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ORIGINAL ARTICLE

# Pathways to achieving nature-positive and carbon–neutral land use and food systems in Wales

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## 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.

**Keywords** Land use · Biodiversity · Policy · Diet · Agricultural productivity

## 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

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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 and the UN Sustainable Development Goals. 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 (UK 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, but 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 2018), 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 2021).

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.

## Methodology

### Welsh context

The focus of this research was the devolved administration of Wales, which sits to the west of England and covers 2,077,000 ha. 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 S1). 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 well-being 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 48 ha, 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 2020), 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 2020). 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.

### 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. 2023). 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 5-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 S3.

## 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.

## Pathway development

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

### 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 2021a, 2019b). This results in an estimated 5% increase in urban area for Wales, from 105,773 ha in 2015 to 110,000 ha in 2050, equaling 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 semi-natural 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.

### 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 2020). 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 1, with the underlying assumptions and justifications seen in the Online Resource and Table S1.

## 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 are shown in Table S2 and Table S3.

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.

n 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 S4), 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 S5). 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 Online Resource.

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 S6). 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.

**Table 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<br>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<br>Productivity increases for dairy (+37%) and lamb (+17%) | No change for beef<br>Productivity increases for poultry (+10%), dairy (+50%) and lamb (+52%) beef and lamb | As for Pathway 2, but with additional increases for lambing (+41%) |
| Stocking density | Current stocking densities of 2.2 livestock units per hectare on intensive grassland and 0.92 on extensive grassland | Slight increases in stocking density (132% compared to baseline) | 100% of the grazing ruminants on intensive grassland by 2050<br>Stocking density doubles on grassland by 2050 | Increase to 50% of grazing ruminants using extensive grassland, from 25% today |
| Afforestation targets | Current levels | Slight increases to 20,000 ha planted by 2030, rising to 80,000 ha by 2050 (4% of total area) | Increases to 43,000 ha planted by 2030 (average of 5000 ha/yr from 2023), rising to 180,000 ha (8% of total area) by 2050 (7500 ha/yr from 2035) | Increases to 43,000 ha planted by 2030 (average of 5000 ha/yr from 2023), rising to 180,000 (8% of total area) ha by 2050 (7500 ha/yr from 2035) |
| 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:<br>• 50% reduction by 2025<br>• 60% reduction by 2030<br>• Zero Avoidable food waste by 2050<br>Post-harvest losses reduced by 50% by 2050 | Reduction in food waste:<br>• 50% reduction by 2025<br>• 60% reduction by 2030<br>• Zero Avoidable food waste by 2050<br>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 |

## Results

### 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 (Fig. 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 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 (Fig. 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 (Fig. 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 (Fig. 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.

## 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 (Fig. 2A). The Improvements on current trends pathway projects slight increases in 'other natural land', and afforestation targets lead to some increases in new forest (Fig. 2B).

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' (Fig. 2C). 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 (Fig. 2D).

The status quo and improvement on current trends pathways assume that new woodland planting follows existing

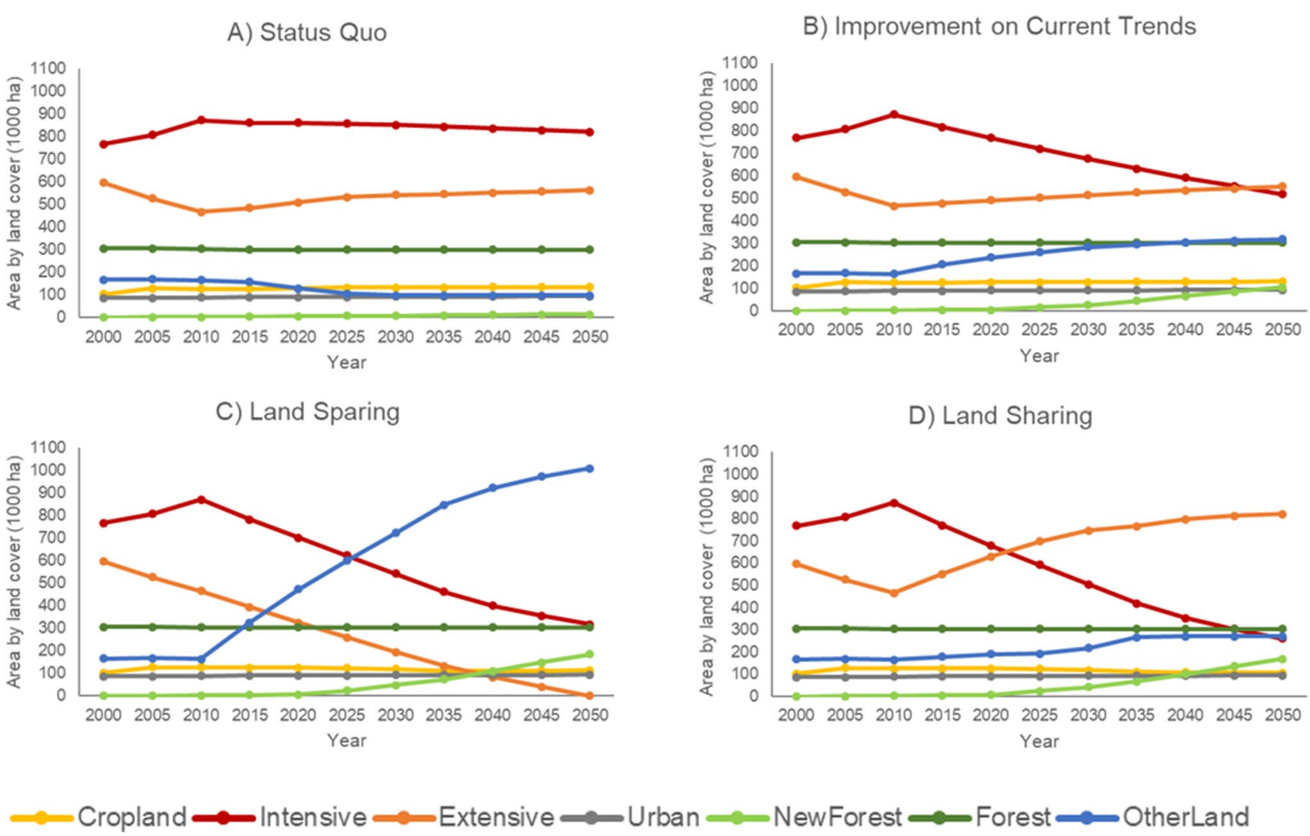
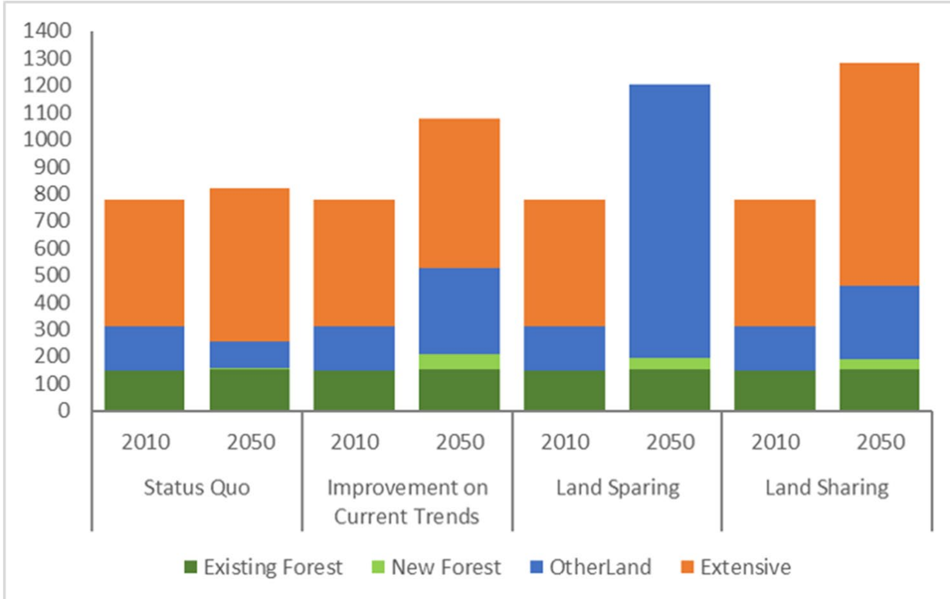



**Fig. 1** **A**–**D** Projected land use change for the four pathways. Note: 'Intensive' represents intensively grazed high-input ('improved') grassland and 'Extensive' represents species-rich semi-natural grassland. 'Otherland' is defined as mainly peat bog, heath and wetlands. Results are every 5-year time step, which are connected by a line to highlight the trends in land use change up to 2050

**Fig. 2** **A**–**D** 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




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.

## 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 (Fig. 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 (Fig. 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 (Fig. 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 (Fig. 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.

## 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.

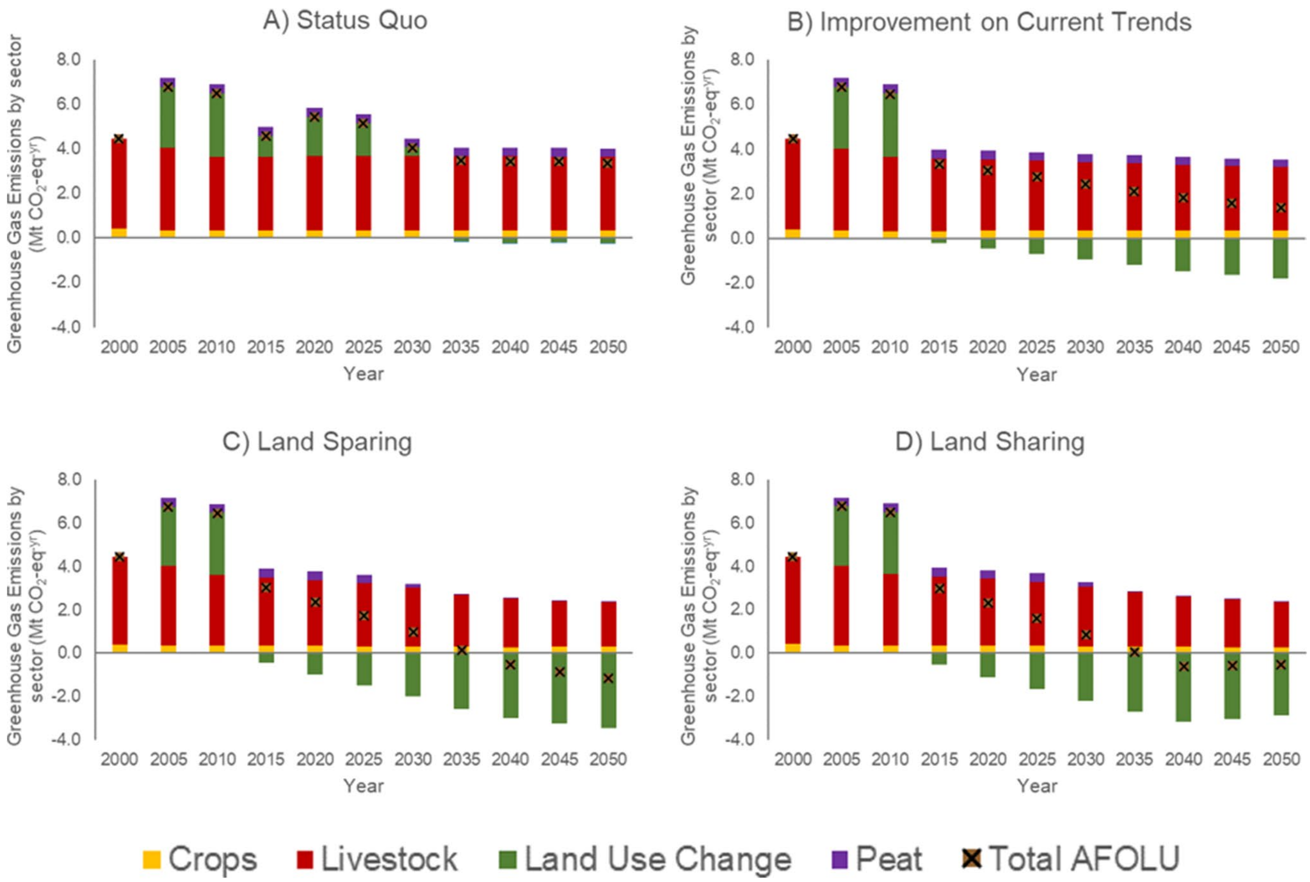



**Fig. 3** **A–D** Projected GHG emissions for the four pathways

## 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' (Fig. 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.

## 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' (Fig. 5B). This indicates a high dependence in the land sparing scenario on assumptions of increases in productivity and stocking rates.

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 S4B).

## 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 (Fig. 6).

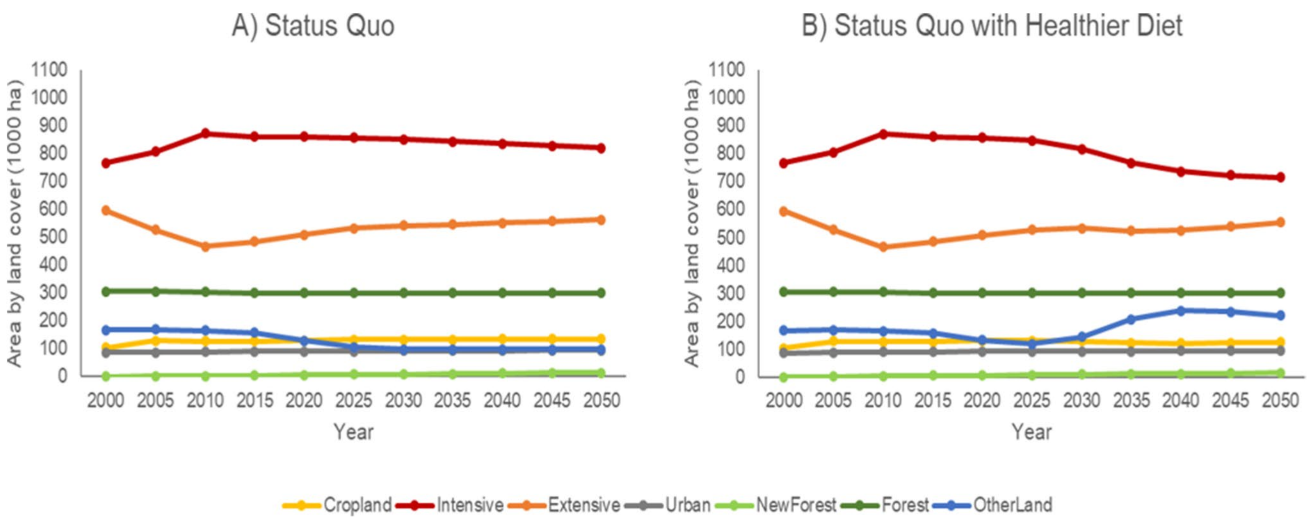



**Fig. 4** Projected land use change in the status quo pathway: **A** with all assumptions and **B** including the healthier EatWell diet

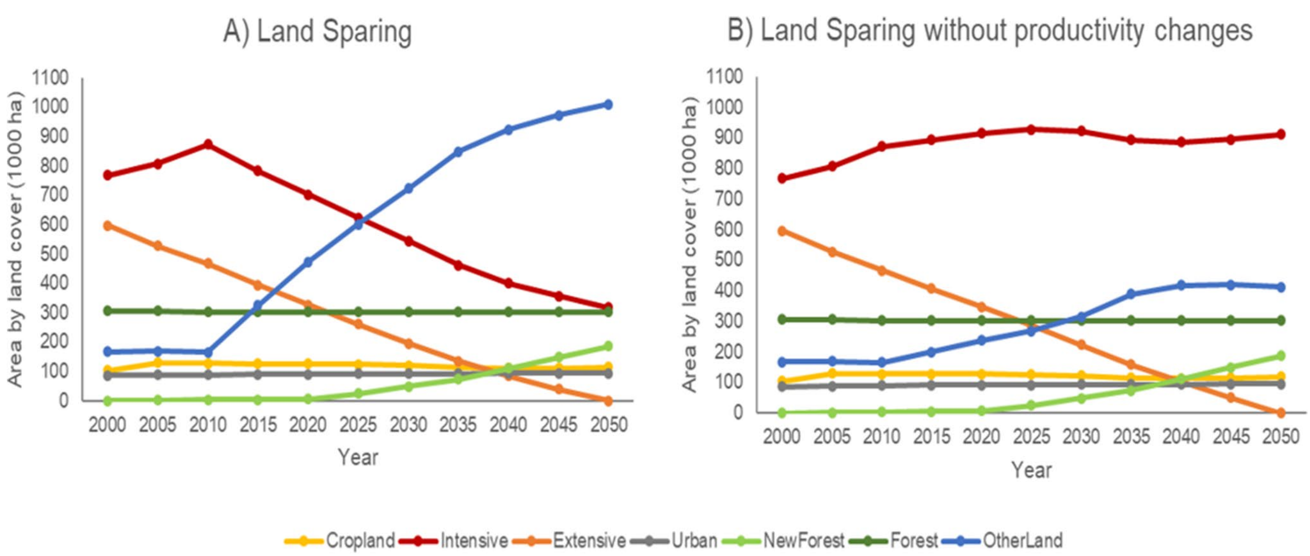



**Fig. 5** Projected land use change for the Land Sparing pathway: **A** with all assumptions and **B** without increases in productivity and stocking rate

## 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.

### 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 2021b).

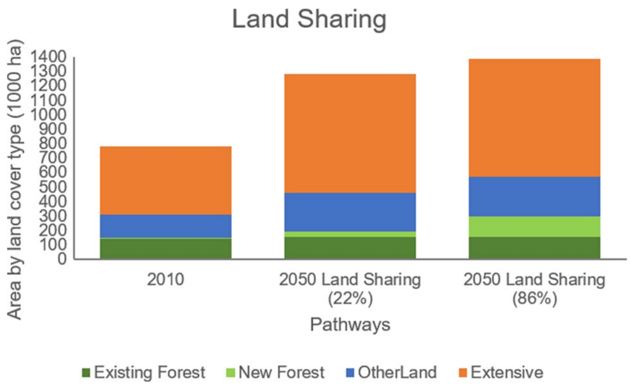



**Fig. 6** Land that can support biodiversity conservation for land sharing pathway, achieving the desired 500,000 ha when 86% of new forest is planted for biodiversity

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). Whilst 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.

## 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. 2014), having the potential to aid in sequestrating carbon (Flectcher et al. 2021), 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, remain 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, whilst 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.

## 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 regard to releasing land for biodiversity) are increases in productivity and improvements in agricultural technology. There would also be further policies required to encourage land owners 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.

## 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 Low Carbon Delivery plan (Welsh Government 2021b, 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.

## 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, Hedenus 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).

## 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.

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**Data Availability** The datasets are available from the corresponding author on reasonable request.



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