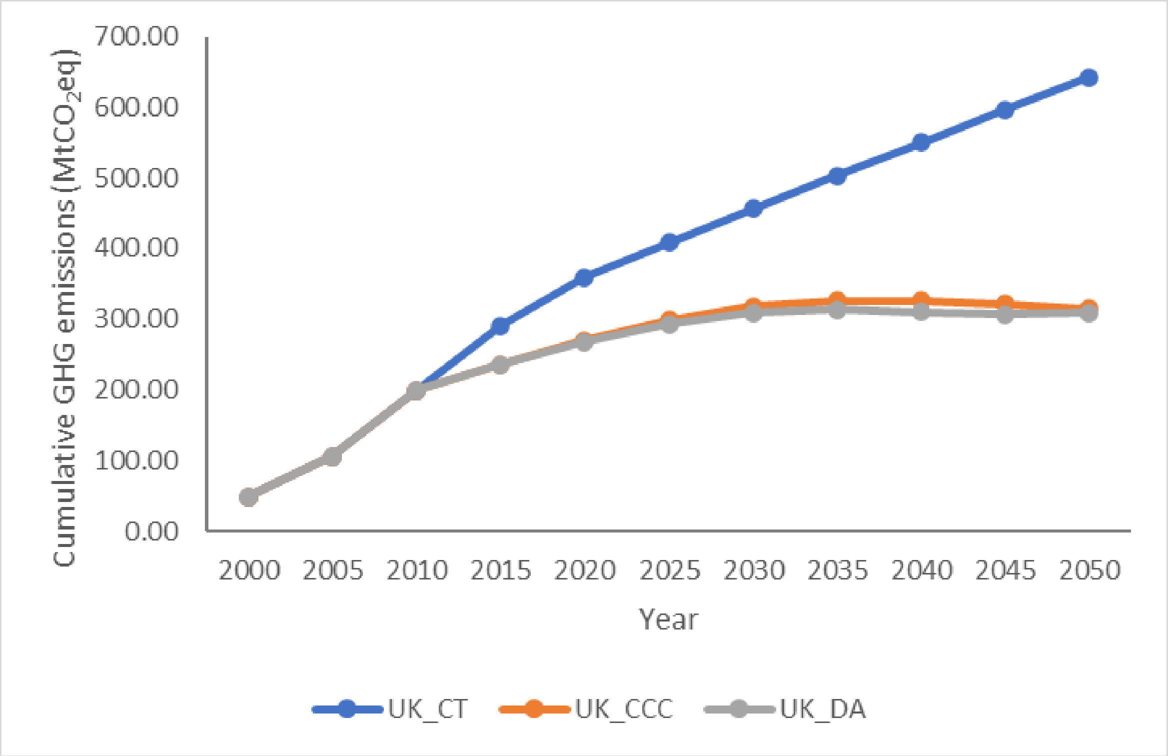

Figure 4.5: Cumulative emissions for the AFOLU sector from the aggregated pathways in the UK

4.4.2. Biodiversity & protected areas

4.4.2.1. Land to support biodiversity

The CT pathway results in slight increases in simulated land available for biodiversity in Wales and Northern Ireland, due to increases in new forest and extensive grassland in both nations. In contrast, in Scotland a decrease in land for biodiversity is simulated due to a reduction in ‘other natural land’ to allow for the expansion of cropland, grasslands and new forest. Similarly for England, a decrease in land available for biodiversity is projected under the CT pathway due to decreases in ‘other natural land’ to allow for the expansion of other land-uses.

For the devolved nations, the DA pathway simulates more additional land for biodiversity in 2050 than the CCC pathway for all nations (Table 4.3), primarily driven by increases in extensive grassland. The smallest area of land for biodiversity simulated under the DA pathway is in Northern Ireland, an increase of 469,950 ha between 2010 and 2050, followed by Wales, an increase of 545,000 ha, with 65% of the land for biodiversity in 2050 being extensive grassland (Figure 4.6). For Scotland, land available for biodiversity is simulated to increase by 681,730 ha, with 26% of this being extensive grassland and 66% ‘other natural land’ (Figure 4.6). Alternatively, for England increases are simulated to be almost twice as the sum of the other devolved nations, increasing by 3,881,770 ha. This is driven by the reduction in cropland and intensive grassland, releasing land for conversion to ‘other natural land’ for biodiversity, as well as increases in extensive land (Figure 4.6).

The land to support biodiversity under the CCC pathways is predominantly ‘other natural land’ (Figure 4.6), due to the assumptions in these pathways that extensive grassland is reduced towards zero in 2050. This pathway simulates the most land for biodiversity in England (Table 4.3), increasing by 3,444,660 ha from a 2010 baseline.

When aggregated to the UK, the DA pathways simulate 5,578,650 ha of additional land for biodiversity, 48% of which is ‘other natural land’. This is greater than the aggregated CCC pathways, resulting in an additional 4,683,370 ha of land for biodiversity.

Table 4.3: Total land available to support biodiversity conservation in the devolved nations for each pathway.

Country	Pathway	Total land for biodiversity (1000 ha) in 2010	Total land for biodiversity (1000 ha) in 2050	% change
Wales	CT	746.85	788.43	6%
	CCC	745.99	1230.53	65%
	DA	745.99	1291.20	73%
Scotland	CT	4368.28	4173.26	-4%
	CCC	4367.36	4788.30	10%
	DA	4367.36	5049.09	16%
Northern Ireland	CT	384.08	390.45	2%
	CCC	383.73	715.03	86%
	DA	383.73	853.68	122%
England	CT	2645.35	2138.64	-19%
	CCC	2632.57	6079.17	131%
	DA	2632.57	6514.34	147%
UK	CT	8144.55	7490.79	-8%
	CCC	8129.65	12813.02	58%
	DA	8129.65	13708.30	69%

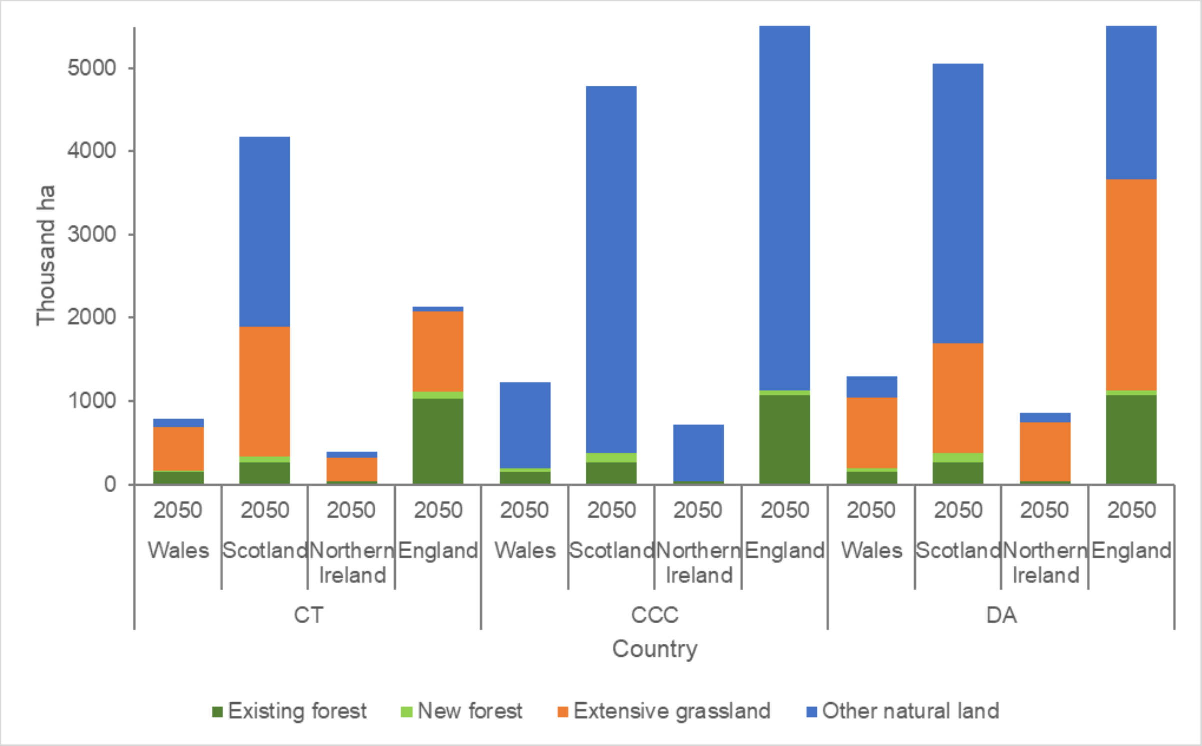

Figure 4.6: Composition of land available to support biodiversity under the three pathways for the four nations of the UK.

4.4.2.2. Protected areas

Results from the CCC pathway simulation show that Wales and Scotland exceed the 30% protected area target by 2030, whilst England and Northern Ireland have just under 30% in both 2030 and 2050 (Table 4.4). When aggregated to the UK level, the CCC pathways simulate 31% of total land as protected area in 2030 meeting the target of The Kunming-Montreal GBF (Table 4.4).

Table 4.4: Share of total land that is protected for the three pathways: Current Trends (CT), Climate Change Committee (CCC) and Devolved Administrations (DA).

Country	**Pathway**	**Share of Total Land Protected 2030 (%)**	**Share of Total Land Protected 2050 (%)**
Wales	CT	14.0	14.0
	CCC	32.7	32.7
	DA	44.4	48.8
Scotland	CT	12.4	12.4
	CCC	31.9	31.9
	DA	61.8	65.8
Northern Ireland	CT	8.7	8.7
	CCC	28.7	28.7
	DA	29.0	29.0
England	CT	3.1	3.1
	CCC	29.9	29.9
	DA	30.3	30.3

UK	CT	7.3	7.3
	CCC	30.7	30.7
	DA	41.4	43.1

Under the DA pathways, Wales and Scotland are simulated to increase their share of total land that is protected from 33% to 44% and from 32% to 62%, respectively, by 2030. This equates to 919,700 ha of protected land in Wales in 2030 comprised of forest and extensive land; compared to 4,803,000 ha of protected land in Scotland in 2030 comprised predominantly of ‘other natural land’ (Figure 4.7). Protected areas are simulated to continue to increase in Wales and Scotland towards 2050 (Table 4.4), through the creation of ‘other-natural land’ and forest that become protected. For England, the DA pathway projects that 30% of land is protected by 2030, equating to 4,004,972 ha. This is an increase of 58,440 ha and, thus England do not reach their target of protecting 500,000 ha of additional land in 2030. This is due to a plateau in land-use change that prevents protecting more natural land. In Northern Ireland, 29% of land is simulated to be protected by 2030, equating to 409,000 ha, therefore missing the 30% target. Both nation’s see protected areas remain the same towards 2050 (Table 4.4), again due to limited changes in land.

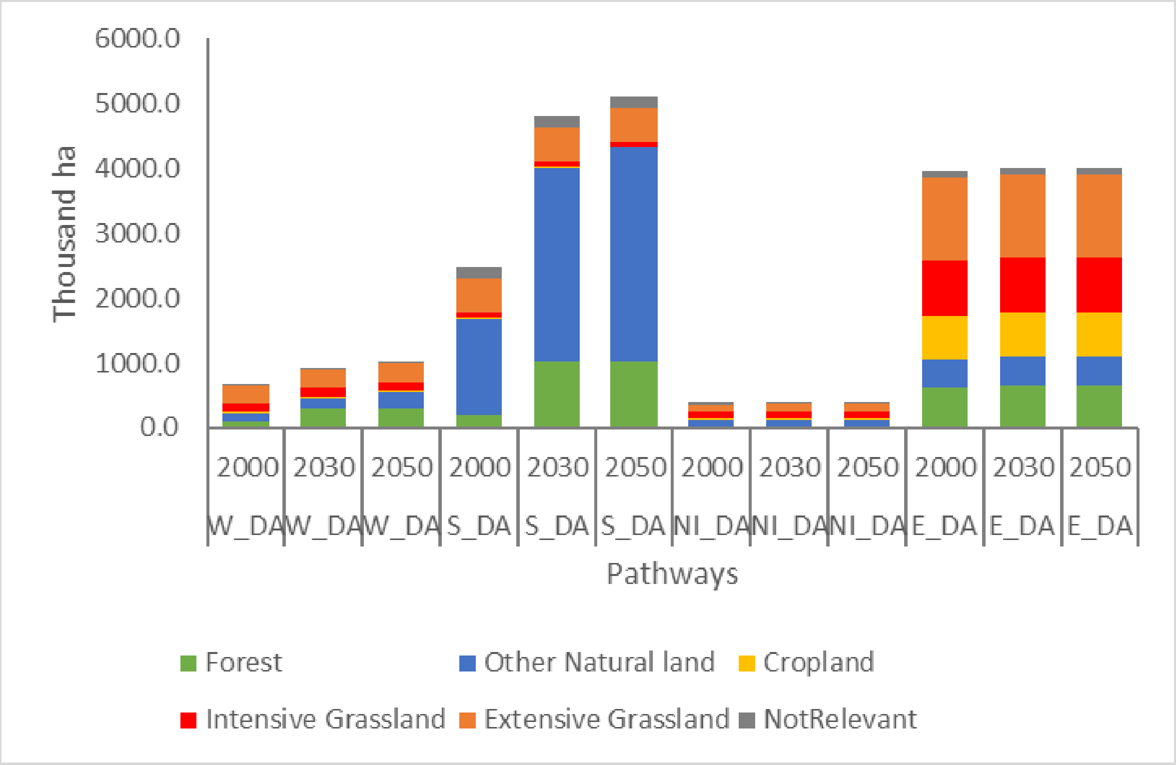

Figure 4.7: Composition of protected areas for the DA pathways in Wales (W), Scotland (S), Northern Ireland (NI) and England (E).

When aggregated to the UK, the DA pathways simulate 41% of land protected in 2030, exceeding the 30 x 30 commitment. The DA Pathways continue to increase the total protected areas through to 2050, most notably for Scotland (Table 4.4).

4.4.3 Autonomy

Comparison of the aggregated CCC and DA pathways to the UK provide an indication of whether the CCC recommended pathways provide greater or lesser benefits for climate and biodiversity targets than if the devolved administrations followed their own national polices and aspirations (as captured in the DA pathways). In addition, we can analyze alternative combination of pathways across the four nations to assess which provide the greatest benefits in terms of UK climate and biodiversity targets.

For example, if climate targets are prioritized the greatest cumulative GHG sequestration due to land-use change is simulated under the CCC pathway for Wales, Scotland and Northern Ireland, but under the DA pathway for England. This leads to cumulative sequestration of -77.0 $MtCO_2eq$ for the UK, which is a higher carbon sink than aggregations based on all nations following the same pathway (Table 4.5). The same aggregation also leads to the lowest cumulative emissions from the AFOLU sector through the time-period (of previous aggregations) of 300.72 $MtCO_2eq$ (Table 4.5).

This aggregation produces a greater total area of land for biodiversity conservation in the UK than the aggregated CCC pathways (Table 4.5), but less than all the DA pathways aggregated. This therefore emphasizes the need for considering the different policy priorities of the devolved nations, as the DA pathways provide a more beneficial future for biodiversity, but a mixture of pathways (Wales, Scotland and Northern Ireland: CCC; England: DA) is the most beneficial for GHG emissions.

Table 4.5: Cumulative emissions for aggregation of pathways for land-use and AFOLU sector

Pathway Aggregation	Cumulative Emissions – Land becoming a Carbon sink ($MtCO_2eq$)	Total Cumulative emissions from the AFOLU sector ($MtCO_2eq$)	Land available to support biodiversity conservation (1000 ha)
UK_CT	173.76	642.36	7490.8
UK_CCC	-62.43	314.07	12,813.0
UK_DA	-70.95	308.98	13,708.3
UK_Mixed (Wales, Scotland and	-77.00	300.72	13,248.2

Northern Ireland: CCC; England: DA)			

4.5. Discussion

Climate change policy for the AFOLU sector is challenged by complex biophysical and socioeconomic contexts (Brown, 2020). This paper explores the complexities of delivering on national policy commitments in a country where key climate-related policy areas are devolved. The outcomes of the FABLE modelling illustrates the different capabilities of the UK nations to deliver on climate targets for the AFOLU sector relating to net-zero, and their implications for delivering on biodiversity targets. Aggregating the pathways allows exploration of how the differing policy aspirations and approaches of UK Government and the Devolved Administrations may affect the ability of the four nations to collectively achieve national and international commitments.

4.5.1. Achieving net-zero

The CCC note that the AFOLU sector does not need to reach net-zero, and emissions from agriculture need to be offset by land becoming a carbon sink (CCC, 2020a). The results presented in this paper focus on these two elements of the land-use system: land becoming a carbon sink and total emissions from the AFOLU sector.

The CCC pathways generally result in the greatest carbon sink in 2050 for all the devolved nations except for Northern Ireland, primarily driven by the release of land from agricultural activity that can be afforested or restored to ‘other natural land’ to sequester carbon. When aggregated to the UK, the sink reaches -28.71 $MtCO_2eq$ in 2050. This is greater than the carbon sink cited for the Balanced Net-Zero Pathway in the CCC report (-19 $MtCO_2eq$). Similarly, simulated total AFOLU emissions, were negative for Wales, Scotland and England in 2050, but remains positive for Northern Ireland. When aggregated to the UK, the CCC pathways are negative in 2050, at -7.16 $MtCO_2eq$, which are lower than the CCC results of 16 MtCO2eq in 2060 (CCC, 2020a). These contrasting values are perhaps an indication that more research is required to support the recommendations for the devolved nations, to include more localised priorities of their governments.

A key policy area for achieving net-zero is afforestation, which necessitate changing substantial areas of land. However, most of the UK land is already used for agriculture or is important semi-natural open habitats (Bradfer-Lawrence, 2021). The land-use change results show that due to the high aspirations for protected ‘other natural land’ (that do not allow for changes in land-use), there is no further afforestation in Scotland’s

DA pathway after 2030. By 2050, this means Scotland will miss their afforestation target of 640,000 ha by 2050 by 138,000 ha. Missing the afforestation target means the carbon sink from land-use change, and other climate benefits, do not reach their full potential. These results align with research by Burke et al. (2021) whose scenarios for afforestation indicated that there is not enough land in the UK to meet the afforestation targets set. In contrast, research by Bradfer-Lawrence (2021) suggests that there is sufficient potentially suitable land to meet the CCC's woodland targets, but doing so at the scale required will have long-lasting and wide-ranging impacts on biodiversity and agricultural production. Wider assessments, therefore, of broad scale land-use change impacts are urgently needed (Finch et al., 2020).

4.5.2. Biodiversity and protected areas

Protected areas designations have the potential to be one of the more effective tools for protecting biodiversity in the UK (Bailey et al., 2022). The UK has been described as one of the most nature-depleted countries, with a decline in the distribution of species throughout the past 50 years (Hayhow et al., 2019). In September 2020, the UK Government pledged to protect 30% of its land by 2030 to support the recovery of nature (UK Government, 2021), and is supported by the devolved nations. The current portfolio of protected areas across the devolved nations is extremely valuable for nature, protecting the UK's biodiversity and contributing to nature recovery (Bailey et al., 2022). The simulated results show greater increases of protected land under the DA pathways, due to the assumption of the CCC pathways that only current designated areas continue to be protected. This difference in results highlights the different, more ambitious aspirations of Wales and Scotland in relation to protecting the natural environment, as both countries aspire to expand protected areas up to 2050 in the DA pathways.

When the DA pathways are aggregated, 41% of the UK is protected by 2030, increasing to 43% in 2050. However, the degree to which land is effectively protected for conservation in the UK varies greatly depending on the designation and the condition of the site, be that 'favourable recovering' or 'unfavourable recovering' (Starnes et al., 2021). Research suggests that 21% of UK land could be considered effectively protected at present, if this is assumed to include all categories of designation and those sites in an 'unfavourable recovering' condition (Starnes et al., 2021), leaving less work to do to achieve the 30 x 30 targets. However, Bailey et al. (2022) warn that the UK Government must be cautious about what is counted towards the 30 x 30 targeted due to the condition and management of different designations of protected areas, as many designations allow for agricultural activity that can be intensive, hence considering sites with strict protection, and in more favourable condition, would make the area smaller and the 30 x 30 target considerably harder to achieve than the results here might suggest.

In the DA pathways, land for biodiversity in Scotland is primarily ‘other natural land’; mainly bog, heath and wetland, whereas in England and Wales, land for biodiversity is predominantly extensive grassland, under the assumption that it is managed for biodiversity. Previous research has indicated that grasslands can play an important role in supporting biodiversity (Qi et al., 2018), and extensively managed grasslands, like those dominant in the DA pathways, are recognized for their high biodiversity (Bengtsson et al., 2019). Therefore, reversion to extensive, low input grasslands presents an opportunity to develop carbon sinks and biodiversity benefits for the UK (Gregg et al., 2021). However, encouraging or incentivizing a transition to extensively managed grassland is a challenge for the devolved nations with research noting the potential future yield gaps between more extensively managed grasslands versus intensively managed grasslands (Qi et al., 2018), as well as the economic burdens of management and change for farmers.

4.5.3. Autonomy and multi-level governance

A key challenge for coordinating future UK environmental policy is how to manage the different approaches to policy that may emerge at a devolved level (Burns et al., 2018), whilst ensuring national and international commitments are met. The simulated results indicate variation among the devolved nations’ land-use changes, carbon sinks, AFOLU emissions and protected areas, meaning their contribution to the UK’s climate targets can also vary.

This paper explored whether the UK would meet climate and biodiversity targets by aggregating the devolved nation pathways results by all CCC pathways, all DA pathways, and the optimal combination for cumulative emissions over the time-period. The latter showed that a combination of CCC and DA pathways yielded optimal results for cumulative emissions for the UK. However, this aggregation created less land for biodiversity. Moreover, since devolution, Wales and Scotland have sought to develop their own ambitious environmental policies, so perhaps devolving power to sub-national authorities could lead to more positive outcomes (Burns et al., 2018). However, given Northern Ireland’s history of weak environmental governance, and criticism of England’s lack of detail in environmental plans, allowing for full autonomy over the environment for all nations may negate the positive outcomes (Burns et al., 2018). The results provide evidence in contrast to the assumption autonomy would negate positive outcomes, particularly for GHG emissions, with England's national polices (DA Pathway) simulated to have lower cumulative emissions.

Climate mitigation requires action at all levels of governance, from the international, to the national and local levels (Monni and Raes, 2008). The global political agenda has placed great priority on sustainable development and climate change, which by their nature transcend national and sub-national boundaries, and levels of governance (Royles, 2021). International decision-making predominates, while sub-national governments increasingly act as implementers of those decisions (Royles, 2012). In the UK, our results indicate that allowing for more bottom-up approaches to policy design, sub-national countries' aspirations can be integrated into national action for successfully achieving international climate targets.

Whilst this research has focused on the relationship between the national (UK) and sub-national (devolved nations) levels for determining climate policy, interactions also exist at the local level (i.e., local councils and climate action groups), and further challenges of scale arise within the national context. Across the devolved nations' policy aspirations, agricultural policy has been criticized for appearing to adopt a one-size-fits all approach, failing to duly recognize the specific needs of smaller or hill farms, that are often the glue of rural communities and economies (Petetin 2022). By treating all farmers the same, new policies and schemes could create unfairness in the system, and it is hoped, that the actual implementation of schemes will assess more granularly the ranges of farming systems (Petetin, 2022). As well as this, a just transition to net-zero is now a high priority for Scotland and Wales, with Scottish Ministers establishing The *Just Transition Commission* in 2019 (Just Transition Commission, 2020). The Commission is to advise the Scottish Government on how just transition principles can be applied to climate action in Scotland, and work directly with farmers and communities to ensure fairness across changes towards net-zero (Just Transition Commission, 2020). Similarly, in 2022, the Welsh Government established a consultation on developing a Just Transition Framework for Wales for moving towards net-zero and have a clear understanding of the impacts of change will have on all of society (Welsh Government, 2022b).

4.5.4. Trade-offs

Land-use strategies require the integration of often conflicting demands of society on natural resources, with the objective of fulfilling demands for human wellbeing, without impairing biodiversity and ecosystem function (Seppelt et al., 2013). The identification of trade-offs is therefore important to achieve efficient planning given conflicting demands. The FABLE Calculator integrates a complex set of parameters relating to land-use and food systems to help understand the importance of considering all aspects of the food and land-use system whilst designing a suite of policy measures to achieve net-zero. This design supports understanding of potential conflicts, trade-offs and synergies between the policy decisions, something which policymakers need to be aware of (Smith and Harrison et al., 2022).

Previous research by Jones et al. (2023b) used the FABLE Calculator to develop pathways of alternative land-use futures for Wales, in collaboration with the Welsh Government. The results showed that the Land-sparing pathway (the CCC pathway) and the Land-sharing pathway (the DA pathway) had similar outcomes for carbon sequestration and net-zero. However, the biodiversity gains were greater under the Land-sharing pathway (Jones et al., 2023b), which aligned more closely with their policy aspirations. The results showed the Welsh Government that they had sufficient land area to succeed with net-zero and biodiversity targets, under a suite of policy measures guided by their own aspirations, through adopting more multifunctional landscapes that achieved multiple policy goals.

The pathways presented in this paper have similar trade-offs to those in Jones et al. (2023b), whereby the DA pathways better support biodiversity conservation towards 2050. The lower productivity, expansion of extensive grasslands, increases in protected areas, and afforestation rates create more multifunctional landscapes, where production, sequestration and biodiversity conservation can occur simultaneously on the same land. This supports the recommendations of Royal Society *Multifunctional Landscapes* report (Royal Society, 2023), which sets out guiding principles for creating landscapes that meet society's many needs efficiently and sustainably.

When exploring different pathways, those deemed most successful not only depend on the capacity to deliver a suite of policy changes, but also depend on the priorities of the policymakers and governments in charge of the decisions. The results indicate that policymakers have a clear decision to make when developing future land-use and agricultural policy; between achieving net-zero through intensification, or conserving biodiversity and protected areas.

The CCC note that Scotland, Wales and Northern Ireland produce 23% of carbon emissions in 2018, account for 16% of the UK's population, and are approximately half of the UK's land area (CCC, 2020a). However, despite Scotland having a smaller total land area than England, the results show that it has the greatest potential for afforestation throughout the period, planting more hectares than England, Wales and Northern Ireland combined. This means that despite contributing less than 23% of emissions, Scotland has a greater capacity for carbon sequestration and abatement within these pathways. Therefore, as an example, when aggregated to the UK level there may be a reliance on Scotland to achieve its land-based targets beyond what is initially required to counteract the high volumes of total GHG emissions in England. These trade-offs between the nations, and the priorities driving the UK policies and targets, therefore need to be further explored.

4.5.5. Limitations and future research

A key strength of the FABLE calculator, as described by Jones et al. (2023a), is that it can be used to explore how different assumptions can affect sustainability outcomes with reasonable estimates of multi-objective impacts, making it a valuable tool for cross-sector stakeholder engagement, exploration, and opening dialogue. Previous research using the FABLE calculator for the UK has highlighted limitations with using the calculator such as uncertainty in the input parameters, notably productivity, simplified calculations of GHG emissions and the lack of spatially explicit modelling of the pathways (Smith and Harrison et al., 2022; Jones et al., 2023a). Whilst this research has built upon these studies, notably through developing versions for the devolved nations that reflect the different contexts (Smith and Harrison et al., 2022), the pathways simulated in this research are a simplified version of the land-use and food systems in the devolved nations and, therefore, the results and analysis have certain limitations.

Firstly, previous modelling with the FABLE calculator included stakeholder input into the development of the pathways (Smith and Harrison et al., 2022, Jones et al., 2023b). For this research, other than the Welsh pathways, the DA pathways were developed based on available policy documents, without insight from those designing future policy. Therefore, the DA pathways reflect current policy aspirations, but do not consider all combinations of future policies. Secondly, the FABLE calculator is not an economic model, and there are no costs associated with the pathways. There is, therefore, no consideration in this research of how the new agricultural policies or payment schemes in the devolved nations would impact land-use change decisions at a farmer level. Finally, the FABLE calculator is not an optimization model, and the explored pathways are based on existing and recommended policies to understand what could be achieved given multiple policy goals for land and food systems, and not necessarily the optimal combination of pathway assumptions, which would require model inversion. Further work could therefore optimize the pathways through automated processes, to achieve both climate and other policy goals.

4.6. Conclusion

Through simulated pathways to sustainable land-use and food systems, this research provided an indication of the potential contributions of the devolved nations of the UK to its international and domestic climate agreements. Using the FABLE Calculator, pathways based on current trends in policy were compared to pathways based on the CCC recommendations, and pathways based on national policy aspirations. Compared to the CT pathways, both the CCC and DA pathways see a transformation of land, through increased aspirations in afforestation, agricultural productivity, and biodiversity conservation. The CCC pathways generally result in a greater carbon sink compared to the DA pathways for Wales, Scotland, and Northern Ireland. However, for England, the DA pathway cumulatively sequesters more carbon than the CCC pathway. The DA pathways create more land for biodiversity compared to the CCC pathways for all devolved nations. England produced the most significant increase in land to support biodiversity conservation under both pathways. The complexity of autonomy and scale are highlighted in working towards a common climate goal, and despite the greater ambitions in environmental policy of Wales and Scotland, their size and capacity to enact on those ambitions is counteracted by the size, and perceived lesser ambitions, of England and the UK. The findings emphasize the importance of the choice in priorities between climate and biodiversity that policymakers have at the sub-national and national level, with the need for more concerted efforts to address climate change and protect natural resources within and across each nation.

5. Spatially explicit exploration of pathways towards sustainable land-use change in the UK

Abstract

Policy interventions for achieving sustainable land-use, climate mitigation and adaptation, and reversing biodiversity decline often have a spatial dimension. Spatially-explicit land-use change projections provide crucial evidence for policymakers on the consequences of implementing individual and combinations of policy measures, and are imperative for exploring location-specific implications of different policy alternatives. This paper integrates aggregated land-use change projections from a non-spatial model (the FABLE Calculator) with a downscaling model, to generate land-use change maps for the UK in 2050, across three policy pathways. The results highlight areas that are more likely to undergo land-use changes by 2050, regions that remain unchanged across the pathways, and identify areas for more targeted policy interventions across the UK. This paper emphasises the added value of spatial outputs for providing a more meaningful method for testing and refining policy strategies.

5.1. Introduction

Land-use has changed dramatically over recent decades, with Winkler et al. (2021) estimating that almost a third (32%) of global land areas have experienced land-use change between 1960-2019. Land-use changes are driven by many factors, including biophysical conditions, population changes, economic activity and governance (Sleeter et al., 2012). These changes affect human livelihoods, such as through the supply of food, freshwater and multiple other ecosystem services (IPCC, 2019). They also contribute to ongoing increases in greenhouse gas (GHG) emissions (IPCC, 2019) and biodiversity loss globally (IPBES, 2019). Effective management of land and land-use change can increase carbon storage and avoid GHG emissions, and aid the reversal of biodiversity decline (Griscom et al., 2017). Therefore, land-based climate mitigation strategies have gained significant attention in climate policy (Roe et al., 2019), with many national governments now adopting nature-based solutions into their policy planning to reduce net GHG emissions in ways which also benefit biodiversity. However, the impacts of these solutions, and their spatial feasibility on the land, remain uncertain (Bradfer-Lawrence et al., 2021).

Global agreements, such as the Paris Agreement, Kunming-Montreal Global Biodiversity Framework and the Sustainable Development Goals have led to increases in policy development and target-setting at national and sub-national levels (IPCC, 2023). Many of these targets involve transforming the use of land to achieve climate, biodiversity, food and other sustainability goals, and there is an urgent need to translate such targets into action on the ground (Mosnier et al., 2023). Moreover, global intergovernmental bodies, including the IPCC, IPBES and the UN’s Environment Programme, all state the importance of spatially explicit assessment of land-use change for understanding complex interactions between human activities and the environment, identifying at-risk areas, guiding and prioritising interventions, and exploring the effectiveness of land management strategies (IPCC, 2019; IPBES, 2019; UNEP, 2019). Policymakers require evidence on the spatial feasibility of implementing individual, and combinations of, actions that account for the multiple demands on land, and how the consequent different spatial configurations of land-use transformations contribute to policy goals (Garbolino and Baudry, 2021; Carvalho Ribeiro et al., 2013). Spatially explicit land-use modelling improves understanding of spatial patterns of land-use and land-use change and their consequences for optimising synergies and minimising trade-offs between outcomes at different scales (Thomson et al., 2019). By predicting the spatial, and temporal, distribution of land-use changes, areas can be targeted for intervention, developing appropriate, and location-specific, strategies (Lesschen et al., 2005).

Land-use models play an important role in exploring future land-use change dynamics (Verburg et al., 2019), aiding in evaluating potential trade-offs between different demands for land-use, and the complex linkages and feedbacks between the different drivers of land-use change (van Soesbergen 2016). Therefore, land-use models can provide valuable support for policy and decision-making (Prestele et al., 2016). Policy and decision-making on land-use typically takes place at national and sub-national scales. Hence, it is important that land-use scenarios and models are able to represent the local priorities, cultures and contexts that are vital for informing national policies (Mosnier et al., 2023b). The Food Agriculture, Biodiversity, Land-use and Energy (FABLE) consortium has developed a unique decentralised approach to land-use modelling that empowers country teams to develop and model their own national pathways focused on domestic priorities and targets, and iteratively refine them so that they collectively meet global goals (Mosnier et al., 2023). The consortium developed the FABLE Calculator, an open-source Excel-based tool for modelling national projections of food and land-use systems (Mosnier et al., 2019). The FABLE Calculator is a simple integrated model designed to remove the technical and economic barriers associated with implementing complex and compute-intensive integrated assessment models at national scales (Jones et al., 2023a).

Land-use models do not always have sufficient spatial resolution to allow them to be used effectively in policy decision-making (Woodman et al., 2023). For example, land-use model outputs may be at a scale that is too coarse for meaningful exploration or testing of policy alternatives (Voight and Troy, 2008). To address this, a range of spatial downscaling methods have emerged to translate land-use information from coarser to finer geographic scales, while maintaining consistency with the original dataset (van Vuuren et al., 2010). The simpler downscaling methods disaggregate data from different scales; either by assuming that elements have the same growth rates (proportional downscaling) or by using an average regional value to disaggregate data (convergence downscaling) (van Vuuren et al., 2010). More complex algorithms consider statistical downscaling, which derive statistical relationships between observed historic data and global model data to produce fine resolution data (Tabari et al., 2021) or dynamic downscaling, where multi-scale models are coupled and interactively link data of different scales as part of the modelling process (van Vuuren et al., 2010). For land-use, previous research has used statistical downscaling to downscale coarse resolution land-use projections to a higher spatial resolution; at a global scale for an increased number of land-use types (Hoskins et al., 2016); a country scale for future land-use change projections (West et al., 2014) or a catchment level for exploring precipitation futures and land-use (Hofman et al., 2022). Research has also incorporated stakeholder engagement into downscaling for validating the narratives and assessing unexpected changes in the Pyrenees (Houet et al., 2017); or to include an element of local context and decision-making into downscaling land-use change projections to a landscape level in the UK (Rickebusch et al., 2011).

In June 2019, the UK Government expanded The UK *Climate Change Act (2008)* and introduced a legally binding target for the UK to achieve net-zero GHG emissions across the UK economy by 2050 (Brown et al., 2023). The UK is also a signatory to international agreements such as the Paris Agreement and the Kunming-Montreal Global Biodiversity Framework (GBF). However, agriculture and land-use formed approximately 21% of UK GHG emissions in 2021 (CCC, 2023), and current land-use policy and measures, particularly afforestation and peatland restoration, fall short of what is required to reach net-zero (CCC, 2023). In addition, the UK lacks a shared, spatially explicit evidence base to support land-use decision-making that integrates data, technology and scientific knowledge (Geospatial Commission, 2023). Hence, the UK Government and its devolved administrations of England, Wales, Scotland and Northern Ireland recognise the urgent need for spatial evidence on how to transform land-use to achieve multiple policy targets related to net-zero, biodiversity and people.

Currently, agricultural, land-use and environmental policies in the UK are said to be failing to achieve their environmental goals, as well as failing to support economically viable rural communities (Collas and Benton, 2023). The UK has a relatively large population and small land area, with many competing potential land-uses and multiple ecosystem services required from this finite land resource, coupled with complex issues of land tenure and political governance (Field et al, 2020). With the ramifications from the UK's exit from the European Union and increasing public concern about the impacts of climate change and the biodiversity crisis (Burchardt et al., 2020), the UK and its devolved governments are under increased pressure to develop sustainable land-use and environmental policies. Therefore, previous research has provided evidence for informing future land-use and environmental policy for the UK by developing land-use scenarios based on the UK's carbon budgets and net-zero goals, and illustrating the consequences for diet and GHG emissions (Collas and Benton, 2023); or pathways for sustainable land-use and food systems based on national targets that are consistent with achieving global goals (Smith and Harrison et al., 2022). However, these studies were non-spatial, presenting changes in land-use at an aggregate level and, thus, unable to test the spatial feasibility of future policies or spatially target interventions.

This paper aims to contribute further to the evidence base for policy development and decision-making in the UK by integrating non-spatial land-use change projections with a downscaling model to create spatial land-use change maps for the UK at a 1 km spatial resolution. The land-use change projections are outputs from modelling different policy pathways encompassing measures on afforestation, agricultural productivity, peatland restoration and dietary change. Thus, spatialising the outputs aims to provide a more precise indication of where land-use change would occur as a consequence of policy changes, to allow for more targeted interventions. Additional spatially explicit constraints on the land-use changes are introduced during the optimisation process, to further test the feasibility of policy changes represented in the pathways. The paper concludes with a discussion on the potential consequences of the modelling approach and maps of land-use changes, and their implications for policy development and decision-making.

5.2. Materials and methods

5.2.1. Overview of approach

Outputs from a food and land-use systems model, the FABLE Calculator, were integrated with a downscaling optimisation model to generate fine scale projections of land-use for 2050 in the UK. The FABLE Calculator is an integrated food and land-use systems model (Mosnier et al., 2019), that simulates the consequences of national food and land-use pathways. The pathways are developed through in-depth policy review and stakeholder engagement to represent different policy aspirations for transforming land-use. The Calculator outputs were used as inputs to a downscaling algorithm, to create spatially explicit land-use change projections at a spatial resolution of 1 km^2 across the UK.

The downscaling approach uses existing land-use data and explanatory spatial data at a spatial resolution of 1 km to model the probability of land-use transitions. The explanatory data on drivers of land-use change were sourced, processed and used within a multinomial logistic (MNL) regression of land-use transitions to estimate the probability of land-use change at the 1 km^2 resolution. The FABLE outputs were then projected to the 1 km resolution by considering which 1 km cells were most likely to transition to achieve the overall projected land-use. Using a Bayesian approach to model fitting, a sample of posterior draws from the regression model were then used in the downscaling to capture the associated uncertainty with land-use transitions. The methods were implemented using the *downscalr* R package (Krisztin, Wögerer, and Ringwald, 2022) using the workflow presented in Figure 5.1.

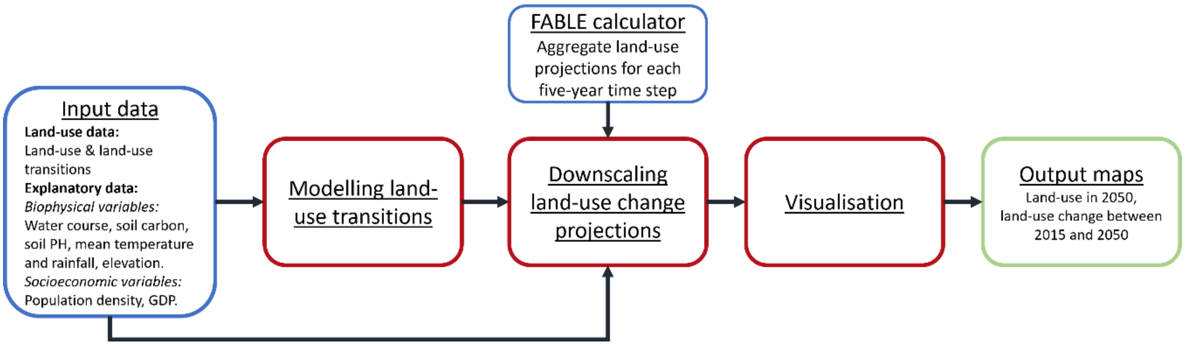

Figure 5.1: Workflow of methods

5.2.2. Data

5.2.2.1. FABLE land-use change outputs

The land-use change projections used in the downscaling are outputs from the FABLE Calculator. The FABLE Calculator takes pathways comprised of a series of policy measures relating to agriculture and land-use sectors, such as afforestation, agroecology, agricultural productivity, peatland restoration and dietary change; and aims to solve the transformations that are required to achieve them (FABLE, 2020). Using the FABLE Calculator, Jones et al. (in review) developed three pathways for sustainable land-use and food systems in the UK, taking into consideration the aspirations and contexts of the devolved nations of England, Wales, Scotland and Northern Ireland. An overview of the pathways can be seen in Table 5.1.

Table 5.1: Overview of different pathways quantified using the FABLE Calculator (Jones et al., in review)

Pathway	**Summary**
Pathway 1: Current Trends (CT)	Continuing with no changes to current policies.
Pathway 2: CCC pathway	Transformation of land-use to sequester carbon and restore peatlands combined with ambitious increases in productivity.
Pathway 3: DA pathway	These pathways were developed based on the policy aspirations of the devolved nations. **Wales**: Using land management techniques, the Welsh policy aims to deliver biodiversity restoration, carbon sequestration and production simultaneously on the same land. **Scotland**: The pathway has more ambitious targets for achieving net-zero by 2045, with a focus on multifunctional land-use, reducing food waste and restoring nature. **Northern Ireland:** Given the infancy of climate policy, very similar to current trends, with slight increases in afforestation. **England:** Aspirations to increase areas of land for biodiversity, without compromising productivity**.**

The specific outputs of the FABLE Calculator used in the downscaling algorithm are the land-use changes for each 5-year time step from 2015 to 2050. These are non-spatial aggregate totals of land-use in hectares for seven land-use classes: Urban, Cropland, Intensive Grassland, Extensive Grassland, Forest, Other Natural Land (mainly bog, heath and wetlands) and Not Relevant (water, coasts, rock and bare ground). The outputs were scaled and converted to km^2 for use in the downscaling algorithm.

5.2.2.2. Land-use data

For modelling the land-use transitions, two types of land-use data are required: land-use transitions and land-use data for the baseline map. The UKCEH Land Cover Map (LCM) 2015 was used as the baseline map, representing the diverse UK landscape. Land in the UK is predominantly used for agriculture, with 42% grassland and 24% arable land (Rowland et al., 2017a, b). The rest of the UK includes 15% mountainous, heath and bog areas, 8% forested areas, 6% urban and 5% water and coastal ecosystems (Rowland et al. 2017a, b) (Figures C1 and C2).

Land-use transitions were based on differences between the UK Land Cover Maps (LCM) for 2007 (Morton et al., 2014, Morton et al, 2011) and 2015 (Rowland et al., 2017a, b). These spatial data are available at 1 km2 spatial resolution, include coverage of all the UK, and can be mapped to the land-use classes of the FABLE outputs (Table 5.2). Figure C2 shows the LCM for 2015 mapped to the FABLE land-use classes.

Table 5.2: Mapped land-use classes from LCM and FABLE land-use classes

Code	**LCM Aggregate Class**	**FABLE Land-Use Classes**
1	Broadleaf Woodland	Forest
2	Coniferous Woodland	Forest
3	Arable	Cropland
4	Improved Grassland	Intensive Grassland
5	Semi-natural Grassland	Extensive Grassland
6	Mountain, Heath, Bog	Other Natural Land
7	Saltwater	Not Relevant
8	Freshwater	Not Relevant
9	Coastal	Not Relevant
10	Built-up Areas and Gardens	Urban

5.2.2.3. Explanatory variables

The explanatory variables required for the MNL consist of data that could influence land-use change. Spatial explanatory variables were obtained at a 1 km^2 spatial resolution. Data included bio-geophysical, land management and socio-economic information (see Goodwin et al., 2022 for further details) (Table 5.3).

Table 5.3: Explanatory Variables used in the Multinomial logit model

Variable	**Coverage**	**Source**
Land-use change	UK	Rowland et al., 2017a, b; Morton et al., 2014; Morton et al., 2017.

Land-use (Baseline year)	UK	Rowland et al., 2017a, b; Morton et al., 2014; Morton et al., 2017.
Woody linear features	GB	Goodwin et al., 2022
Distance to minor roads	GB	Goodwin et al., 2022
Distance to major roads	GB	Goodwin et al., 2022
Population density	UK	Reis et al., 2017
Water courses	UK	Goodwin et al., 2022
Soil carbon	GB	Goodwin et al., 2022
Soil pH	GB	Goodwin et al., 2022
Soil and sand content	GB	Goodwin et al., 2022
Mean temperature	UK	Goodwin et al., 2022; Hollis et al., 2022
Mean rainfall	UK	Goodwin et al., 2022; Hollis et al., 2022
Elevation	UK	Goodwin et al., 2022; OSNI, 2023

Spatial data on protected areas from the World Database on Protected Areas (UNEP-WCMC and IUCN, 2023) were also included in the downscaling module, to provide restrictions on where land-use change could occur in accordance with the stricter designations of protection.

5.2.3. Modelling land-use transitions

A multinomial logistic regression model (MNL) was used to model the historic land-use transitions in the downscaling algorithm. This approach allows for more than two unordered and discrete response variables (Lin et al., 2014) and has been shown to be a robust method if the aim is to obtain probability maps of land-use change (Dendoncker et al., 2006). For this research, we used a MNL implemented in a Bayesian framework to analyse the relationships between historic land-use transitions (the LCM 2007 and the LCM 2015 mapped to FABLE land-use classes) and a set of biophysical and socio-economic explanatory variables (Table 5.3), to obtain outputs for use in the downscaling. The outputs capture the different possibilities of how the explanatory variables might affect land-use transitions, and result in an understanding of the potential drivers of land-use change over time. The spatial relationships between the land-uses are captured within the modelling, through an average of the neighbouring pixels' land-use and explanatory variable outputs. Based on the posterior predictive distribution from the MNL, each pixel for the land-use map of the UK is, therefore, assigned a probability of a being a certain land-use type, given those explanatory variables. This is termed the set of posterior draws. We used the mean MNL posterior draws in the downscaling model, as well as a sample of 100 posterior draws to explore the uncertainty in the downscaling projections.

5.2.4. Downscaling land-use change projections

The downscaling model takes the posterior draws from the MNL and uses an optimisation algorithm, a solver function, to output fine spatial resolution land-use change projections, which are consistent with the FABLE outputs. It bridges the gap between observed land-use change (LCM), drivers of land-use change (explanatory variables) and aggregated land-use change projections (FABLE Outputs).

The downscaling algorithm is applied to all of the UK, examining each 1 km^2 pixel from the LCM. The algorithm takes the aggregate areas of land being converted from one land-use to another from the FABLE outputs and combines this with the probabilities (posterior draws) of the land-use transitions from the MNL. Using the solver function, it systematically adjusts the possible changes in each pixel to match the aggregate land-use projections from FABLE as closely as possible by minimising the difference between the posterior draws and the aggregate land-use values from the FABLE Calculator. Further technical details of the downscaling algorithm can be found in Krisztin, Wögerer and Ringwald (2022), (https://github.com/tkrisztin/downscalr).

5.3. Results

5.3.1. Spatial patterns of land-use and land-use change in 2050

The results from the downscaling of the FABLE Calculator outputs show that all the pathways are spatially feasible given the biophysical and protected area constraints (Figure 5.2). The spatialisation of the three pathways produced different patterns of land-use, representative of the different policy configurations. The CT pathway showed only small changes from 2015, the mapped CCC pathway indicated a large proportion of UK land area being released from agriculture and converted to the other natural land class (for biodiversity), and the DA pathway showed a more mixed pattern of increases in extensive grassland and other natural land.

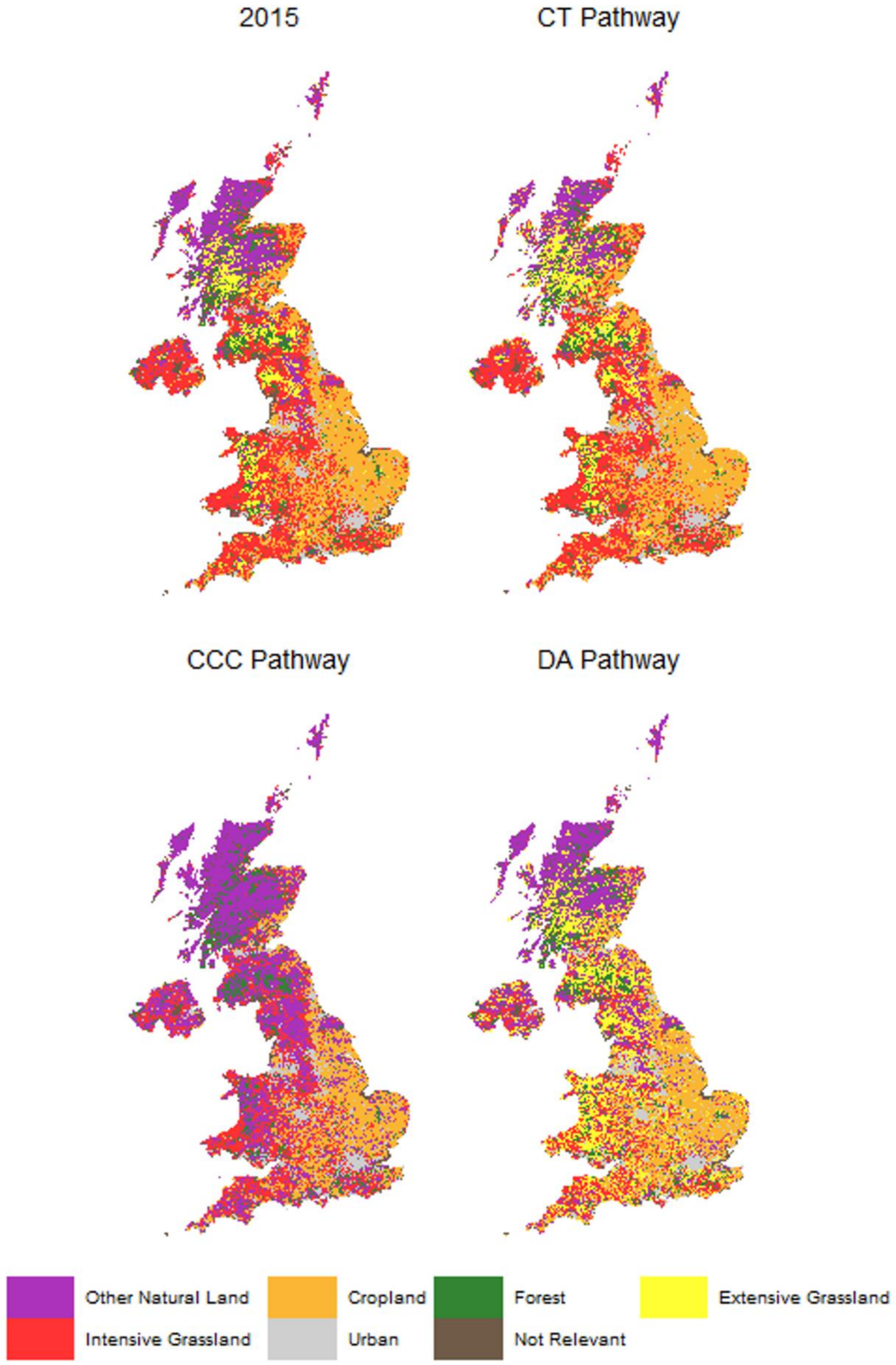

Figure 5.2: Land-use in 2050 for each of the FABLE pathways

The changes in each land-use class from 2015 and 2050 are presented Figure 5.3. Cropland areas decrease in 2050 for the CCC and DA pathways, due to the productivity increases in the pathways, however the spatial pattern of cropland remains similar. Likewise, the area of intensive grassland reduces due to assumed gains in productivity in these pathways. The area of extensive grassland is reduced to zero in the CCC pathways in 2050. Alternatively, the area of extensive grassland is greater in the DA pathway than in the CT pathway in 2050 and compared to the 2015 baseline. Other natural land, which is important for supporting biodiversity, reduces in the CT pathway from 2015, with losses in the south of the UK, but increases in spread in the CCC and DA pathways. Slight increases in urban areas are projected in all pathways to account for increases in the UK population.

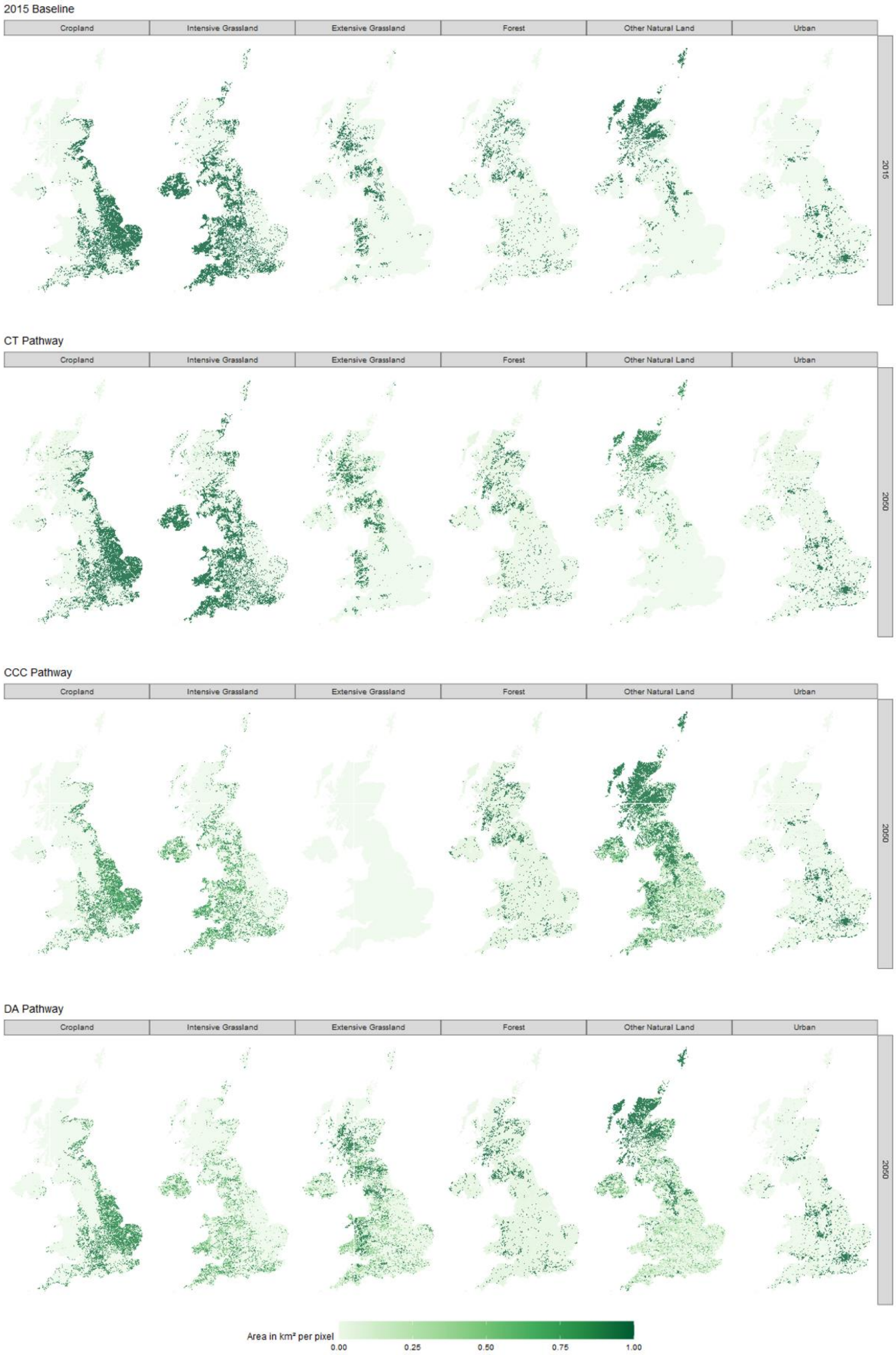

Figure 5.3: Land-use changes by land class for the three pathways between 2015 baseline and 2050

5.3.2. Uncertainty in downscaled projections of land-use in 2050

Variation in the projected land-use change values for each pixel was captured by utilising 100 draws from the posterior distribution from the MNL. Using each of these posterior draws within the downscaling model provided a set of 100 samples of the downscaled land-use projections. Across the 100 samples, the downscaling algorithm outputs a value for the proportion of each 1km^2 pixel that is of each land-use type, with a maximum value of 1 across the pixel. The range in the proportions across the 100 samples provides a metric representing consistency of the downscaled outputs across the samples.

Table 5.4 shows how the percentage of pixels were distributed across the 0 to 1 range for each pathway in 2050. Larger ranges indicate variation amongst the outputs of the downscaling algorithm across the samples, whilst smaller ranges close to zero indicate that across 100 samples the downscaling algorithm outputs the same value each time.

Table 5.4: The percentage of observations and their corresponding ranges for the three pathways. The observations are different for each pathway due to accounting for observations of land-use that are not present in the baseline and are restricted from changing in the algorithm (i.e., we removed rows where the baseline is zero and all the sample values are zero for certain land-use types such as "not relevant" to create a more accurate picture of where the range is zero across the values).

	CT	**CCC**	**DA**
Range	**%**	**%**	**%**
0 - 0.1	93.62	82.38	83.49
0.1 - 0.2	3.17	6.74	6.96
0.2 - 0.3	1.44	4.34	4.43
0.3 - 0.4	0.66	2.75	2.29
0.4 - 0.5	0.44	1.69	1.38
0.5 - 0.6	0.34	1.03	0.72
0.6 - 0.7	0.20	0.59	0.4
0.7 - 0.8	0.07	0.3	0.2
0.8 - 0.9	0.04	0.12	0.09
0.9 - 1	0.02	0.06	0.04

For the CT pathway, 94% of observations have a range of 0 to 0.1 across the samples, while only 0.02% exhibit a range of 0.9 to 0.1. This prevalence of low ranges suggests a high degree of consistency in the model outputs, wherein the downscaled samples consistently produce similar values for each land-use observation. For the CCC pathway, 82% of observations exhibit values ranging from 0 to 0.1 across the samples, with only

0.06% displaying a range of 0.9 to 1, the highest among the three pathways. Despite the larger changes in land-use types projected in this pathway, a significant proportion of observations exhibit similar values across the 100 samples. Similarly, for the DA pathway, 83% of observations have a range of 0 to 0.1, with 0.04% with a range of 0.9 to 1.

5.3.3. Uncertainty in land-use changes between 2015 in 2050

The downscaled outputs were further analysed to assess any uncertainty in the downscaling process, through exploring the difference between the 2015 baseline and 2050 downscaled value for each land-use type per pixel across each of the 100 samples. Figure 5.4 presents maps of the sum of these differences for each pixel by each land-use type. The maps highlight the areas of repeated change amongst the samples. Given that the maximum difference from the baseline map per pixel is 1, the closer the sum of difference to -100/100 the more that a land-use type is consistently lost/gained across most or all of the downscaled outputs.

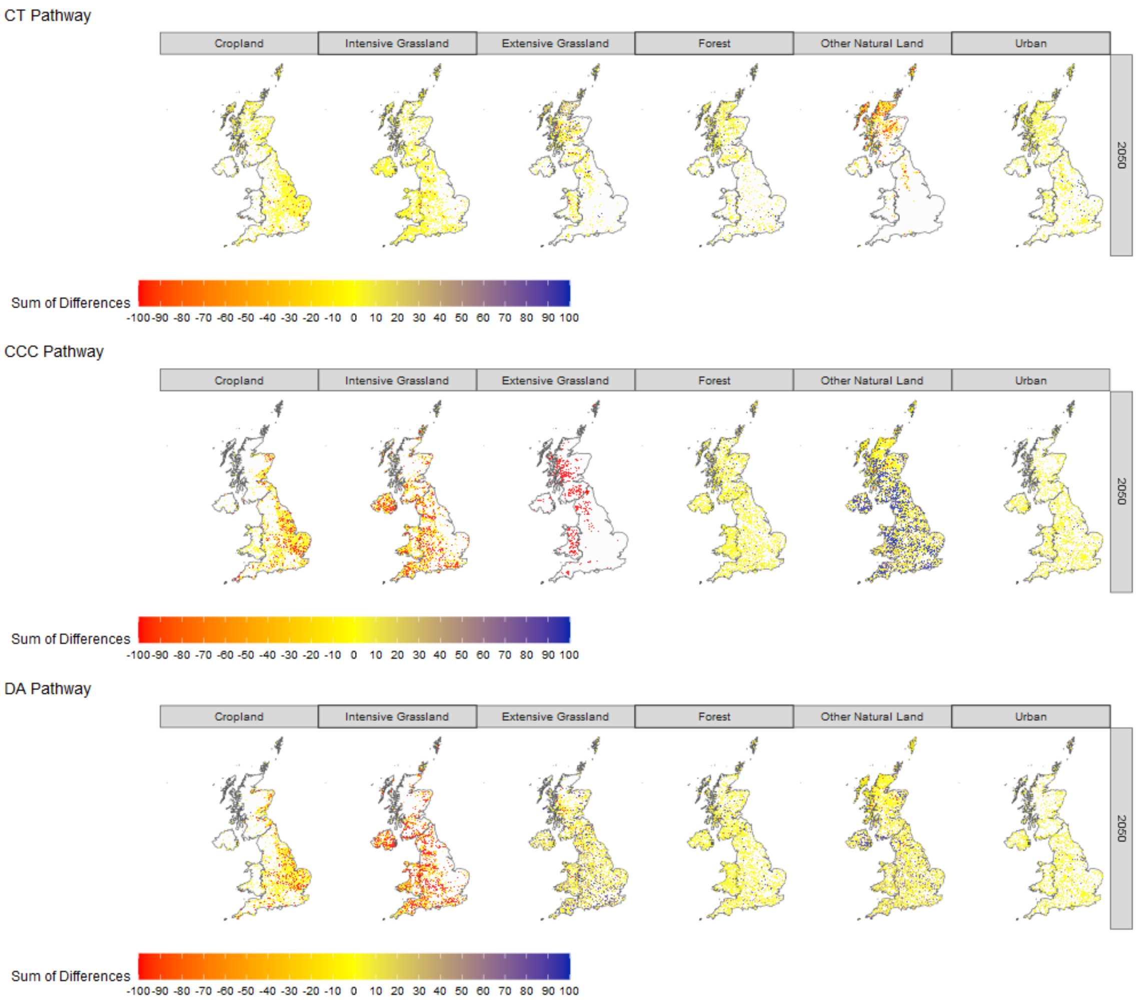

Figure 5.4: The mapped sum of differences across the 100 samples for each pathway in 2050

In the CT pathway, where policy changes are relatively minimal, few pixels show changes in land-use from the baseline, and the sums of differences across the 100 samples are mostly (81%) between -10 and 10, suggesting a small deviation from the land-use configuration in 2015. The spatial pattern of these land-use changes (Figure 5.4) shows that despite the small changes in policy, there are notable losses of habitat, particularly in the other natural land category, where 88% of the category losses are dispersed throughout Scotland.

Given the ambitious policy targets in the CCC pathway, significant changes in land-use are simulated by the FABLE Calculator from 2015 onwards. The spatialised downscaled outputs also present this, with high sums of differences between the baseline and 2050 across the samples, indicating high confidence in land-use change at the 1km^2 pixel level. For example, areas where there is high confidence of increases in other natural land can be identified in central Scotland and northern England; due to the sums of differences ranging between 90 and 100 (Figure 4). Scotland also has the highest confidence in land-changes to forest in the CCC and DA Pathways, encompassing 70% and 55% of forest areas with sums of differences between 90 and 100 respectively. Conversely, Figure 5.4 also presents areas where land-use categories are consistently lost, where the sums of differences are -90 to -100. For example, there is widespread loss of extensive grassland in the CCC pathway, approximately half of which is in Scotland (53%) followed by England (25%) and Wales (19%). These losses can be attributed to the CCC pathway's emphasis on releasing extensive grassland for achieving biodiversity goals, which is accompanied by gains in the other natural land category.

Given the emphasis on multifunctional landscapes in the DA pathway, fewer changes in land-use are simulated by the FABLE Calculator compared to the CCC pathway, as evident from the comparison of maps for each pathway in Figure 5.3. In addition, there is lower confidence in the spatialisation of these changes, which are predominantly gains in extensive grassland and other natural land, and losses in intensive grassland (Figure 5.4), with these losses primarily occurring in England. These less consistent differences between the downscaling values and the baseline map across the 100 samples indicates the possibility space for the pixel changing land-use types is more uncertain in the DA pathway. This uncertainty, and the smaller sums of differences, perhaps indicate more subtle changes in land-use at a more local scale, which would require slightly different interventions, as well as perhaps further monitoring of their effectiveness. In addition, despite Northern Ireland being smaller in size than Wales, the gains in other natural land in the DA pathway are more consistent and approximately 40 times higher than in Wales. Similarly, there are greater losses of intensive grassland in Northern Ireland than in Wales, which could indicate an increased reliance on Northern Ireland in this pathway for those marginal gains.

5.3.4. Areas of no change

Further analysis was undertaken to explore the areas that consistently do not change across the 100 samples for each pathway, i.e., where the sum of differences equals zero. For the CT pathway, 155,563 km2 (62% of the UK) does not change across the 100 samples, predominantly cropland and intensive grassland (Figure 5.5), reflecting the small changes in policy. In contrast, only 28% and 23% of the UK do not change across the 100 samples in the CCC and DA pathways, respectively (Figure 5.5).

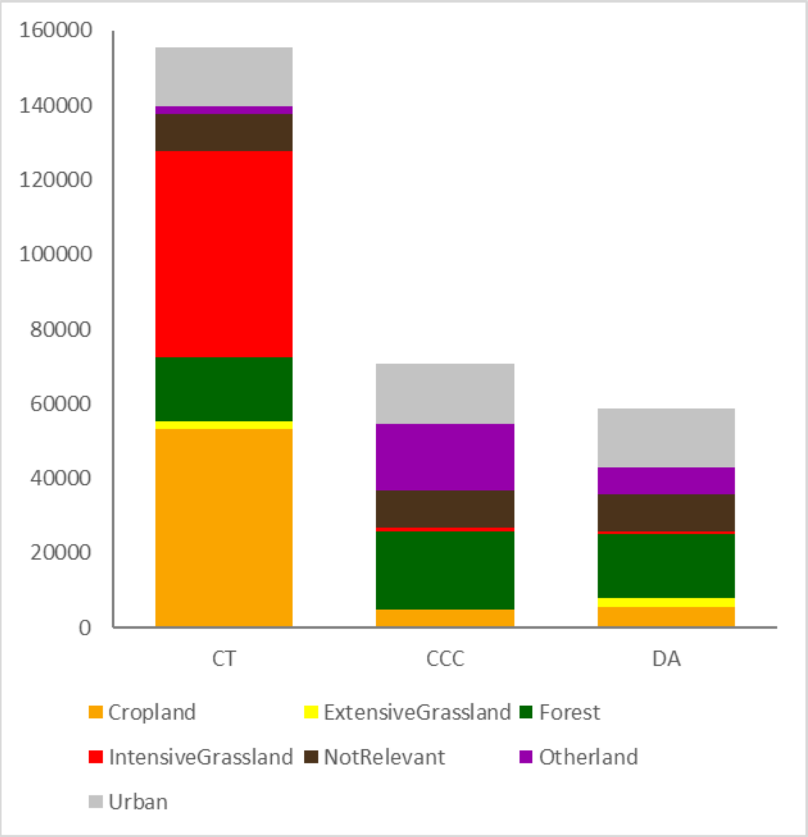

Figure 5.5: Aggregate areas of no change

Figure 5.6 displays the areas of no change for each pathway, by land-use type. The CT pathway predominantly sees no changes in cropland in England, and intensive grassland across Wales and Northern Ireland. In contrast, the CCC pathway has the more widespread areas of no change of other natural land and forest areas, particularly in Scotland, central areas of the north of England and central Wales. Likewise in the DA pathway, other natural land and forest were the more widespread areas of no change across north and east Scotland, as well as areas of no change of extensive grassland across Scotland and central Wales.

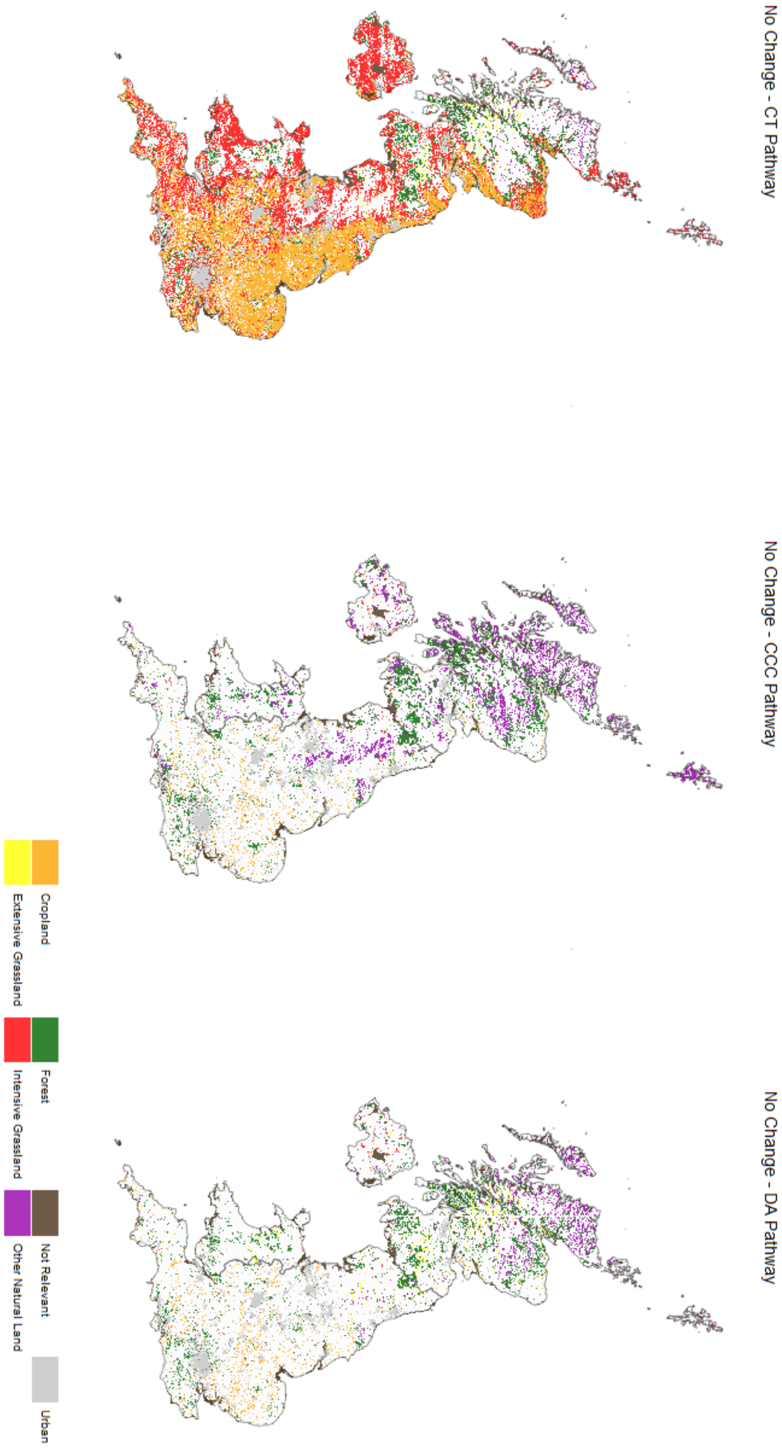

Figure 5.6: Areas of no change for each land-use types in each pathway

Other natural land that remains unchanged is the highest in Scotland across all three pathways. In the CCC pathway, despite Scotland having the largest amount of other natural land that consistently changes in 2050 (sum of differences = 100), it also has the highest areas of no change (70% of other natural land that remains the same, compared to 20% in England) (Figure 5.7). Similarly, Scotland also has the highest areas of no change for forest across the three pathways, and extensive grassland in the DA pathway. The land classes of other natural land, extensive grassland and forest are assumed in the FABLE Calculator to reflect land that support biodiversity; Hence, these results perhaps reflect a reliance of Scotland to protect and increase land to support biodiversity in the future.

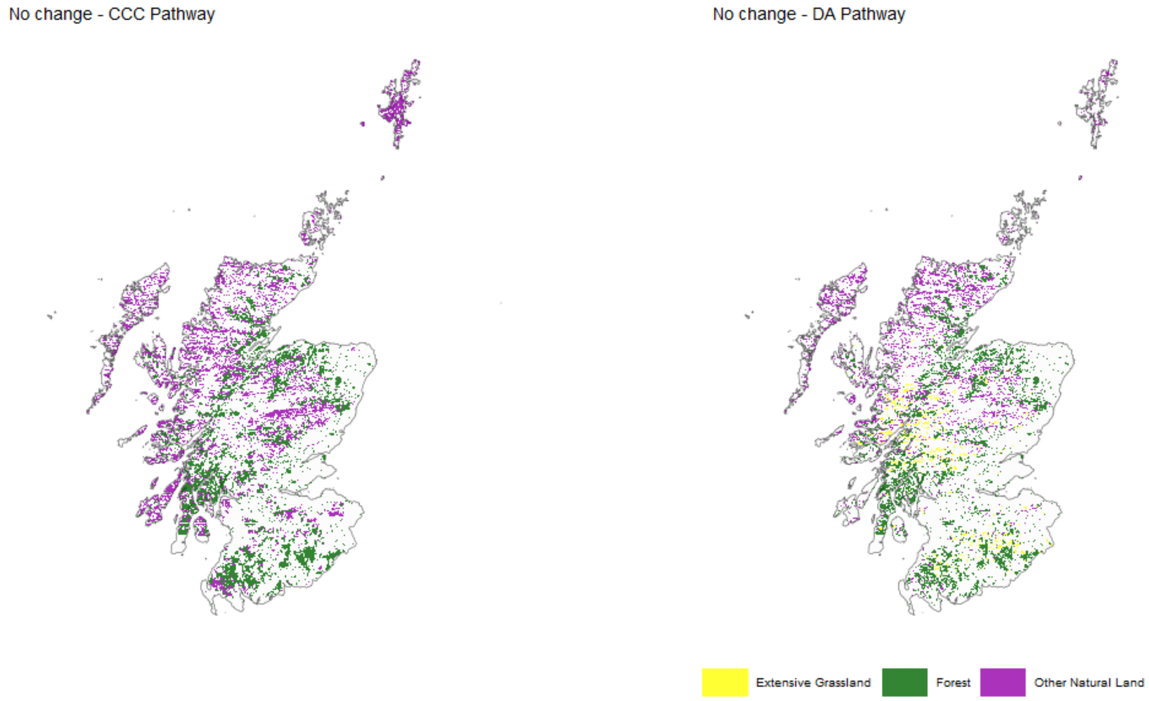

Figure 5.7: Areas of no change for extensive grassland, forest and other natural land in Scotland; the land classes used in the FABLE Calculator to estimate land that supports biodiversity

5.4. Discussion

5.4.1. The importance of downscaling land-use projections

Narrative scenarios are often quantified by land-use models to depict possible trajectories of future land-use change and their associated societal and ecological impacts (Mallampalli et al., 2016). Many scenario studies focus on aggregate land-change, without a spatial component, such as the FABLE Calculator (Mosnier et al., 2019). Previous research developing FABLE pathways notes the limitation of the lack of spatiality in the Calculator, calling for further spatial interpretation and geospatial resolution to resolve how land-use changes could actually occur (Smith and Harrison et al., 2022, Jones et al., 2023b, Mosnier et al., 2023b, Gonzalez-Abraham et al., 2022). The integration of the FABLE outputs and the downscaling algorithm presented here are indicative of a reproducible framework that can be further used by country teams in the FABLE consortium.

The downscaled outputs in Figure 5.2 illustrate that the projected land-use changes from the FABLE Calculator could feasibly occur. That is, there is theoretically enough land to achieve the projected land-use change based on historic land-use transitions, biophysical conditions and restrictions due to protected areas. This is tested through the choice of covariates used in the downscaling algorithm, which are chosen to adequately cover factors that drive and constrain land-use change. Downscaling methods commonly use the statistical relationship between land-use and covariates, such as population density, elevation or soil quality, to determine the likelihood of finer spatial resolution pixels transitioning to different land-uses (Woodman et al., 2023). Downscaled national land-use projections reveal regional patterns in potential changes in land-use (West et al., 2014). Thus, in the case of the UK, having a visualisation of where changes in land-use could occur can be beneficial for further refinement of policy options, particularly at the national and sub-national or regional level. This is particularly relevant when the development of pathways includes significant stakeholder engagement and is aligned with national and sub-national policy aspirations.

Despite the high percentage of values consistently reported across the 100 samples (Table 5.2, Section 5.3.2) demonstrating the downscaling algorithm’s tendency to repeatedly assign the same values, the ultimate realism of the spatial outputs relies on the accuracy of the FABLE modelling and the downscaling algorithm to represent the processes and dynamics of the food and land-use system in the UK. Therefore, the reliability of the modelling outputs hinges on the interplay between the FABLE Calculator, the downscaling algorithm, and the assumptions underlying the chosen pathways. Nevertheless, the outputs presented here do provide evidence of the policy pathways feasibility.

5.4.2. Implications of spatialisation of land-use changes for policy

Systematic use of evidence in the policy development process is widely expected to produce more accurate policy (Head, 2015). However, the projected outputs from scenarios of future land-use change may differ substantially from what is desired by actors in the land-use system (Verkerk et al., 2018). Downscaled land-use outputs could be integral to the evidence base for identifying mismatches between proposed policy measures and what society wants (Verkerk et al., 2018). Policy-makers select specific policy options to encourage or prevent certain actions or decisions by targeted actors in a system, often with a lack of knowledge on the consequences (Hauck et al., 2019).

Previous research on the UK FABLE pathways notes the need for integration with spatially explicit tools, particularly for identifying where changes in land cover could be prioritised to most benefit climate mitigation strategies and biodiversity (Smith and Harrison et al., 2022). Therefore, downscaling the outputs from the FABLE pathways offers another dimension to the FABLE analysis. Through examining the spatial patterns of land-use and land-use change, the results indicate how complex combinations of policy measures in the FABLE pathways relating to land-use change, such as afforestation, agricultural productivity, peatland restoration, biodiversity conservation and dietary change, may unfold on the ground. Whilst the FABLE Calculator can simulate whether there is enough land to achieve the changes required by policy measures to inform the viability of these measures (Jones et al., 2023b), the results presented here indicate where these land-use changes may occur, allowing for more targeted policy interventions, at both the national and sub-national level. This is vitally important as increasing focus on landscape and regional scales is crucial for operationalising sustainability measures, which manifest at local, regional, national and even global scales (Wu, 2019). Furthermore, the analysis of the differences between the 2015 and the downscaled outputs for 2050 can serve as a proxy for the uncertainty of land-use changes, showing areas where the downscaled changes are more consistent (and less uncertain) across the samples and vice versa. Being able to locate areas that are changing land-use may be beneficial for targeting future policy interventions, as they will perhaps require more support, both financial and technical assistance, for the policy measures to succeed.

Locating areas where certain land-use changes are consistently projected based on policy measures that aim to achieve climate and biodiversity goals are particularly useful for countries like the UK, who have multi-levels of governance where these policy areas are devolved. They provide an indication of the locations within each of the devolved nations where it might be valuable to target policies to incentivise land-use change. They also show if land-use change in particular devolved nations are likely to be critical in order for the UK as a whole to meet its climate and biodiversity. For example, the results show the importance of Scotland for gains in the forest land-use class and Northern Ireland for gains in the other natural land class for supporting carbon sequestration and biodiversity. However, implementing such land-use changes relies on appropriate support measures from these devolved administrations, that would benefit from coordination across the four nations. Therefore, there is perhaps a need for the UK countries to develop and coordinate national land-use frameworks to ensure policy commitments across the nations that involve land are compatible, as recommended by The Royal Society's Multi-functional landscapes report (Royal Society, 2023).

The outputs from this paper are not intended to designate areas that must change, but rather intended for use as an exploratory tool for building understanding of how differing policy interventions captured by the pathways may result in differing spatial patterns of land-use and land-use change across the UK, forming an integral part of the evidence base for policy development. They could also be used more dynamically, as a deliberative tool, to encourage discussions amongst various stakeholders, not just policy actors, on the potential consequences of differing perspectives on desirable land-use changes.

5.4.3. Implication of land-use change for biodiversity and GHG emissions

Downscaling is often essential to better asses the impacts of land-use change on biodiversity and natural areas, which not only depend on the quality of land-use, but also the spatial configuration of landscapes (Dendoncker et al., 2006). The UK is one of the most nature-depleted places, with the abundance and distribution of species declining since the 1970s (Hayhow et al., 2019). Land-use change has contributed the largest relative negative impact on natural systems since the 1970s (IPBES, 2019), with agricultural expansion being the most widespread form of land-use change (IPBES, 2019). Globally, conversion to pasture and croplands has resulted in approximately 20-30% losses in local species richness (Newbold et al., 2015). Likewise for the UK, conversion to agricultural land has been the most important driver for biodiversity decline over the last 45 years, as well as increased use of fertiliser and pesticides (Hayhow et al., 2019).

The ability of scientists and conservation practitioners to assess land-use change impacts on biodiversity relies on spatially consistent information on anthropogenic activity of an area of interest (Hoskins et al., 2016). The FABLE Calculator indicates land that can support biodiversity, which is composed of species rich semi-natural grassland, other natural land (mainly peat bog, heath and wetlands), and a user-defined proportion of forested area for biodiversity, such as broadleaf natural woodland (Jones et al., 2023b). The effects of land-use on biodiversity manifest primarily at local or regional scales, which are often not captured by global-level land-use mapping (Hoskins et al., 2016). Hence, by locating areas where these land-use categories are projected to change, or where there is no change, can provide an indication as to where policy efforts for conservation or restoration of natural land may need to be targeted, to aid in meeting biodiversity targets.

A key policy problem for many governments is how to design and implement policy that incentivises agricultural management that stimulates both productivity growth and environmental sustainability (Deboe, 2020). Three-quarters of land in the UK is affected directly by agricultural policy (Hayhow et al., 2019), thus, agricultural policy has a great influence on future land-use change and management in the UK. Since the exit from the EU, the UK Government and devolved nations have re-designed environmental policy. Evidence presented by DeBoe (2020) suggests that policies that incentivise the expansion of agricultural areas, or the conversion to more intensive agriculture, can cause severe environmental harm, through destruction of habitats, increasing erosion, decreasing carbon sinks and increasing emissions from increased input use. Given the increased emphasis on land-based mitigation strategies to reduce net-GHG emissions, it is important to consider the implications of changes in agricultural land-use and management. Whilst the spatial outputs do not spatialise emissions per se, they can provide an indication of where potential carbon sinks are increased or reduced, through the projected changes in land-use. For example, in Figure 5.2 areas of forest, other natural land and extensive grassland across the pathways provide an indication of where carbon sinks might be located in 2050. When examining the land-use changes, specific areas which could become carbon sinks can be identified, thus providing an indication of where interventions could be prioritized to ensure the carbon sinks reach their maximum potential. For example, certain losses of intensive grassland coupled with increases in other natural land in eastern Scotland (Figure 5.4) indicate the changes in land-use that would be beneficial for carbon sequestration.

5.4.4. Limitations and future research

This paper downscaled land-use change projections from the FABLE Calculator to produce spatial outputs. This spatialisation adds value to outputs from the FABLE Calculator, but there are limitations in the methodology.

Firstly, limitations of the FABLE Calculator itself are outlined in previous research, including lack of representation of other habitats such as wetlands (Zerriffi et al., 2022); lack of dual use land-use categories such as agroforestry (Gonzalez-Abraham et al., 2022); and a simplified approach to GHG emission calculations (Smith and Harrison et al., 2022). The FABLE consortium is consistently making improvements, with current plans to improve the representation of agroforestry, as well as the representation of forestry.

Secondly, to downscale the FABLE outputs, the prior module relies on explanatory variables to calculate the probability of land-use changes, as well as spatial data on land-use and historic land-use changes. Obtaining 1 km^2 spatial resolution data for the UK was challenging, particularly finding equivalents to ensure coverage of Northern Ireland and to integrate transitions. Available land-use change products (such as the UKCEH Land Cover Change (LCC) maps (Rowland et al., 2020a, b) had land-use categories that were too broad to map to FABLE land-use classes, thus the LCMs for different years had to be used. Other research has developed downscaling algorithms that do not rely on extensive covariate data and require minimum inputs. For example, LandScaleR (Woodman et al., 2024) uses a kernel density estimation approach to incorporate information from neighbouring pixels into the land allocation routine. More generally, geostatistical techniques, such as Kriging and Gaussian random fields, could overcome these issues, which would be particularly useful for reproducibility within the FABLE network, where spatial data might not be available for all countries.

Finally, whilst our results indicate that an approach such as the CCC pathways could have sizeable implications for the UK countryside, negative environmental impacts can result from land-use change include GHG emissions, deteriorating soil quality, use of scarce water resources, and biodiversity loss (Smith et al., 2013). Whilst some of this is captured in the FABLE Calculator (GHG emissions and land loss for biodiversity), the spatial outputs do not consider the impacts on the areas of the land-use changes being simulated and are focused on feasibility rather than further impacts. Equally, large-scale restoration of other natural land is likely to benefit ecosystem service provision, including water purification, recreation and flood mitigation (Lamb et al. 2016), which also are not evident from the mapping here. Including spatial data on emissions, air quality or soil pollution could increase our understanding of the impacts of the land-use changes simulated.

5.5. Conclusions

This paper integrated non-spatial land-use projections from the FABLE Calculator with a downscaling algorithm, demonstrating the effective spatialization of FABLE pathways at a finer resolution. The outputs contribute to the realism and applicability of the FABLE pathways and framework, as they are more realistically constrained due to the spatially explicit factors encapsulated in the MNL and downscaling algorithm. Incorporating these constraints are vital for their validation, and for the targeting of policy in the national and sub-national context, as well as for global integration. Whilst the FABLE Consortium are continuously making improvements, future research using the downscaling approach presented here should explore the incorporation of additional explanatory variables and advanced spatial analysis techniques to further refine the land-use projections. Through further integration of socioeconomic, environmental and land management data, the complex drivers of land-use change and their spatial dynamics should be captured, thus, enhancing the accuracy of projections and its application to the real world. Given that policies for climate mitigation and biodiversity often have a spatial dimension, the ability to map land-use changes at fine resolutions and reflect the uncertainty in the results enhances their relevance for policy support, allowing policymakers to better understand and address specific challenges and opportunities within their jurisdictions.

5.6. Acknowledgements

The authors acknowledge the support of the *downscalr* developers at IIASA for their support in using the package, as well as the FABLE Secretariat in developing and maintaining the UK and devolved versions of the FABLE calculator and providing technical assistance in the modelling process.

6. Discussion

6.1. Introduction

Given the urgent need for immediate and decisive policy action to transform land-use in the UK and devolved nations, this thesis aimed to examine alternative pathways for land-use and food systems for achieving international, national and sub-national climate and biodiversity agreements. Pathways for land-use and food systems were developed and their feasibility assessed, the trade-offs and synergies between achieving multiple policy goals were analysed, and the implications of the different pathways were evaluated. The pathways presented in this thesis encompass a wide range of policy measures and policy targets across the land-use and food system that reflect changes in demand (population changes, dietary change and food waste), land-use management (afforestation, stocking densities, biodiversity conservation and peatland restoration), and innovation (crop and livestock productivity). Through modelling these pathways using the FABLE Calculator, which aims to solve the major transformations required to achieve policy targets from the present-day land-use configurations (FABLE, 2020), the different policy combinations could be tested. The modelling, and consequent spatialisation, reinforces the intricate relationship between land-use, climate change mitigation, biodiversity and food production, as well as the complexities in developing integrated strategies for the effective transformation of land for achieving policy targets.

This discussion chapter presents and further elaborates on the key findings from the analytical chapters, with reference to the four objectives of the thesis:

- To develop **alternative pathways** for sustainably transforming land-use and food production in the UK for climate and biodiversity.
- To assess the **feasibility** of these pathways at the UK and devolved levels through spatialising pathway outputs.
- To analyse the **challenges, opportunities, trade-offs, and synergies** within the pathways for achieving climate change mitigation, biodiversity and food production policy goals within the land-use sector.
- To evaluate the **policy implications** of the pathways across national and sub-national scales and their influence on meeting the UK's international environmental commitments.

The discussion concludes with a reflection on some of the limitations of the modelling approach adopted in the thesis, and considerations of future research.

6.2. Pathways for achieving net-zero and reversing biodiversity decline

The two focal global challenges considered throughout this thesis were reducing GHG emissions to achieve net-zero and reversing biodiversity decline. Pathways are increasingly used in climate science to explore different alternative futures and provide decision-makers with accessible narratives of potential consequences of policy actions (Hauck et al., 2019). The pathways developed in this thesis allowed for different combinations of policy aspirations to be modelled and the consequent land-use change and GHG emissions further examined, demonstrating different options for achieving the UK's climate and biodiversity goals.

Previous research indicated that current environmental and climate policy in the UK is insufficient to achieve its climate targets (Rye et al., 2017). The results from Chapters 3 and 4 support this statement, demonstrating that a continuation in current policy will not be sufficient for achieving climate and biodiversity targets. This is evident across all the devolved nations. Under current policy trajectories, GHG emissions from crop and livestock production remain high, and sequestration of carbon due to afforestation and conversion of agriculture to natural land remains low, which also reduces the land available for biodiversity conservation. Therefore, the results indicate that policy changes are required to raise the ambition and overcome these challenges.

Developing pathways of alternative policy configurations with higher ambitions indicates how the UK and devolved nations can transform land-use to contribute to climate and biodiversity targets more effectively. For example, the development of the CCC pathways in Chapters 3 and 4 provided an alternative suite of policy measures with a stronger ambition to sequester carbon and release land from production for afforestation and biodiversity conservation. The modelling of the pathways with the FABLE Calculator indicate that for all the devolved nations this pathway sequesters the most carbon up to 2050, as well as simulating the greatest emissions reductions from the AFOLU sector. These changes are driven by increases in agricultural productivity, coupled with changes in diet leading to a reduction in meat and dairy consumption, which reduces the land required to support the diets of future populations. Land to support biodiversity conservation is created as 'other natural land', comprised as mainly heath, peat bog and wetland areas, and a defined proportion of forestry. Agricultural productivity and carbon sequestration occur on separate areas, which could have significant impacts on the way UK land looks and is managed (Green et al., 2005).

In contrast, engagement with policy officials in Chapter 3 revealed the need to explore a different configuration that better aligned with the policy aspirations, legislation and context of the devolved governments. The DA pathways represented an alternative suite of policy measures, which used land management techniques to deliver sequestration, biodiversity conservation and production on the same land. While the simulated carbon sequestration benefits across the devolved nations were similar to the CCC pathways for each devolved nation, these pathways created more land to support biodiversity. Extensive grassland, comprising of low intensity livestock farming, was included in this land under the assumption it is managed for biodiversity. This led to mixed landscapes where nature conservation and restoration and production occur concurrently.

The pathways also provide a “reality check” to policymakers about what could potentially be required to achieve their aspirations. For example, in Chapter 3, the Welsh Government wanted to create an additional 500,000 ha of land for biodiversity. However, woodland planting was set to be in line with Welsh Government policy where 22% is assumed to be semi-natural woodland for supporting biodiversity and the rest assumed to be plantations. Under these assumptions, the 500,000-ha target was not met. Therefore, an additional test was conducted to determine how this target could be achieved. This revealed that the target could be attained by specifying that 86% of new woodland planting should support biodiversity, which would have significant consequences for new forestry planting and management. This highlights the benefits of modelling pathways to determine whether the intended policy changes effectively contributed to biodiversity targets.

In summary, the results from the FABLE Calculator indicate that achieving net-zero and supporting biodiversity conservation in the devolved nations required changes from current policy. The alternative pathways developed in Chapters 3 and 4 can lead to beneficial land-use changes that reduce GHG emissions and biodiversity conservation. These findings emphasise the potential of developing pathways for sustainably transforming land-use and food production for achieving climate and biodiversity targets in the UK. However, there are further considerations as to whether these pathways are feasible in reality.

6.3. Feasibility of alternative land-use configurations in the UK

The outputs from the FABLE Calculator summarised in the previous section are non-spatial, presenting land-use change at an aggregate level. Therefore, to explore the spatial feasibility and implications of the alternative policy pathways, the FABLE outputs were downscaled and spatialised in Chapter 5. The maps created in Chapter 5 contribute to the realism of the pathways, as they are more realistically constrained due to the spatially-explicit factors encapsulated in the downscaling algorithm, indicating the plausibility of the pathways. The downscaled outputs provided an indication as to the level of landscape change required to satisfy the policy changes in the pathways, with the analysis providing an indication of where in the UK land-use types are gained or lost. This builds on previous critique of the lack of spatially-explicit outputs of previous FABLE modelling (Smith and Harrison et al., 2022, Mosnier et al., 2023b, Gonzalez-Abraham et al., 2022). The outputs from Chapter 5 can, thus, aid policymakers in identifying areas that are potentially more important for realising climate and biodiversity targets, providing valuable knowledge for spatial targeting of policy. For example, there are consistent changes to other natural land areas across Scotland and Northern Ireland in all the pathways, indicating that these areas are potentially important for natural land protection, restoration and biodiversity conservation.

Understanding how to allocate land for delivering multiple objectives is a major challenge in the land-use sector. The different configurations of land-use presented in Chapters 3 and 4 result from different combinations of policy measures to achieve net-zero and protect biodiversity, that are informed by the policy aspirations of the UK and devolved governments. These policy combinations target a land-sparing (CCC Pathway) and a more land-sharing (DA pathways) narrative. Green et al. (2005) described a land-sparing configuration as one where increased yields on agricultural land reduce the need to convert natural habitats, resulting in landscapes with high-yielding farmland and natural habitats concurrently. Productive areas are intensified to increase yields, and thus this pathway carries a higher risk of environmental harm associated with intensification and fertiliser use. A land-sparing approach would also have far reaching implications for the UK countryside, and would affect landowners, rural communities, ecosystem services and biodiversity (Lamb et al., 2016). These changes are reflected in the outputs of Chapter 5, where the spatialised outputs for the CCC pathway show significant changes in land-use, with a high-confidence of decreases in agricultural land, particularly extensive grassland approximately half of which is in Scotland (53%), and concomitant increases in other natural land. This indicates areas where farmers may need support if they are leaving agriculture.

A contrasting approach, a more “wildlife friendly farming”, reduces negative effects of agricultural inputs, maintaining more extensive farming integrated with patches of natural habitats in the landscape (Green et al., 2005), later renamed land-sharing (Phalan et al., 2011). It involves farming an entire region at the lowest yield necessary to deliver the food production target (Finch et al., 2020), producing landscapes where biodiversity conservation is integrated with production activities. Land-sharing practices often prioritise more longer-term sustainability, in contrast to conventional intensification such as in the land-sparing approach that seeks short-term solutions to achieve higher yields (Grass et al., 2018). The land-sharing pathway in Chapter 3 was developed to better align to the Welsh Governments aspirations and policy legislation for the environment, in particular new legislation on agricultural pollution. It maintained biodiversity conservation as a priority, which is reflected in the pathway development and assumptions, such as increased protected areas, managing grassland for biodiversity and reducing pollution through decreased fertiliser usage. The spatialised outputs in Chapter 5 for the DA pathways, that align with the land-sharing approach, result in fewer changes in land-use, with a lower confidence in the areas that gain extensive grassland and other natural land, and lose intensive grassland. This uncertainty perhaps indicates more subtle changes within this pathway, where land-use types are more integrated.

The benefits of both approaches are, however, not guaranteed. The different economic and implementation considerations might also limit the extent to which the technical potential of the two configurations could be realised in practice (Lamb et al., 2016). Additionally, there can be overlaps in how land-sparing and land-sharing approaches are conceptualised. A clear distinction between the realised strategies is complicated as neither are tied to particular spatial scales and both can be represented by production with preserved natural habitats (Sidemo-Holm et al., 2021). Grass et al. (2018) argue that land-sparing and land-sharing approaches are not mutually exclusive, and both are needed to balance management needs for the multifunctionality of agricultural landscapes. More multifunctional landscapes refer to diversified and complex land-use designed to provide a variety of environmental, social and economic benefits, potentially incorporating many, often competing, interests from different stakeholder groups (Hölting et al., 2020). They can capture elements of both land-sharing and land-sparing systems, as well as other approaches such as agroforestry. In the UK, the Royal Society advocates for more multifunctional approaches to landscapes. This approach should consider simultaneously the market (food, timber and energy crops) and non-market (habitats, carbon sequestration, flood alleviation) products and services produced by the land (Royal Society, 2023). They also argue that there must be a recognition of the multitude of land-use combinations and management strategies that cover a range of different spatial and temporal scales (Royal Society, 2023).

The land-sparing and land-sharing pathways that were developed and modelled can be viewed as extremes, to capture the extent of what might be possible using a common pathway framework and modelling approach across each of the devolved nations. Whilst the results in Chapters 3 and 4 indicate that both approaches provide significant benefits for climate and biodiversity compared to continuing current trends, in reality a combination of both approaches might be required to fit local contexts and wider considerations. The spatialisation in Chapter 5 of this thesis provides an indication of where different land-uses could be best utilised to achieve climate and biodiversity goals. For example, under both approaches, the highest confidence in land-use changing to new forest areas were in Scotland, thus, indicating the potential for concerted carbon sequestration efforts in these areas. However, it is through working closely with local landowners, managers and other stakeholders that improvements in land management decisions can better consider where changes should be made in practice.

One of the key messages for stakeholders from the results of this thesis is to recognise that there are limits to what the land can achieve in the quest for net-zero and reversing biodiversity decline, and the reliance on the land for net-zero targets is unsustainable in the long-term. Land is considered vitally important for generating negative emissions through CO_2 removals (Roe et al., 2019), and the climate change mitigation achievements of the pathways presented in this thesis rely on transformation of the land-use sector to sequester carbon whilst maintaining food production and habitats. However, land is a finite resource, and with projected increases in population and consumption, pressures on land-use will inevitably intensify as competition for land increases. Also, not all land is suitable for all land-uses. For example, the suitability of land for food production can vary due to climatic, soil or topographical constraints (Smith et al., 2013), while afforestation may be deliberately constrained on certain soil types, such as deep peatlands, to avoid negative consequences for GHG emissions (Matthews et al., 2020). These factors and constraints also vary spatially across the devolved nations and the UK. Thus, the incorporation of spatial explanatory variables of soil characteristics, climate variables such as temperature and rainfall, elevation, population density and historic land-use change in Chapter 5 helps capture some of this suitability in the projected land-use changes. The analysis in Chapter 5 indicated that both the CCC and DA pathways are feasible given these spatial constraints, thus, there is theoretically enough suitable land to achieve the projected land-use changes simulated by the FABLE Calculator.

Land management is also central to preventing and reversing biodiversity decline, through restoration of natural land and protecting habitats. However, changes in land-use are also major drivers of biodiversity loss, such as agricultural expansion and urbanisation (Burns et al., 2016). Therefore, the dual demands of carbon sequestration and reversing biodiversity decline increase pressure on this finite resource. The pathways developed focus on carbon sequestration and the land becoming a carbon sink, due to the land-use sector being the only sector where actions for climate change mitigation go beyond emissions reduction and sequester additional carbon. There is an argument, therefore, that more action towards reducing GHG emissions and halting biodiversity decline should come from other sectors, such as energy, industrial systems or aviation (Carr-Whitworth er al., 2023), as well as pairing with demand side measures to alleviate some of the pressures on land (de Connick et al., 2018).

6.4. Climate or biodiversity targets: can we have it all?

The complex interactions between land-use, climate change, biodiversity and food production outlined in Chapter 2 of this thesis present challenges for developing pathways to meet international and national agreements and achieve sustainability outcomes. Meeting the needs of rising populations, reducing GHG emissions, conserving natural areas and halting biodiversity loss will further exacerbate the conflicting demands on land (Lambin and Meyfroidt, 2011). The pathways presented in Chapters 3 and 4 encompass various different priorities, targets and actions leading to multiple, sometimes conflicting, demands on land-use. Sustainable land-use management must account for the potential trade-offs between biodiversity conservation, productive land-uses and the provision of ecosystem services (Fastre et al., 2020). Implementing a particular policy, mitigation or adaptation measure may affect the feasibility and effectiveness of other options (de Conick et al., 2018). Therefore, the identification of trade-offs is vital for developing policy measures that have conflicting demands on land, to ensure a fair transition to net-zero, where negative consequences are understood and kept to a minimum.

Balancing the benefits for biodiversity, GHG emissions reduction and maintaining food production remains a challenge, as it is difficult to achieve benefits for climate and biodiversity without compromising food production (Bullock et al. 2024). Trade-offs between agricultural production and the environment vary in relation to the different modes of intensification, across spatial scales, and against the realities of local environmental contexts (Thomson et al., 2019). An example from the pathways presented in this thesis are the utilisation of grassland areas to achieve the climate and biodiversity targets. Grasslands are of global importance for achieving this balance, as not only are they a source of livestock feed and food, but also act as a carbon sink, ecological buffer, and a source or haven of biodiversity (Qi et al., 2018). In Chapters 3 and 4, the CCC pathways achieve better results for net-zero by relying on increasing productivity in intensive grasslands to meet food production demands with less area, thereby, releasing land for carbon sequestration. Intensive agriculture, however, continues to be a major cause of environmental harm (Bullock et al., 2024). Thus, the net-zero successes could cause further negative impacts, including further GHG emissions from increased fertiliser use, pollution from application of toxic pesticides and fertilisers, and soil degradation and erosion (Newton et al., 2021), all of which could cause biodiversity loss. How we manage agriculture to meet rising demand, therefore, is pivotal to the future of biodiversity (Balmford et al., 2018). In contrast, extensively managed grasslands are globally recognised for their high biodiversity and additional non-agricultural services such as water supply and flow regulation, pollination and cultural values (Bengtsson et al 2019). The DA pathways in Chapters 3 and 4 focus on the expansion of extensive grassland areas to provide more land to support biodiversity conservation while also contributing to climate targets. However, extensively managed grasslands are often considered to have lower productivity (Bengtsson et al., 2019), thus, there are potential trade-offs between biodiversity and meeting food demand. Therefore, the results of this thesis perhaps indicate that policymakers have a decision to make when developing future land-use, environmental and agricultural policy between prioritising climate targets through intensifying production and releasing land for habitat restoration and carbon sequestration, or prioritising biodiversity through reducing intensity of production and managing land to benefit biodiversity.

Research by Streck (2023) notes that the Kunming-Montreal Global Biodiversity Framework (GBF) and Paris Agreement are highly complementary agreements, where each depends on the other's success to be effective. Actions to reduce GHG emissions and sequester carbon, can also benefit biodiversity. Facilitating nature-based solutions at the national scale in the UK, like those represented in the pathways, could offer many benefits for people and biodiversity, as well as contributing to net-zero targets (Bradfer-Lawrence et al., 2021). For example, restoring forests and planting new woodland can increase carbon sequestration and natural flood management, as well as increasing and protecting biodiversity should new woodlands be planned and managed to promote biodiversity (Seddon et al., 2020). In addition, changes in diet not only free up land for carbon sequestration and restoration of natural land, they also deliver health benefits through reducing overconsumption and increasing uptake of healthy foods (Smith and Harrison et al., 2022). The sensitivity analysis in Chapter 3 showed how dietary changes to lower meat and dairy consumption in the Current Trends pathway can enable decreases in pasture area and concomitant increases in other natural land. This indicates that changes in diet are an important driver of changes in land-use change that has benefits for both nature and people.

6.5. Policy implications of pathways for achieving international and national climate and biodiversity agreements

As highlighted in Chapter 2 of this thesis, the UK is at an important juncture with its climate and environmental policy, necessitating a strategic rethink of the way decisions related to land-use are made or incentivised. For over 40 years, the relationship between the UK Government and the farming sector has been dominated by the EU's Common Agricultural Policy (CAP), which has determined the public subsidies paid to farmers (Bateman and Blamford, 2019). Leaving the EU means governments are formulating replacements for CAP, as well as other environmental and regulatory policies and legislation. There is now an opportunity for the UK nations to design new rural support measures, providing an urgent need for integrated evidence. The analytical Chapters 3-5 examined alternative pathways for UK land-use and food systems to achieve national and international agreements. Chapters 3 and 4 developed pathways with a combination of policy measures, such as afforestation, livestock and crop productivity and peatland restoration, to reduce GHG emissions, enhance carbon sinks and support biodiversity conservation. The modelling using the FABLE Calculator simulated the land-use changes that result from these combinations of policy measures. The chapters also consider policy implications across national and sub-national scales, in particular the important context of regional autonomy and multi-level governance in the UK, and spatially-explicit effects that can inform policy targeting.

To achieve net-zero climate and biodiversity targets and international agreements and make effective strategic decisions, it is necessary for policymakers to have access to relevant and reliable evidence regarding any potential solutions or actions for their specific contexts and political landscapes (Stafford et al., 2021). For policy and decision-makers, the outputs of Chapter 3 have proven to be useful, both in terms of the participatory co-development process, and in assessing alternative potential polices.

Firstly, the sensitivity analysis in Chapter 3 led to compelling evidence for developing policy for seeking dietary shift in the Welsh population for both health and planetary outcomes, with the inclusion of specific text to this effect, i.e., "*Over the next 20 years the ambition is to shift the population's diet closer to the Eatwell Guide*", in the Welsh Government Low Carbon Delivery plan (Welsh Government, 2021c, p 22). In addition, a new cross-departmental working group in this area was set up within the Welsh Government to consider how policy related to dietary change should consider how it can contribute to net-zero and biodiversity targets, as well as how it can provide co-benefits for health and nutrition. To support this, research in the behavioural, economic and social sciences is needed to develop more equitable and effective policy levers for diet, health and food waste reduction (Smith et al., 2024). Secondly, co-creating pathways with the Welsh Government ensured that they better reflected their policy aspirations at the devolved nations level. Stakeholder engagement is a central part of the FABLE Consortium's approach, to ensure that pathways are of interest to relevant stakeholders, represent local priorities, contexts and cultures, and are therefore more likely to be implemented (Jones et al., 2023a, Mosnier et al., 2023). The participatory approach described in Chapter 3 greatly benefitted the Welsh Government stakeholders, as it encouraged them to work across different policy departments that previously had tended to work in silos. This facilitated discussion of the multiple policy needs and objectives that should be included in the pathways and the adaptations that were needed in the FABLE calculator to represent the national context of Wales, thereby, increasing buy-in across the government. The participatory approach also increased the impact of the research through igniting discussions on a longer-term horizon for policy, the future of the agricultural sector in Wales, and establishing a new policy group directly related to the results from the chapter. These direct impacts also indicate the role pathways can play in the science-policy interface.

The UK Government and devolved administrations have a number of legislative and policy commitments that create a complex nexus of issues involving land-use (Royal Society, 2023). According to Reay (2020), governance of a net-zero transition must take full account of national and sub-national legislation and powers, with a risk of misaligned competencies perhaps hindering sub-national progress, and aggregated targets then being missed. In the UK, the asymmetric devolution agreements, and the powers responsible for agriculture and environment being largely devolved, create a complex tiered governance structure working on environmental issues. Sub-national governments are important actors for climate and biodiversity policy, as evaluated in Chapter 4 of this thesis. The DA pathways represent regional autonomy for the devolved nations, through pathways that capture their own aspirations, with the analysis indicating their contributions to UK commitments. The analysis showed that when aggregated to the UK level, implementation of the CCC pathways in all four UK nations created the greatest carbon sink and a combination of DA and CCC pathways across the four nations yielded optimal results for cumulative GHG emissions, from both GHG emissions from agriculture and carbon sequestration across the time period. However, this combination of pathways created less land for biodiversity, while implementing the DA pathways in all four nations simulated more land for biodiversity conservation. Given the perceived differences in aspirations across the devolved nations and the differing outcomes of the pathways from the research in Chapter 4, communication and coherence between the four UK nations across the different areas of land-use policy is critical to ensuring different policy commitments are compatible and working towards a common goal. In addition, policymakers should consider the impacts of large-scale initiatives for carbon sequestration on biodiversity and food production. For example, large-scale afforestation incorporated in the pathways should focus on restoring a wider range of habitats, and using native species where possible, adopting more sustainable management that aligns sequestration with nature recovery (Smith et al., 2024).

How the UK and devolved governments implement land-use and related policy in practice requires evidence on the spatial implications of policy changes. Integrated models are being used increasingly by policymakers for testing policy, due to their ability for facilitating joined-up, rather than siloed, policymaking. Chapter 5 of this thesis integrated land-use change projections from the FABLE Calculator with a downscaling model to generate land-use change maps. The spatially-explicit outputs are imperative for the identification of location-specific implications of policy alternatives, highlighting the added value of spatial outputs for providing more meaningful testing and refinement of policy strategies. The findings indicate that the policy changes within the pathways are theoretically feasible given spatial constraints. The analysis of the differences between 2015 and 2050 can act as a proxy for uncertainty of land-use changes, indicating areas where the downscaled changes are more consistent across the samples. Being able to locate these areas with consistently changing land-use is beneficial for targeting future policy interventions, through more targeted financial and technical assistance and support. Additionally, for the UK, the analysis in Chapter 5 also provides an indication of the locations within the devolved nations where land-use might be critical for the UK to meet its climate and biodiversity agreements. The findings highlight the importance of adapting land-use policy to local contexts, whilst ensuring the UK collectively meets international agreements. Specifically, new agricultural support schemes, that are potentially major shifts in policy, have the potential to cause unintended consequences from the desired outcomes, which may be universal or more specific to a certain location, farm type or habitat (Harrison et al., 2023). Therefore, the development of new schemes requires spatially-explicit evidence for targeting agricultural support schemes, to increase the effectiveness and efficiencies of policy measures for more cost-effective optimal outcomes for climate and biodiversity (Guo et al., 2020). However, the schemes can be perceived as unjust if payments are only available for certain regions or farm times.

Combining qualitative and quantitative data, like in the pathway development process and consequent modelling in this thesis, is considered crucial to understanding the complex dynamics of nature conservation and land-use patterns, offering a more holistic view of complex problems (Kinnebrew et al., 2020). A more interdisciplinary research approach can facilitate more effective political and social interventions (Kinnebrew et al., 2020) that work across policy departments to consider and capture wider policy implications across land-use decisions. Currently there is no single process across the UK and devolved nations to aid in the prioritisation of the different pressures on land and the decisions that underpin, or undermine, them across the different governance scales. Land-use frameworks are becoming increasingly explored as a mechanism for addressing multiple challenges and demands on land-use, to deliver integrated, collaborative and place-based decision-making and optimising multifunctional benefits from land (FFCC, 2022). For example, Scotland is the only UK nation to currently have a Land-use Strategy (Scottish Government, 2021), while England has a forthcoming Land-use Framework, deemed essential for making the most of England's land (House of Lords, 2022). In contrast, neither Wales nor Northern Ireland have used land-use frameworks. Therefore, the UK nations should develop and coordinate spatially-explicit land-use frameworks to ensure coherence across different areas of land-use policy, whilst supporting greater integration between national, regional and local scales and levels of governance (Royal Society, 2023). Land-use frameworks are also considered vital in understanding and incorporating sectors under different statutory frameworks that are influential on land (House of Lords, 2022). For example, housing and infrastructure for future populations creates an additional demand on land-use, that is under its own planning system that regulates development, across governance levels (House of lords, 2022). The current planning system has its own priorities; thus, frameworks should be spatially structured to facilitate decision-making to reconcile rural and urban planning decisions, and encourage strategies that avoid loss of high value farmland (Smith et al., 2024). In addition, strong collaborative policy support across sectors is also required to support UK farmers and producers in adapting to change and transition to more sustainable food production, whilst protecting employment, incomes and local culture. Insights from multiple disciplines are, therefore, vital in developing pathways through incorporating different perspectives, aspirations and implications.

6.6. Limitations and future research

Throughout this thesis, each chapter has outlined specific limitations. Some broader limitations of the thesis are considered here.

Firstly, the development of the pathways in Chapter 3 and 4 focused on the perspectives of policy, through engaging with the relevant policy officials and reviewing policy documents. Thus, the wider societal perspectives were not captured. The participation of different stakeholders helps enhance the credibility and legitimacy of scenarios (Volkery et al., 2008). Therefore, the integrity of the pathways could be improved by incorporating perspectives other than those of policymakers, such as stakeholders from the farming business sector, other land-owners/managers, non-governmental organisations and citizens. More specifically, for the pathways presented here, there is a distinct absence in their design of input from farmers and land managers who would largely be responsible for implementing the changes. Agricultural policy in the UK has been criticised for its one-size-fits-all approach, failing to duly recognize the specific needs of smaller or hill farms (Petetin, 2022). The absence of those stakeholders in the pathway development process, therefore, means they do not capture the variation and aspirations of all farmers and land-managers in the UK. This lack of representation could reduce the efficacy of the pathways in achieving their objectives as these wider needs, aspirations or capacity to implement have not been considered or prioritised. Similarly, the modelling presents an “ideal world” picture, where multiple aspects need to change for the pathways to succeed.

Secondly, the thesis does not address how the changes could be incentivised. For example, the dietary change and food waste assumptions rely on consumer behaviour, which is difficult to model as it can be incentivised in different ways, including through relying on altruism from both the public and landowners, and through financial incentives or tax burdens. Effective financial support systems will be fundamental to achieving net-zero via land-use change (Reay, 2020). Therefore, the economic costs of the policy changes, including the costs of technological innovations or losses due to changes in demand, should be better captured in the modelling presented in this thesis. In addition, there is little consideration in the policy pathways of an increased use of biofuels or renewable energy sources within the land-use and food system, and how that might impact land-use change or conflicts in demand for land. While this can be modelled to some extent in the FABLE calculator, as a proportion of food product or coppice wood and miscanthus grass, bioenergy policy was not fully captured in the pathways.

The scale of the transformation of land-use outlined in this thesis in achieving climate and biodiversity targets means it is essential to expand both the capabilities of the model and integrate it with other tools. For example, the modelling presented does not capture the entire land-use and food system. While assumptions related to food waste and post-harvest losses are included in the pathways, the broader food system, particularly food processing, retail and supply chains, is ignored. Improving the capabilities of the model to include these wider aspects would enhance the results and perhaps their useability in an industry context.

Furthermore, the interactions between the devolved administrations are more intricate than what could be modelled and aggregated in Chapter 4. Whilst unique in their contribution of evaluating regional autonomy of the devolved nations and meeting UK climate and biodiversity, the trade interactions between the countries are not captured. This is particularly relevant for livestock trade, where the dietary change in one devolved nation could impact demand in another nation, more than their own populations' changes in diet. Similarly, there is no consideration of a perhaps “off-shoring” of emissions between devolved nations, and how that could be evaluated in their pathway or policy design. Additionally, integrating the FABLE calculator with advanced trade models would enable consideration of changes in future trade both between the four UK nations and globally, greatly enhancing the value of the pathways for informing policy.

Finally, there is no consideration of how external processes could impact the land-use changes in the spatial downscaling in Chapter 5, which could be improved through integrating additional algorithms to better consider climate changes such as: how sea-level rise might affect land availability or leave agricultural areas at increased risk of flooding (Edwards, 2017); how temperate changes or water availability might impact what crops can grow where and when in the future (Marklein et al., 2020); or how the occurrence of extreme weather events might impact food supply (Hasegawa et al., 2021). Incorporating additional aspects into the modelling, whilst improving the downscaling algorithm, could increase the realism and utility of the outputs in the future.

Despite the above limitations, the findings and insights presented in this thesis remain valuable, offering a significant contribution to the understanding and development of effective policies and transformations for meeting international and national agreements on climate and biodiversity.

7. Conclusion

This thesis examined the intricate and complex relationship between land-use and food production systems for achieving climate and net-zero targets, whilst protecting, restoring and conserving biodiversity through developing national scale pathways. The pathways integrated targets from international and national policy agreements with sub-national contexts, emphasising the need for comprehensive, coordinated strategies to address these challenges effectively. The development of pathways with policymakers ensured that policy aspirations included in the pathways were grounded in national context and are, therefore, of interest to relevant stakeholders and decision-makers. Using a modified version of the UK FABLE calculator, the pathways were modelled to solve the transformations of land-use necessary to achieve the climate and biodiversity targets from the historic and present-day land configurations. The aggregate-level land-use changes were spatialised, testing their feasibility, which further enhanced their useability in policy discourse.

Firstly, the results of the thesis reiterate to national stakeholders and decision-makers that current policy is insufficient and unsustainable and will be unable to achieve net-zero or conserve biodiversity across any of the devolved nations, or the UK as a whole. They further highlight that widespread, transformational change is urgently required.

Secondly, the alternative configurations of land-use, as a result of different policy combinations, indicate that while the results for net-zero can be similar between the CCC and DA pathways, greater gains for biodiversity conservation are simulated in the DA pathways across the devolved nations. This pathway assumes carbon sequestration, biodiversity conservation and food production occur simultaneously on the same land, as opposed to releasing land for separate carbon sequestration activities. These alternative configurations highlight that there are a multitude of policy options available to decision-makers, with different trade-offs and synergies, the desirability of which may depend on the goals and aspirations of the UK Government and devolved nations. These results emphasise a key policy question – how can future land-use policy best balance targets for net-zero and climate with biodiversity and nature conservation, alongside maintaining a thriving agricultural sector. Strong policy support is required for UK farmers, growers, producers and their local communities to transition to more sustainable food production and adapt to changing climate and dietary patterns, while protecting employment, incomes and local culture.

Integration of the FABLE non-spatial projections with a downscaling algorithm showed the enhanced realism and applicability of the FABLE pathways, through testing their feasibility given land constraints, as well as identifying more regional or local areas of change. This is critical in moving from theoretical, high-level objectives, to more localised and practical solutions.

Overall, this research demonstrates the need for significant changes in policy, with increased ambitions across afforestation, crop and livestock productivity, stocking densities, biodiversity conservation, peatland restoration, dietary change and food waste. It emphasises the need for integrated strategies across different levels of governance, and a nuanced understanding of spatial dynamics to effectively address international and national climate and biodiversity agreements. The findings underscore the urgent need for innovative, coordinated policy measures for supporting and incentivising transformative land-use changes. Through embracing these strategies, policy and decision-makers can pave the way towards a sustainable future that successfully balances climate and biodiversity goals.

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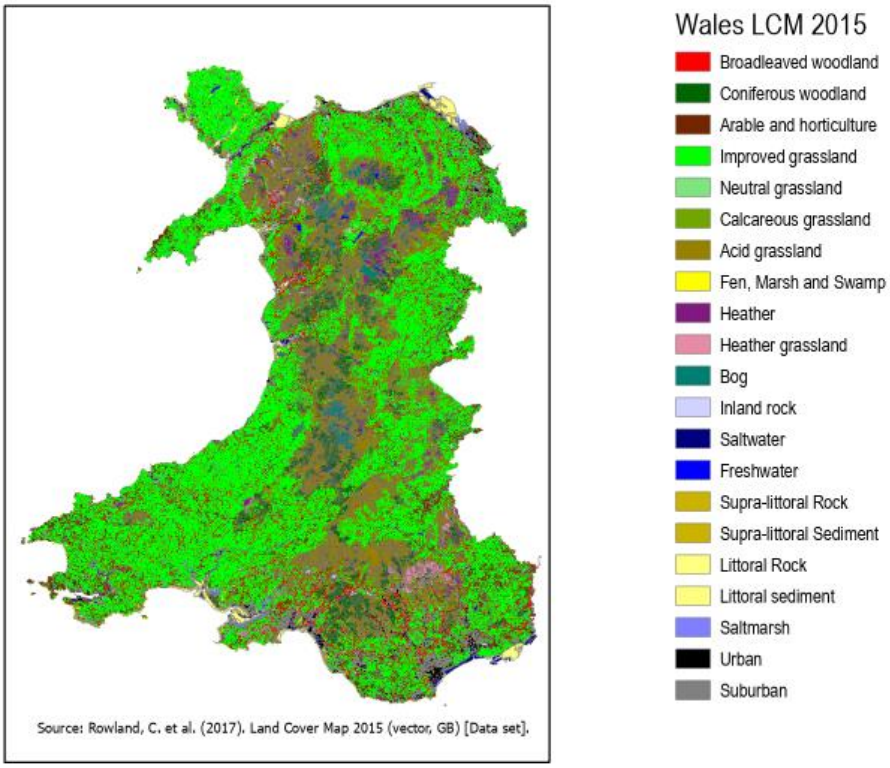
9. Appendices

A) Supplementary material for Chapter 3



Source: Rowland, C. et al. (2017). Land Cover Map 2015 (vector, GB) [Data set].

Figure A1: Land cover in Wales, UK CEH LCM categories. Source: Rowland et a., 2017a, b)

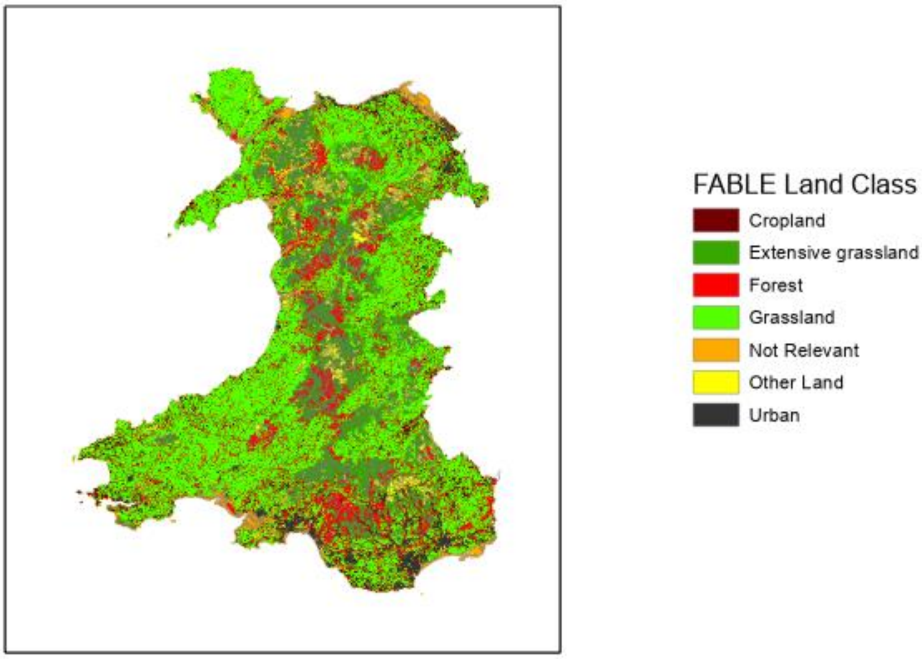


Figure A2: Wales land cover with the FABLE land use categories

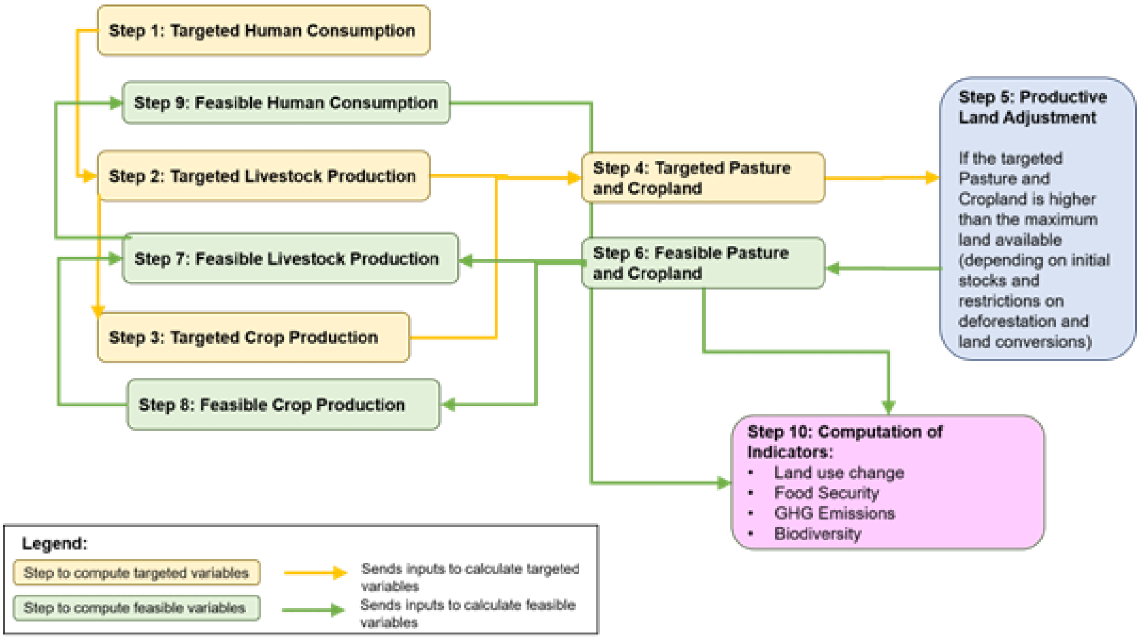


Figure A3: Calculation steps for the FABLE Calculator, adapted from Mosnier et al., 2020

The calculator can be used to determine whether future policy scenarios will achieve targets for GHG reduction and biodiversity conservation, and can be used to identify major imbalances in, and threats to, national food security and land use systems.

Narratives for the four pathways

1. *Common assumptions across the four pathways*

Population estimates, used to calculate future food demand, are taken from the Office for National Statistics (ONS) which forecasts the Welsh population to increase from 3.153 million in 2019 to 3.258 million by 2050 (ONS, 2019). The demand for land for urbanisation was based on the projections of population growth and associated increases in housing (110,000 new homes by 2039 from the Welsh Government's 20-year spatial plan and additional infrastructure from previous urbanisation scenarios (Welsh Government, 2021b). This resulted in an estimated 5% increase in urban area for Wales, from 105,773 ha in 2015 to 110,000 ha in 2050. This included the footprint needed for future solar and wind developments in Wales. At this moment there are no plans for policy to increase the amount of energy derived from biofuels, due to the physical geographical constraints of Wales.

Whilst the outcomes of leaving the EU still remain uncertain, the level of uncertainty is reduced to some extent by the existence of an EU trade deal. However, the impacts of future trade agreements remain unknown. Therefore, in the absence of further information, it was assumed that the share of total consumption that is imported and the quantity (in tonnes) of total production exported remain the same up to 2050.

For each pathway it was assumed that any woodland planting would be subject to Glastir Woodland Creation constraints and sensitivities (Welsh Government, 2019a). Furthermore, all planting would be compliant with UK Forestry Standard (Forestry Commission, 2017), which include conditions on the minimum area of open ground managed for conservation, proportion of the forestry unit species, and how much of the forest management must be managed for conservation and biodiversity. For Pathway 1 and 2, new forest was assumed to be created in line with the existing split between broadleaved (51%) and coniferous (49%) woodland. For Pathway 3 and 4, new forest is created in line with Welsh Government policy that 22% should be aimed at supporting biodiversity, assumed to be semi-natural woodland, and the rest is assumed to be plantations.

2. *Pathway 1 – Status Quo*

The first pathway corresponds to the lowest boundary of feasible action, continuing with no changes to current policies. It is characterised by no constraints on agricultural expansion except in protected areas, which do not include National Parks, Areas of Outstanding Natural Beauty (AONBs) and Heritage Coasts. There are no changes to post-harvest losses, food waste and diets. Livestock and crop productivity remain as today, peatland restoration remains in line with the current Peatland Action Plan (Natural Resource Wales, 2020) and there are small areas of woodland creation in line with recent rates.

3. *Pathway 2 – Improvement on Status Quo*

The second pathway represents slight improvements to the current system, in line with current trajectories and reflecting current trends in policy. The protected areas in which agricultural expansion is limited are expanded to include National Parks, AONBs and Heritage Coasts. Peatland restoration increases slightly from Status Quo to 800 ha year^{-1} between 2020-35 in line with the extended Peatland Action Plan. Crop productivity and livestock productivity for beef and poultry remain as today, but dairy yield follows incremental improvements in productivity, and there are slight increases in stocking density. The pathway includes existing trends in food waste reduction, but there are no changes to post-harvest losses and diets. Afforestation targets are slightly improved with tree planting of 20,000 ha by 2030 and a further 80,000 ha by 2050.

4. *Pathway 3 – Land-sparing*

The third pathway, and the first representing system change, is the Land-sparing pathway, which broadly represents the UK land use strategy proposed by the UK CCC in its *Land use: Reducing emissions and preparing for climate change* report (CCC 2018), and further referenced in *the path to Net Zero and progress on reducing emissions in Wales* (CCC, 2020). The pathway focuses on an intensification of agricultural production on the most productive land. This, together with reductions in food waste and dietary changes, allows some land to be released for biodiversity conservation and afforestation to sequester carbon. Agricultural expansion is prohibited on existing habitats within protected areas, including National Parks, AONBs and Heritage Coasts. Large increases in productivity for crops (+65%) and livestock are assumed, with increases for dairy achieved through improved breeding and optimising cow diet, and efficiency increases in beef production and lambing rates due to technology improvements. There is a shift towards 100% of the ruminant grazers on intensive grassland, and none on extensive grassland, with stocking densities doubling. Afforestation targets increase in this scenario to 180,000 ha by 2050 and all peatland (90,000 ha) is restored to a natural state by 2030. There are improved targets for food waste, leading to zero avoidable food waste by 2050, and post-harvest losses are reduced by 50% by 2050. The population is expected to move to a healthier, more plant-based diet by 2050, captured as the ‘Eatwell’ diet (the UK Government policy tool used to define government recommendations on eating healthy and achieving a balanced diet; PHE, 2020).

5. *Pathway 4 – Land-sharing*

The fourth pathway, representing a different approach to system change to the Land-sparing pathway, is the Land-sharing Pathway. This pathway is closer to Welsh Government policy ambitions and is based on the principles of the Sustainable Management of Natural Resources strategy and the Environment (Wales) Act, which aim to deliver multiple objectives on the same land (Welsh Government, 2018). It is characterised by no agricultural expansion on any existing semi-natural habitats and has an aspiration to create 500,000 ha of additional habitat on agricultural land. Extensive grazing is allowed on semi-natural grassland, and the proportion of the ruminant livestock using extensive (semi-natural) grassland is assumed to increase from 25% today to 50% by 2050. Crop productivity is assumed to increase by 39%, and livestock productivity follows the same assumptions as Pathway 2, but with additional increases in lambing (41%). Afforestation, food waste and peatland restoration targets are the same as Pathway 3, but post-harvest losses are reduced by 50% by the earlier target date of 2030. As with the Land-sparing pathway, the population is assumed to move to a healthier, more plant-based diet, captured as the 'Eatwell' diet, by 2050.

Table A.1: Detailed assumptions, parameterisations and underlying rationale for the 4 pathways for Wales.

Domain	Parameter	Pathway 1: Status Quo	Pathway 2: Improvement on Current Trends	Pathway 3: Land-sparing	Pathway 4: Land-sharing
Population	*Population projection – million inhabitants*	The Population is expected to reach 3.258 million by 2050 based on ONS predictions (ONS, 2019)	As for Status Quo	As for Status Quo	As for Status Quo
Land	*Constraints on agricultural expansion*	No constraints on agricultural expansion	Constraints on agricultural expansion within National Parks	No agricultural expansion on existing habitats	No agricultural expansion on existing habitats and 500,000ha of habitat created on agricultural land (Welsh Government, personal

					communication, 2021)
	Afforestation Targets	Total woodland creation in 2020/21 was around 280 ha. Assume 300 ha/y to 2050 (Welsh Government, personal communication, 2021).	The current Welsh Government target is to create 2,000 ha of new woodland p.a., rising to 4,000 ha as soon as possible. Planting 20,000 ha by 2030 and a further 80,000 ha by 2050. This will lead to 106,000 ha created by 2050 (Welsh Government, personal communication, 2021).	43,000 ha planted by 2030 (average of 5,000 ha/yr from 2023), rising to 180,000 hectares by 2050 (7,500 ha/yr from 2035) (Welsh Government, personal communication, 2021).	40,000 ha planted by 2030 rising to 180,000 ha by 2050 (7,500 ha/yr from 2035) (Welsh Government, personal communication, 2021)
	Urban Expansion	5% increase in urbanisation, from 105,773 ha to 110,000 ha (Welsh Government, 2021)	Same as Status Quo	Same as Status Quo	Same as Status Quo
Biodiversity	*Protected Areas (% of total land)*	Existing designated sites protected for nature are maintained. This is the FABLE default but with no target to increase to e.g. 17%.	Existing designated sites protected for nature are maintained. Agriculture expansion constrained within National Parks. This is simply equivalent	Same as for Improvement on Current Trends	To reverse decline in biodiversity, all semi-natural habitat (excluding woodland) is protected. This would increase protected areas for nature to 29.5%. A further 500,000 ha of

			to including NPs within protected areas.		habitat is created on farmland (output not input) (Welsh Government, personal communication, 2021).
Productivity	*Crop Productivity*	As for the UK, in 2050, crop productivity remains the same: • 7.7 tons per ha for wheat (7.1 with climate change impacts). • 5.7 tons per ha for barley. • 43.9 tons per ha for potatoes. Based on FAOSTAT historic yields for 2010 (FAO, 2020)	Same as for Status Quo	As for the UK, by 2050, crop productivity reaches: • 12.7 tons per ha for wheat (12.0 with climate change impacts). • 9.4 tons per ha for barley. • 72.4 tons per ha for potato. Based on assumption that yields for all crops increase by 65% (Smith and Harrison et al., 2022).	As for the UK, by 2050, crop productivity reaches: • 10.7 tons per ha for wheat (10.1 with climate change impacts). • 7.9 tons per ha for barley. • 61 tons per ha for potatoes. Based on assumption that yields for all crops increase by 39% from the 2010 value, in line with the revised CCC medium projection (Smith and Harrison et al., 2022).
	Livestock Productivity	Dairy Yield, Beef, Chicken to remain the same	Between 2015 and 2050, yields: • Dairy: Yield per cow 7784 l/cow in 2015. Current trend is 82 l/cow increase/yr. 35yr x 82 litre = 2870	Between 2015 and 2050, yields: • Dairy: 50% increase for milk. • Beef: Remain at 123.6 kg/head of population for cattle meat	Same as Improvement on Current Trends. Lamb: 41% increase (Welsh Government, personal

			litres, 7784 + 2870 = 10,654 l/cow in 2050 if current trend is maintained (37% increase). • Beef: Remain at 123.6 kg/head of population for cattle meat. • Poultry: Remain at 1.37 kg/head of population for chicken meat. • Lamb: 17% increase. (Welsh Government, personal communication, 2021).	• Poultry: Increase by 10% for chicken meat, from 1.37 to 1.51 kg/head of population. Lamb: 52% increase as sheep systems increase in efficiency. (Welsh Government, personal communication, 2021)	communication, 2021)
	Pasture Stocking Rate	No changes to stocking density	Change in livestock density compared to baseline: 132% (Welsh Government, personal communication, 2021).	Change in livestock density compared to baseline: 202% (Welsh Government, personal communication, 2021).	Change in livestock density compared to baseline: 136% (Welsh Government, personal communication, 2021).
	Post-harvest losses	No changes to post-harvest losses	No changes to post-harvest losses	As for the UK, by 2050, the share of production and imports lost during storage and transportation is 0.5%. Based on assumption of a 50% reduction in	As for UK, by 2030, the share of production and imports lost during storage and transportation is 0.5%, i.e. the target is achieved earlier than the

				losses compared to 2015, i.e. achieving the SDG 12.3 target to halve consumer and retail waste but by 2050 rather than 2030 (WRAP, 2020)	Land-sparing scenario. Based on assumption of a 50% reduction in losses compared to 2015 in line with the Courtauld 2025 Commitment (reduction of 20% across supply chain between 2015-2025) and SDG 12.3 target (halve consumer and retail waste by 2030) (WRAP, 2020).
Trade	*Share of consumption which is imported for key imported products (%)*	Exports and imports are estimated from the commodity balance after downscaling production and consumption from UK statistics and then held constant after 2010 (Welsh Government, personal communication, 2021).			
Food	*Average dietary consumption (daily kcal per commodity group)*	By 2030, the average target daily calorie consumption per capita is 2,983 kcal and is: • 168 kcal for fruit and vegetables. • 83 kcal for ruminant meat. • 119 kcal for animal fats. Based on assumption of no change in current diet as in FAOSTAT.	Same as Status quo pathway	Eat Well Diet - by 2030, the average target daily calorie consumption per capita is 2,739 kcal and is: • 196 kcal for fruit and vegetables. • 75 kcal for ruminant meat. • 98 kcal for animal fats. Based on meeting the Eatwell diet recommendations by 2050 (PHE,	Eat Well Diet - by 2030, the average target daily calorie consumption per capita is 2,739 kcal and is: • 196 kcal for fruit and vegetables. • 75 kcal for ruminant meat. • 98 kcal for animal fats. Based on meeting the Eatwell diet recommendations by 2050 (PHE,

				2020; Scarborough et al., 2016).	2020; Scarborough et al., 2016).
	Share of food consumption which is wasted (%)	No change to food waste	Existing trends in food waste reduction - 50% reduction in food waste by 2050, 2%/yr from 2015 (WRAP, 2021)	Wales aims to have zero avoidable food waste before 2050. By 2025: • 50% reduction in avoidable food waste By 2030: • 60% reduction in avoidable food waste By 2050: • Zero avoidable food waste (Note: All waste reduction targets are set against a 2006-07 baseline) (Welsh Government, personal communication, 2021).	Wales aims to have zero avoidable food waste before 2050. By 2025: • 50% reduction in avoidable food waste By 2030: • 60% reduction in avoidable food waste By 2050: • Zero avoidable food waste (Note: All waste reduction targets are set against a 2006-07 baseline) (Welsh Government, personal communication, 2021).
Biofuels	*Targets on biofuel and /or other energy use*	No Change	No Change	No Change	No Change
Climate Change	Crop model and climate change scenario	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 6 W/m^2 (RCP 6.0).	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 6 W/m^2	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 2.6 W/m^2 (RCP 2.6).	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 2.6 W/m^2 (RCP 2.6).

		Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilisation effect (Smith and Harrison et al., 2022)	(RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilisation effect. (Smith and Harrison et al., 2022)	Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilisation effect (Smith and Harrison et al., 2022).	Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO_2 fertilisation effect (Smith and Harrison et al., 2022).

Table A.A.2: Scaled and interpolated LCM values for land use for use in the FABLE Calculator. Source: LCM values for 2000, 2007 and 2015 from Fuller et al., 2002, Morton et al., 2011 and Rowland et al., 2017.

Land Use Class	**2000**	**2005**	**2007**	**2010**	**2015**
Forest	306	276	265	285	320
Cropland	103	154	175	146	98
Grassland	777	816	831	881	965
Extensive grassland	603	533	505	472	416
Other Land	150	159	152	148	124
Not Relevant	52	52	61	52	52
Urban	86	88	88	94	104
Total	**2077.9**	**2077.9**	**2077.9**	**2077.9**	**2077.9**

Note on Table A.2

Values for land cover for 2000, 2007, and 2015 were taken from LCM, and scaled to match the Welsh Government’s total area 2,077,000 ha for Wales to align with other modelling projects in the Welsh Government. These were interpolated for the years 2005 and 2010, to allow for use in the calculator.

Table A. 3: Mapping of LCM Land cover classes to FABLE land cover categories

LCM Land cover classes	**FABLE land cover classes**
Broadleaved woodland	Forest
Coniferous woodland	Forest
Arable	Cropland
Improved grassland	Grassland
Neutral grassland	Extensive grassland
Calcareous grassland	Extensive grassland
Acid grassland	Extensive grassland
Bracken	Other Land
Fen, Marsh, Swamp	Other Land
Mountain, Heath & Bog	Other Land
Inland Bare Ground	Not Relevant
Inland Water	Not Relevant
Suburban	Urban
Urban	Urban
Supra-littoral rock	Not Relevant
Supra-littoral sediment	Not Relevant
Littoral rock	Not Relevant
Littoral sediment	Not Relevant
Saltmarsh	Not Relevant
Dwarf Shrub Heath	Other Land
Bog	Other Land
Inland Water	Not Relevant
Montane	Not Relevant
Inland Rock	Not Relevant
Built-up Areas and Gardens	Urban
Fen	Other Land
Heather	Other Land
Heather grassland	Other Land
Bog	Other Land
Inland rock	Not Relevant
Saltwater	Not Relevant
Freshwater	Not Relevant

Grassland for feed requirements

The volume of grass required for grazing livestock is incorporated into the calculations within the FABLE calculator. The total feed required for grazing animals in t/TLU/year, scaled for the Wales from the UK value, is taken from the Havlik et al. 2013 GLOBIOM model. This calculation also considers the changes in livestock productivity (shifter of livestock productivity compared to 2000 – based on historical productivity changes from 2000-2010). Therefore, the total feed required from grazing (i.e. grass) in tonnes up to 2050 is calculated. This is incorporated into the crop calculations (computed feed consumption, and feasible animal feed), and then as the proportion of land use required to produce this.

GHG emissions and sequestration in the FABLE Calculator

The calculator estimates emissions from crop production, including N2O from synthetic fertilisers and crop residue, and CO2, CH4 and N2O from energy used during cultivation, using emission factors from FAOSTAT (FAO, 2020).

Livestock emissions include CH4 from enteric fermentation in ruminants, and both CH4 and N2O from manure, based on emission factors used in the GLOBIOM model (Herrero et al., 2013).

Land use change includes emissions when land is converted to a different type (e.g. natural land converted to farmland or urban) and carbon sequestered due to afforestation or regeneration of natural land. Land use change emissions in FABLE are calculated based on estimates of carbon stock. When forest or other natural land is converted to farmland or urban, the difference in carbon stock between the two land use types is assumed to be lost immediately. However, when new forest is planted or natural land regenerates from abandoned farmland, carbon sequestration is estimated as the difference in carbon stock divided by the years taken for the forest to grow to maturity or the natural land to regenerate.

The standard land use GHG emission factors in the generic FABLE calculator were replaced by UK-specific factors (Smith et al., 2020) that include changes to the carbon stored in soil as well as above-ground vegetation, and we split forest into semi-natural and plantation, with different carbon stocks and regeneration rates (Table A.1). The calculator was also modified to include emissions or sequestration due to transitions between cropland and pasture, and loss of carbon in farmland soils from urban expansion. However, we do not include emissions from loss of soil carbon during cropland cultivation. For Wales, forest areas were divided into semi-natural forest and plantations, both with different carbon stocks and time to regenerate (Table A.4). A very basic model of peatland restoration was also included, with all peat divided into 'intact' (small carbon sequestration) and 'degraded' (carbon emission source). There was no separate treatment of peatland used for forest, grazing etc. (Table S.5).

Table A.4: GHG emission factors and assumptions regarding time taken to regenerate each type of land cover

Land Use	**% of forest carbon stock**	**Year to Regenerate**	**Tonnes C/ha**	**Tonnes CO2/ha**
Forest	100%	110.00	329.00	1206.33
Plantation	50%	60.00	164.50	603.17
Cropland	15%	NA	49.35	180.95
Other land	60%	125.00	197.40	723.80
Pasture	20%	20.00	65.80	241.27
Extensive grassland	35%	30.00	115.15	422.22
Urban	0%	NA	0.00	0

Table A.5: Divided peatland, based Evans et al., 2015

	Kha
Total Peatland:	90
Of which ...	
Degraded	29
Intact (but only 10% in good condition)	61
Implied amount in poor condition	81

Notes on Table A.5
Estimated emissions from peatlands in Wales is 400 kt CO2e/yr, which equates to 4.93 tCO_2 eq/ha/yr.

Table A.6: Downscaling of parameters for Wales from UK FAOSTAT commodity balance data, based on historical data

FAOSTAT data	**Downscaling**	**Scaling Factor**		
		2000	**2005**	**2010**
Consumption of food	Scaled by ratio between the populations of Wales and the UK (5%)	5%	5%	5%
Consumption of animal feed	Scaled by ratio of animal numbers requiring feed (assumed to be pigs, poultry, half of cattle)	7%	7%	7%

Production of crops, and consumption of seed	Scaled by cropland area ratio	2%	3%	2%
Production of animal products	Scaled by animal numbers:			
	• Ruminants	16%	16%	15%
	• All Livestock	10%	8%	8%
Production of wood	Scaled by forest area	11%	10%	10%
Production of fish	Scaled by data on landings in Welsh ports by UK vessels	2%	2%	2%

Imports, exports and losses:

As a consequence of iterations with the Welsh Government, the imports and exports were calculated through proportioned FAOSTAT data. This was driven by difficulties in calculating trade data for Wales, as well as in depth research being conducted on future trade scenarios (Harrison et al., 2022).

- (Production – consumption – loss) = exports (if positive) or imports (if negative).
- Loss = (production + imports) * UK ratio of loss to (production + imports)
- Stock change = zero

Future exports (scenario assumptions)

- Exports (in tonnes) and the share of consumption that is imported (%) kept constant after 2010
- In future: could model changing exports, e.g. to reflect decrease in global and/or UK demand for meat.

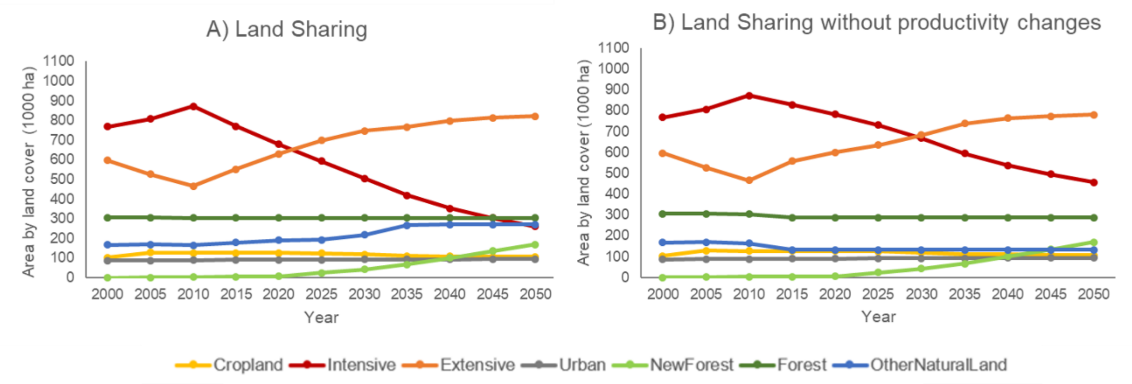


Figure A4: Projected land use change in the Land-Sharing pathway A) with all assumptions; and B) without increases in productivity and stocking rates

B) Supplementary material for Chapter 4

Table B.1: Underlying assumptions for the pathways for each of the devolved administrations.

		Current Trends				CCC Recommended pathway				Devolved Administration Pathway			
Domain	Parameter	Wales	Scotland	Northern Ireland	England	Wales	Scotland	Northern Ireland	England	Wales	Scotland	Northern Ireland	England
Population	*Population projection - million inhabitants*	Population projected to increase to 3.358 million by 2050 (ONS, 2019)	Population projected to increase from 5.465 million in 2020 to 5.559 million in 2050 (ONS,2019)	Population projected to increase from 1.8 million in 2018 to 2.0 million in 2050 (ONS, 2019)	Population projected to increase from rom 56.0 million in 2018 to 63.0 million in 2050 (ONS, 2019)	As for Current Trends				As for Current Trends			

Land	*Constraints on Agricultural expansion*	No constraints on agricultural expansion except for protected areas, which does not include National Parks, AONBs and Heritage Coasts (Smith and Harrison et al., 2022).	No constraints on agricultural expansion except for protected areas, including National Parks, AONBs and heritage coasts.	No agricultural expansion on existing habitats and 500,000ha of habitat created on agricultural land (Welsh Government, personal communication, 2021, cited in Jones et al., 2023a)	No agricultural expansion on existing habitats, including all existing semi-natural habitats.

	Afforestation Targets	Total woodland creation in 2020/21 was around 280 ha. Assume 300 ha/y to 2050 (Welsh Government, personal communication, 2021 cited in Jones et al., 2023).	10,700 ha of new woodland in 2020 (CCC, 2021), assume 11,000 ha/y to 2050	208 ha/yr in 2016/17 planted in Northern Ireland, assume this continues to 2050 (CCC, 2019)	2430 ha/yr planted in 2019/20, assume this continues to 2050 (CCC 2021).	43,000 ha planted by 2030 (average of 5,000 ha/yr from 2023), rising to 180,000 hectares by 2050 (7,500 ha/yr from 2035) (Welsh Government, personal communication, 2021, cited in Jones et al., 2023).	15,000 ha/yr by 2024/25, continuing to 2050 (CCC, 2021)	900 ha/yr of woodland per year (CCC, 2019)	Aims to have 12% woodland cover (UK Government, 2021), equating to 7,000 ha/yr from 2020 onwards.	40,000 ha planted by 2030 rising to 180,000 ha by 2050 (7,500 ha/yr from 2035) (Welsh Government, personal communication, 2021, cited in Jones et al., 2023a)	12,000 ha/yr of new woodland by 2020/21, increasing to 18,000 ha /yr by 2024/25 (Scottish Government, 2019)	1700 ha/yr (CCC, 2019)	Aims to have 12% woodland cover (UK Government, 2021), equating to 7,000 ha/yr from 2020 onwards.
	Peatland Restoration	Current rates of restoration maintained (assume 600 ha/yr)	250,000 ha of peatland restored by 2030 (Scottish Government, 2021)	No Changes to peatland areas	Current rates of restoration	All peatland in Wales is restored by 2030.	50,000 ha/yr restored between 2020 – 2035 (CCC, 2021)	No changes to peatland areas (No official guidance from the CCC) CCC,2021	56,000 ha restored by 2025 (CCC, 2021)	All peatland in Wales is restored by 2030.	20,000 ha/yr per year (Scottish Government, 2020)	No change to peatland (policy in consultation).	35,000 ha restored by 2025 (UK Government, 2021).

	Urban Expansion	5% increase in urbanisation, from 105,773 ha to 110,000 ha (Welsh Government, 2021)	150,000 new homes up to 2032 (Scottish Government, 2021)	estimated new dwelling requirement 2016-2030 in Northern Ireland is: 84,800. Projected new annual dwelling requirement 5,700 (Northern Ireland Statistics Research Agency, 2016).	300,000 new homes by 2025 (DEFRA, 2018)	As for Current Trends	As for Current Trends			
Biodiversity	Protected Areas	Existing designated sites protected for nature are maintained (excluding National Parks, AONBs, Heritage Coasts).				Existing designated sites protected for nature are maintained (including National Parks, AONBs, Heritage Coasts).	All semi-natural habitat (excluding woodland) is protected, to meet 30 x 30 target (welsh Government, personal communication, 2021, cited in	All semi-natural habitat (excluding woodland) is protected, extending the protected areas to at least 30% of land (Scottis	Protected areas are extended to meet the 30 x 30 biodiversity target.	Protect an additional 500,000 ha of land by 2030 (DEFRA, 2018).

				Jones et al., 2023).	h Government 2020).		
Productivity	*Crop Productivity**	As for the UK, in 2050, crop productivity remains the same: • 7.7 tons per ha for wheat (7.1 with climate change impacts). • 5.7 tons per ha for barley. • 43.9 tons per ha for potatoes. Based on FAOSTAT historic yields for 2010 (FAO, 2020)	As for the UK, by 2050, crop productivity reaches: • 12.7 tons per ha for wheat (12.0 with climate change impacts). • 9.4 tons per ha for barley. • 72.4 tons per ha for potato. Based on assumption that yields for all crops increase by 65% (Smith and Harrison et al., 2022).	As for the UK, by 2050, crop productivity reaches: • 10.7 tons per ha for wheat (10.1 with climate change impacts). • 7.9 tons per ha for barley. • 61 tons per ha for potatoes. Based on assumption that yields for all crops increase by 39% from the 2010 value, in line with the revised CCC medium projection (Smith and Harrison et al., 2022).			
	*Livestock productivity**	Dairy, beef and chicken yield to remains constant.	Between 2015 - 2050: Dairy yield: 50% increase Beef yield: remains constant Poultry yield: 10% increase Lamb yield: 52% increase (Welsh Government, personal communication, 2021 *cited* Jones et al., 2023a).	Between 2015-2050: Dairy yield: 37% increase Beef yield: remain constant Poultry yield: remains constant Lamb yield: 41% increases (Welsh Government, personal communication, 2021, *cited in* Jones et al., 2023a).			

	Stocking rate	No changes to Stocking density	Change in livestock density compared to baseline: 202% (Welsh Government, personal communication, 2021). 100% of ruminants on Intensive Grassland by 2050.	50% increase in stocking density between 2015-2050 (based on CCC report). 100% of ruminants on Intensive Grassland by 2050.	Change in livestock density compared to baseline: 136% (Welsh Government, personal communication, 2021, cited in Jones et al., 2023a). 50% of ruminants to be on extensive grassland by 2050.	25% increase in stocking density between 2015 and 2050 (based on CCC medium ambition). 50% of ruminants on extensive grassland by 2050.
	Post-Harvest Losses	No changes to Post-Harvest Losses	As for the UK, by 2050, the share of production and imports lost during storage and transportation is 0.5%. Based on assumption of a 50% reduction in losses compared to 2015, i.e. achieving the SDG 12.3 target to halve consumer and retail waste but by 2050 rather than 2030 (WRAP, 2020)		As for UK, by 2030, the share of production and imports lost during storage and transportation is 0.5%, i.e. the target is achieved earlier than the CCC scenario. Based on assumption of a 50% reduction in losses compared to 2015 in line with the Courtauld 2025 Commitment (reduction of 20% across supply chain between 2015-2025) and SDG 12.3 target (halve consumer and retail waste by 2030) (WRAP, 2020).	

Trade	Share of consumption which is imported for key imported products (%) and Evolution of exports for key exported products (1000 tons). **	Exports and imports are estimated from the commodity balance after downscaling production and consumption from UK statistics and then held constant after 2010 (Welsh Government, personal communication, 2021 *cited in* Jones et al., 2023).	
Food	*Average dietary consumption (daily kcal per commodity group)*	No changes in current diets. By 2030, the average target daily calorie consumption per capita is 2,983 kcal and is: • 168 kcal for fruit and vegetables. • 83 kcal for ruminant meat. • 119 kcal for animal fats.	Population moves to the healthier, EatWell diet by 2030, the average target daily calorie consumption per capita is 2,739 kcal and is: • 196 kcal for fruit and vegetables. • 75 kcal for ruminant meat. • 98 kcal for animal fats. Based on meeting the Eatwell diet recommendations by 2050 (PHE, 2020; Scarborough et al., 2016).

	Share of food consumption which is wasted at household level (%)	No Changes to Food Waste	Wales aims to have zero avoidable food waste before 2050. By 2025: • 50% reduction in avoidable food waste By 2030: • 60% reduction in avoidable food waste By 2050: • Zero avoidable food waste (Note: All waste reduction targets are set against a 2006-07 baseline) (Welsh Government, personal communic	• 50% reduction in food waste by 2030, • 60% reduction in food waste by 2050 relative to 2007 baseline (CCC, 2020)	50% reduction in food waste by 2030 continuing to 2050 (CCC, 2020)	Wales aims to have zero avoidable food waste before 2050. By 2025: • 50% reduction in avoidable food waste By 2030: • 60% reduction in avoidable food waste By 2050: • Zero avoidable food waste (Note: All waste reduction targets are set against a 2006-07 baseline) (Welsh Government, personal communic	• 50 % reduction in household food waste by 2030 • 100 % reduction by 2045 (Scottish Government, 2020)	50% reduction in food waste by 2030 continuing to 2050 (CCC, 2020)	50% reduction in food waste by 2030 100% reduciton in food waste by 2050.

			ation, 2021).			ation, 2021, cited in Jones et al., 2023a).				
Biofuels	_Targets on biofuel and /or other energy use***_	No Change to current biofuels.								

Climate Change	*Crop Model and Climate Change Scenario*	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 6 W/m2 (RCP 6.0). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilisation effect (Smith and Harrison et al., 2022)	As for UK, by 2100, global GHG concentrations lead to a radiative forcing level of 2.6 W/m2 (RCP 2.6). Impacts of climate change on crop yields are computed by the crop model GEPIC using climate projections from the climate model HadGEM2-E without CO2 fertilisation effect (Smith and Harrison et al., 2022).

* Follows the assumptions in Jones et al., 2023a - Under the assumption any new innovations / technology would be shared amoung the 4 devolved nations.

** Given uncertainty of trade, assumptions across the pathways the same

*** Biofuels are represented in FABLE per area of Crop

Study Context: Policy

Each of the nations have their own policies and land-use contexts that determine their capabilities to achieve climate targets, with each of them having responsibility for environment and planning, agriculture, and fisheries.

At the time of its passing, Scotland's Climate Change Act 2009 was one of the most ambitious climate change legislations (Nash, 2021). The Act was amended in 2019, increasing the ambition of Scotland's emissions reduction targets to net-zero by 2045, as well as revising annual and interim emissions targets (Scottish Government, n.d.). The Scottish Parliament also introduced a Land Use Strategy in 2011 (Buchardt, Doak and Parker, 2020) that is required by law to be published by ministers every five years (Scottish Government, 2021a). The most recent Land Use Strategy moves away from a sector-by-sector approach towards a more holistic picture of what sustainable land-use in Scotland could be, balancing the many demands placed on land that go beyond agriculture and forestry (Scottish Government, 2021a).

The Welsh Parliament has made innovative commitments in the passing of the Environment (Wales) Act 2016 to adopt a more integrated approach to managing natural resources to achieve long-term sustainability (Welsh Government, 2016). The Act provides targets for emissions reductions, waste disposal, fisheries and marine life, and sustainable management of natural resources. The Welsh Government also has legislation to ensure public bodies consider the long-term impacts of their decisions through the Well-being of Future Generations (Wales) Act 2015, which puts sustainability at the centre of decision-making (Burchardt, Doak and Parker, 2020).

In contrast to Scotland and Wales, and despite the UK Climate Change Act 2008 requiring Northern Ireland to act on climate change, Northern Ireland has a history of weak environmental governance (Burns et al., 2018). Cave and Pike (2021) note that initiatives to mitigate and adapt to climate change are fragmented, and a more joined up approach is essential for achieving net-zero and other policy targets. The Northern Ireland Assembly passed its first Climate Change legislation in 2022 (Climate Change Act (Northern Ireland) 2022) setting out a legal framework to reduce GHG emissions.

Although there is no direct English legislative body to formulate England-specific policy, the role for land use and agricultural matters is undertaken by the Department for Environment, Food and Rural Affairs (DEFRA) (Kirsop-Taylor, 2020), who often act on behalf of England in developing and drafting environmental policy, with the newly formed Department for Energy Security and Net Zero (DESNZ) responsible for energy supply and ensuring the UK is on track for it's net-zero targets (DESNZ, n.d.). In 2018, The 25

Year Environment Plan (25YEP) set out ambitions for improving and managing the environment (HM Government, 2018). The plan applies to England only and has been criticised for providing insufficient detail on planned targets or monitoring (Burns et al., 2018).

Despite the interconnectedness created by nested tiers of government, policy change can vary by territory (Nash, 2021), and there is a risk that misaligned frameworks and polices will lead to sub-national mitigation being hindered, with aggregated national targets potentially being missed (Reay, 2020).The UK's exit from the European Union (EU) offered an opportunity to rethink the design and ambitions of future environmental policy, with Scotland, Wales and the UK Government indicating a willingness to think strategically. Most notable here is the removal of the EU Common Agricultural Policy (CAP) and farmer payments. The devolved administrations have the freedom to develop their own agricultural and environmental policies, but central government leads on reserved matters related to agriculture, such as trade and overall budget distribution (Petetin, 2022). England, Scotland, Wales and Northern Ireland have their own agricultural ministries that are progressing agricultural and environmental policy in different ways. In Wales, the Agriculture (Wales) Bill is in development, establishing Sustainable Land Management as the legislative framework for future agricultural policy (Welsh Government, 2022). In 2021, the Scottish Government launched a consultation on a future Scottish Agricultural policy (Scottish Government, 2021b), which provided an overview of emerging recommendations from Farmer Led Groups, on technology and efficiency measures, capital funding required to support farmers and improvements in supply chains. DEFRA has developed the Environmental Land Management (ELM) schemes for England, which involved designing new schemes to pay farmers and land managers to provide environmental goods and services, as well as food production (DEFRA, 2023). These differing approaches will begin to be implemented between 2023 and 2025, gradually replacing the basic payments provided under the CAP, which could potentially lead to different changes in food and land use systems across the UK (Booth, 2021).

The UK CCC, the independent advisory body to the UK and devolved administrations, has established scenarios to cut emissions rapidly across the devolved nations (CCC, 2020). Their recommended "Balanced Net-Zero Pathway" represents a decisive transition to net-zero, reaching net-zero in 2050 across all GHG emissions, with over 60% of the necessary reduction achieved before 2035 (CCC, 2020). However, emissions from agriculture do not reach zero, and need to be offset by a carbon sink facilitated through land-use change (CCC, 2020). The CCC state that UK climate targets cannot be met without strong policy action across Scotland, Wales and Northern Ireland, that is tailored to national, regional and local needs (CCC, 2020), and they provide a set of recommendations for policy actions for each devolved administration to meet their recommended pathways (CCC, 2021; CCC, 2020b; CCC, 2019). The devolved administrations of Scotland and Wales have sought to develop their own ambitious environmental policy since devolution (Burns et al., 2018), with Northern Ireland also making progress on its climate ambitions (Cave and Pike, 2021). Therefore, each nation has their own aspirations for the future of environment and land-use policy, which in some areas contradicts that of the CCC.

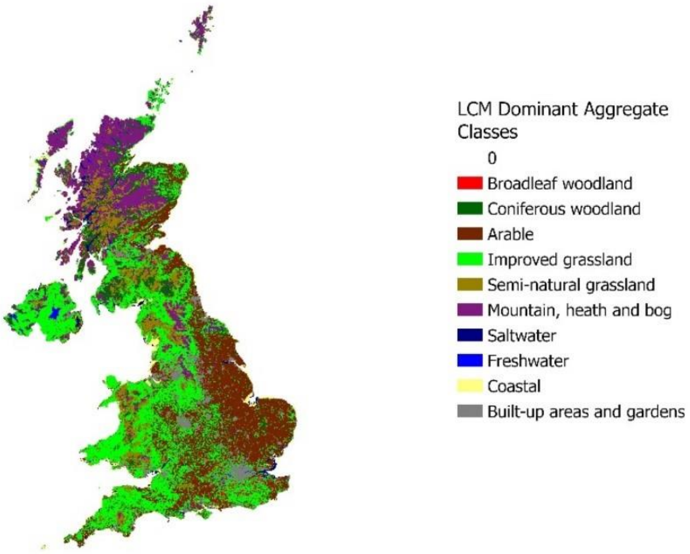


Figure B1: Land Cover in the UK – UK CEH LCM categories. Source: Rowland et al., 2017a, b.

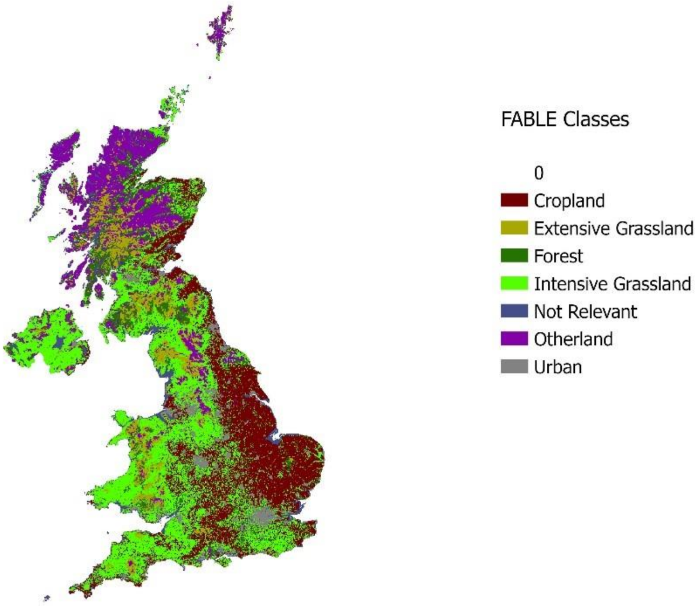
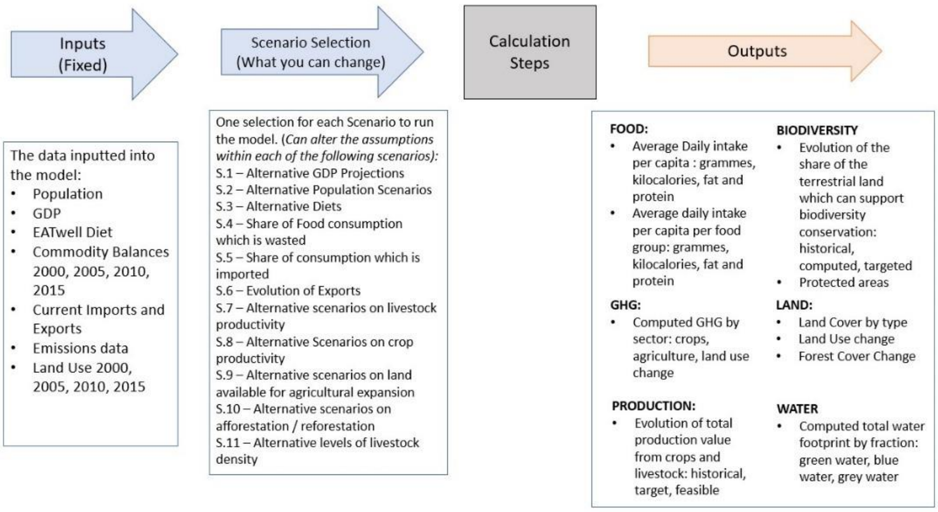


Figure B2: UK Land cover with FABLE Categories Mapping of LCM Land cover classes to FABLE land cover categories using Table S2.



The data inputted into the model:
- Population
- GDP
- EATwell Diet
- Commodity Balances 2000, 2005, 2010, 2015
- Current Imports and Exports
- Emissions data
- Land Use 2000, 2005, 2010, 2015

One selection for each Scenario to run the model. (*Can alter the assumptions within each of the following scenarios):*
S.1 – Alternative GDP Projections
S.2 – Alternative Population Scenarios
S.3 – Alternative Diets
S.4 – Share of Food consumption which is wasted
S.5 – Share of consumption which is imported
S.6 – Evolution of Exports
S.7 – Alternative scenarios on livestock productivity
S.8 – Alternative Scenarios on crop productivity
S.9 – Alternative scenarios on land available for agricultural expansion
S.10 – Alternative scenarios on afforestation / reforestation
S.11 – Alternative levels of livestock density

FOOD:
- Average Daily intake per capita : grammes, kilocalories, fat and protein
- Average daily intake per capita per food group: grammes, kilocalories, fat and protein

GHG:
- Computed GHG by sector: crops, agriculture, land use change

PRODUCTION:
- Evolution of total production value from crops and livestock: historical, target, feasible

BIODIVERSITY
- Evolution of the share of the terrestrial land which can support biodiversity conservation: historical, computed, targeted
- Protected areas

LAND:
- Land Cover by type
- Land Use change
- Forest Cover Change

WATER
- Computed total water footprint by fraction: green water, blue water, grey water

Figure B3: Inputs, what you can change and outputs of the FABLE Calculator

The FABLE Calculator

The calculator is driven by the demand for 88 agricultural (raw and processed) products from crop and livestock sectors, determined by assumptions concerning current and future diets and population levels. For each five-year time step over 2000 to 2050, the calculator computes the *per capita* demand for consumption of different products, the total demand considering food waste, imports and exports, the livestock numbers needed to meet the demand, and the associated demand for cropland and pasture, considering demand for animal feed crops. The final land-use change is then calculated, taking account of competing demands for land for urban expansion, afforestation and protected areas. If there is insufficient land to meet demand, cropland and pasture areas are scaled down to the 'feasible' area, which may result in targets for food consumption not being met. The final 'feasible' land-use change is then used to calculate GHG emissions from agriculture and land use change, as well as food security and biodiversity indicators.

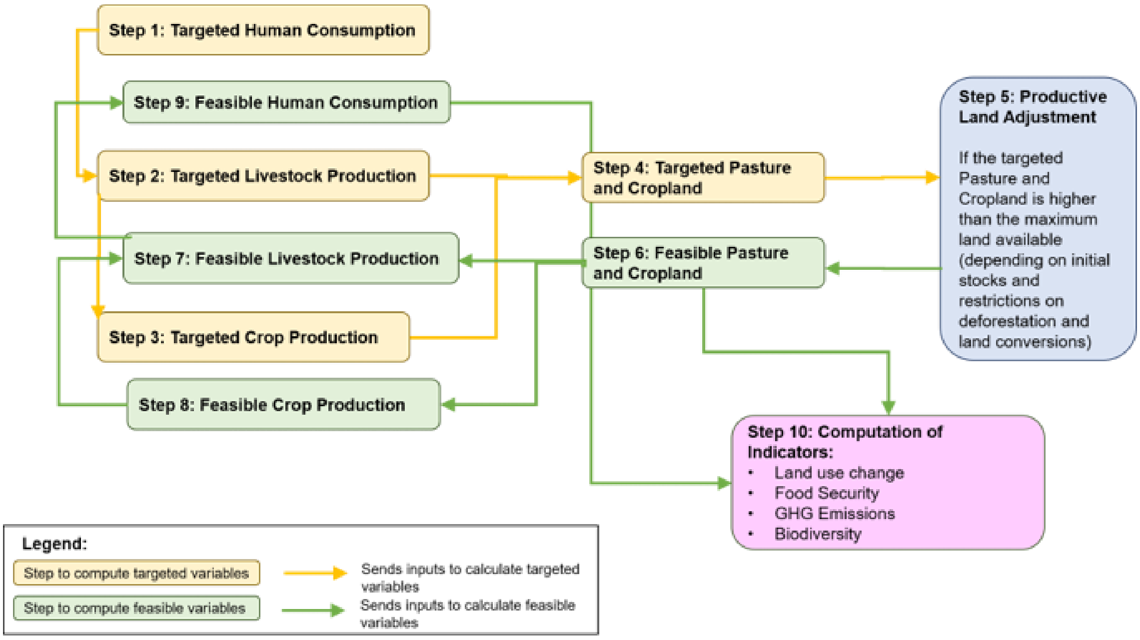


Figure B4: Calculation steps for the FABLE Calculator, adapted from Mosnier et al., 2020

Table B.2: Mapping of LCM Land cover classes to FABLE land cover categories

LCM Land cover classes	**FABLE land cover classes**
Broadleaved woodland	Forest
Coniferous woodland	Forest
Arable	Cropland
Improved grassland	Grassland
Neutral grassland	Extensive grassland
Calcareous grassland	Extensive grassland
Acid grassland	Extensive grassland
Bracken	Other Land
Fen, Marsh, Swamp	Other Land
Mountain, Heath & Bog	Other Land
Inland Bare Ground	Not Relevant
Inland Water	Not Relevant
Suburban	Urban
Urban	Urban
Supra-littoral rock	Not Relevant

Supra-littoral sediment	Not Relevant
Littoral rock	Not Relevant
Littoral sediment	Not Relevant
Saltmarsh	Not Relevant
Dwarf Shrub Heath	Other Land
Bog	Other Land
Inland Water	Not Relevant
Montane	Not Relevant
Inland Rock	Not Relevant
Built-up Areas and Gardens	Urban
Fen	Other Land
Heather	Other Land
Heather grassland	Other Land
Bog	Other Land
Inland rock	Not Relevant
Saltwater	Not Relevant
Freshwater	Not Relevant

GHG emissions and sequestration in the FABLE Calculator

The calculator estimates emissions from crop production, including N2O from synthetic fertilisers and crop residue, and CO2, CH4 and N2O from energy used during cultivation, using emission factors from FAOSTAT (FAO, 2020).

Livestock emissions include CH4 from enteric fermentation in ruminants, and both CH4 and N2O from manure, based on emission factors used in the GLOBIOM model (Herrero et al., 2013).

Land use change includes emissions when land is converted to a different type (e.g. natural land converted to farmland or urban) and carbon sequestered due to afforestation or regeneration of natural land. Land use change emissions in FABLE are calculated based on estimates of carbon stock. When forest or other natural land is converted to farmland or urban, the difference in carbon stock between the two land use types is assumed to be lost immediately. However, when new forest is planted or natural land regenerates from abandoned farmland, carbon sequestration is estimated as the difference in carbon stock divided by the years taken for the forest to grow to maturity or the natural land to regenerate.

The standard land-use GHG emission factors in the generic FABLE calculator were replaced by UK-specific factors (Smith et al., 2020) that include changes to the carbon stored in soil as well as above-ground vegetation, and we split forest into semi-natural and plantation, with different carbon stocks and regeneration rates. The calculator was also modified to include emissions or sequestration due to transitions between cropland and pasture, and loss of carbon in farmland soils from urban expansion. However, we do not include emissions from loss of soil carbon during cropland cultivation.

C) Supplementary material for Chapter 5

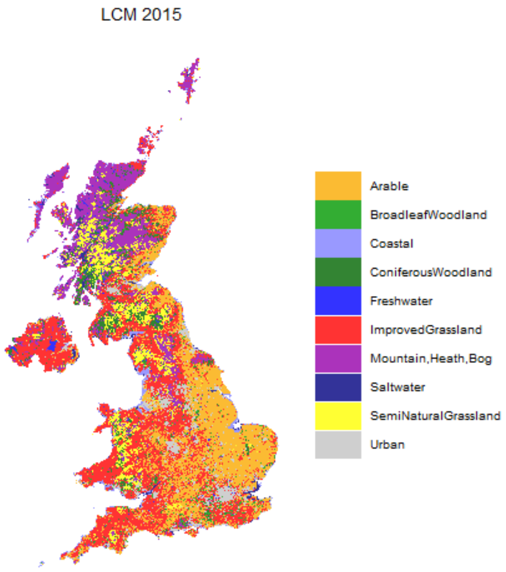


Figure C1: Land Cover in the UK – UK CEH LCM categories Source: Rowland, et al. 2017a, b)

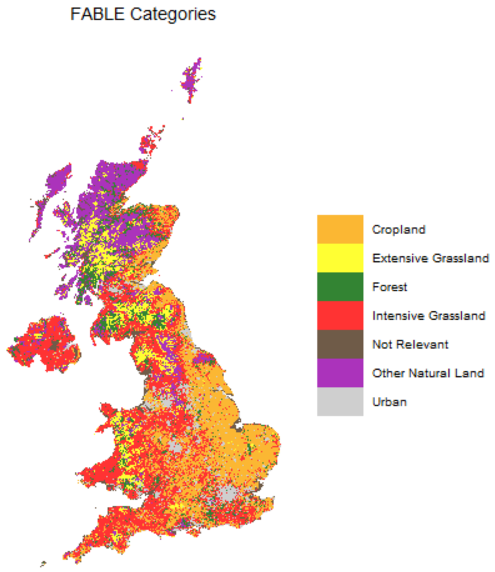


Figure C2: UK Land cover with FABLE Categories

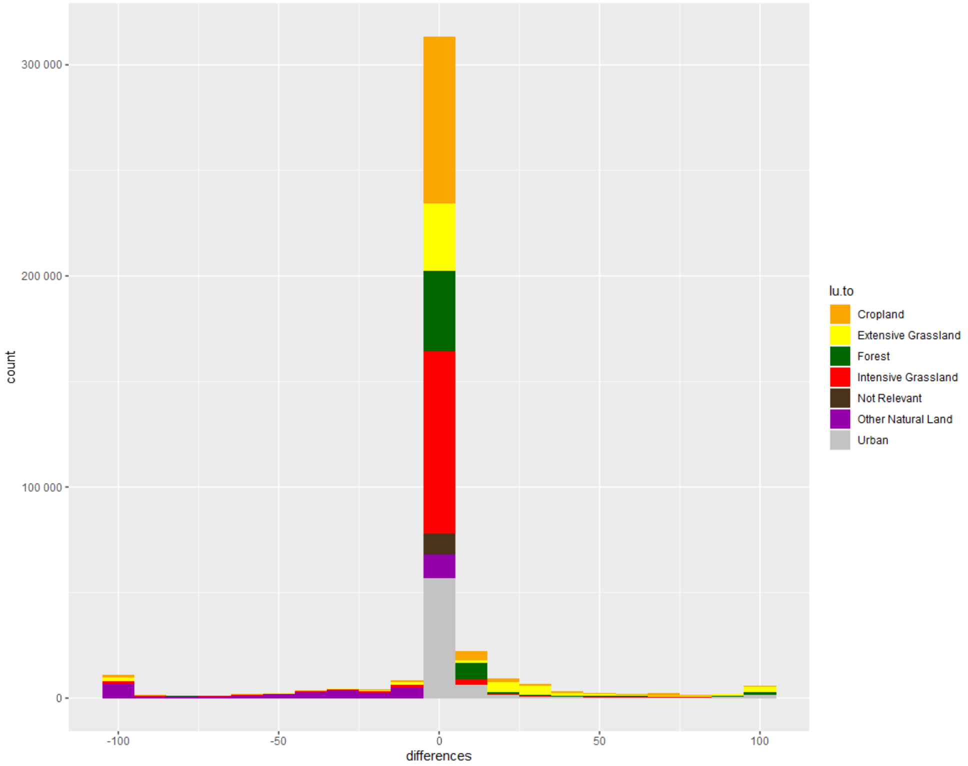


Figure C3: Histogram of sums of differences for Current Trends

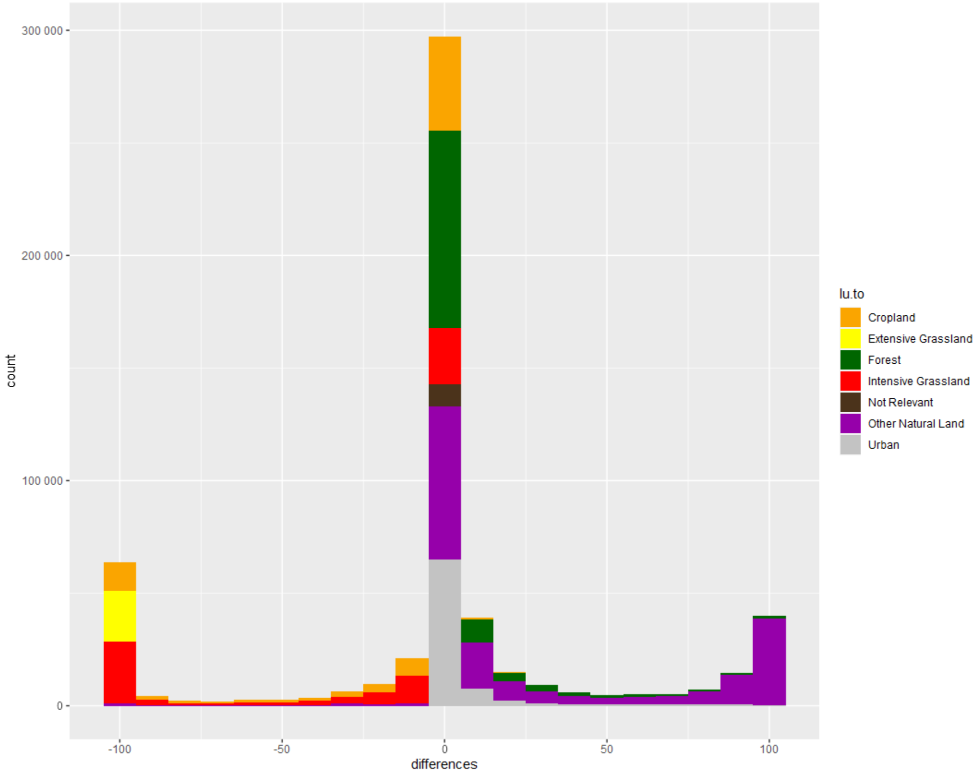


Figure C4: Histogram of sums of differences for CCC

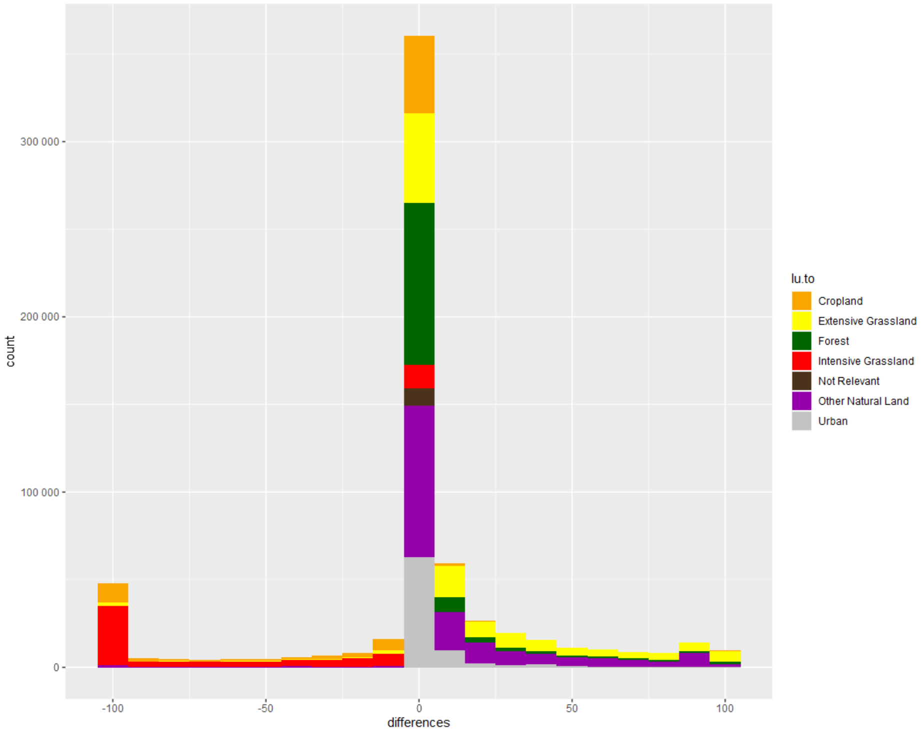


Figure C5: Histogram of sums of differences DA

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