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Rapid adaptive modelling for policy support towards achieving Sustainable Development Goals: Brexit and the livestock sector in Wales

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ABSTRACT

Sustainable use of land is central to achieving the United Nations Sustainable Development Goals (SDG). However, implementation of policy targeting SDG delivery can be driven off track by external factors. There is a pressing need for rapid, adaptable modelling approaches to support policy development against a background of dynamic changes in environmental and political conditions. An example is the imminent departure of the UK from the EU (Brexit), which requires responsive inputs of robust evidence to inform decision making. We combine existing agri-economic modelling with well-tested environmental models, driven by farm survey and landscape data in an adaptive, participatory approach to assess potential agricultural sector responses to Brexit. We explore potential Brexit impacts on land use, environmental outcomes and agricultural jobs in Wales, UK, where agriculture is dominated by animal production on grassland systems. Three potential post-Brexit trade agreements scenarios are considered: EU Deal; No Deal; and Multilateral Free Trade Agreements. For each scenario potential changes in animal numbers in livestock systems in Wales are converted to predicted land use change at field and farm scale and combined with national data sources and models to explore consequences for the environment and jobs. Potential changes in grazing animal numbers range between − 30% (sheep for No Deal and MFTA) and + 53% (No Deal dairy), affecting 3% (EU Deal) to 17% (No Deal) of agricultural land and creating potential losses of 700 (EU Deal) to 7000 (MFTA) full time jobs. Environmental outcomes are mixed, with reductions in greenhouse gas emissions (− 1% EU deal to − 16% MFTA) and variable impacts on pollutant loads to water (N ranges + 3% for No Deal to − 14% for MFTA) across all scenarios. Air pollution is most scenario dependent (+ 11% No Deal to − 12% MFTA), and biodiversity showed a mixed response to each scenario. The findings of this study support Welsh government in developing programmes to manage the Brexit transition proactively, mitigating risks to the environment, rural communities and agricultural sector..

1. Introduction

Sustainable use of land, and the development of appropriate policies to support this, is central to achieving the United Nations Sustainable Development Goals (SDG). Delivering across all 17 SDG (United Nations General Assembly, 2015) whilst meeting demand for doubled food production by 2050 (Searchinger et al., 2018) presents a major global challenge and must be a consideration in all policy development. However, implementation of policy to support the SDG agenda can be driven off track by a range of external factors including market forces, political changes and environmental drivers.

The rapid departure of the UK from the European Union (or Brexit) is a prime example of a political driver with poorly understood potential outcomes for a range of environmental policies targeting SDG. Critically, information was needed much more quickly than permitted by the usual timeline of most academic studies and publication outputs. Similarly, the Covid-19 pandemic has highlighted the need for joint working between scientists and governments and the use of fast, if less sophisticated, modelling approaches that are already well tested, to support urgent response to dynamic situations (Lewis and Coombs, 2020).

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Globally, the effects of the Covid-19 pandemic on agriculture have been sudden and dramatic, with disruptions in supply chains and the availability of farm labour. Following initial shocks from any source, longer term changes in agricultural (and environmental) policy may be driven through increased drive for domestic food security, and focus on the resilience of agricultural system to external shocks and dramatic shifts in market prices (Stephens et al., 2020).

Development of agri-environment policy must account for diverse objectives, in line with the SDG, which can be facilitated through modelling impacts on a range of indicators of environmental quality and services (e.g. greenhouse gas (GHG) emissions, air and water quality, biodiversity, etc.) (Kuhmonen, 2018; Liu et al., 2018). However, implementation of modelling for policy support generally lags behind research and development of methodologies, in part because the semi-chaotic and rapidly changing needs of policy development limit the application of complex models and science (Adelle et al., 2012; Reidsma et al., 2018). This issue is amplified by sudden shocks to the global trade system, causing knock-on impacts on global land use and agriculture, which require rapid policy responses to mitigate adverse consequences (Inglehart and Norris, 2016). Our work provides a novel demonstration of modelling in times of rapid external change, to evaluate the pressures and risks of the external changes and thus support the development of relevant policy options. This differs from the typical use of modelling in the EU agricultural sector, which is to forecast likely outcomes of particular policy options under development (Reidsma et al., 2018).

Here we demonstrate close joint working between researchers and government officials, using rapid adaptive scenario modelling to support policy development against a background of dynamic political change. Agriculture in Wales will be strongly impacted by post-Brexit trade agreements that affect demand for agricultural goods alongside changes in environmental regulations, and fundamental shifts in agricultural support (HM Government, 2018; Welsh Government, 2018a). We demonstrate how existing models can be linked to predict potential land use changes and impacts on agricultural jobs and a range of environmental outcomes. The modelling presented here explores potential immediate effects of post-Brexit trade agreements on the principal systems of Welsh agriculture in the absence of change in current policy and regulations. By modelling the impacts of trade scenarios without change in regulations or rural payments, we can better understand them and plan policy response. We also explore woodland creation as one possible alternative use of agricultural land. The findings support Welsh government in developing programmes to manage the Brexit transition proactively, and to develop policy options for re-targeting rural funding and tailoring environmental legislation to Welsh objectives, creating improvements for multiple outcomes for "securing the future of Welsh farming" (Welsh Government, 2018b), and supporting Wales' commitment to the SDG.

2. Methods

The aim of this work was to provide rapid yet reliable evidence of potential agricultural sector response to changing demand for Welsh agricultural products under a range of possible post-Brexit trade agreements. We demonstrate an adaptive, participatory approach, to support policy development against a background of dynamic changes in environmental and political conditions. The approach links outputs of agri-economic models with well-tested environmental models, incorporating current national farm survey and landscape data, to explore spatial variation in potential impacts on agricultural land use, environmental outcomes and agricultural jobs. The details of the methods reflect the specific context of Wales (see Supplementary material Sections 1–4, and (Cosby et al., 2019), however the overall approach could be applied anywhere with a need to provide rapid evidence to support decision-making.

The participatory modelling and analysis approach consists of four main stages for each post-Brexit trade scenario considered:

1. Predict change in animal numbers needed in each livestock system in Wales to satisfy change in market demand for animal products under each post-Brexit trade agreement.
2. Project the potential agricultural land use changes required to support the new animal numbers in each system, assuming average stocking densities and livestock composition, and map these onto the current (baseline) distribution of livestock farms in Wales
3. Estimate the potential impacts of the new agricultural land use on agricultural employment and a range of environmental issues
4. Evaluate opportunities for new management of land potentially changing to non-agricultural use.

Stage 1 was completed by Welsh Government and the Evidence and Scenarios Roundtable Sub-Working Group (See Section 2.1); Stages 2–4 were completed by researchers, in consultation with Welsh Government (See Sections 2.2–2.4).

Evaluation ensuring that analyses, models, data and assumptions are transparent and "fit-for-purpose" at every stage improves understanding of outputs and produces "proportionality of response" (quality assurance efforts commensurable to relative risk).

The spatially explicit outputs, which can be mapped or summarised from farm to regional to national scale, provide valuable insights into trade-offs and co-benefits arising from potential land use changes. The maps of potential new land use can be compared to other spatially explicit datasets (e.g. socio-economic indicators) that are relevant to integrated policy planning, informing where regional environmental regulations and socio-economic safety nets may be needed to avoid unintended environmental consequences or social and economic hardship.

2.1. Brexit scenarios

A Sub Working Group (SWG), made up of a diverse range of key stakeholders, representing farming, forestry, water industries, trade and conservation bodies, and many other organisations (listed in Supplementary Section S1), produced the following representative trading scenarios (published in Welsh Government, 2018a):

- EU Deal: EU-UK FTA trading environment. Trade with the EU-27 nations, with non-tariff barriers in place increasing transaction costs. This scenario is closest to business as usual.
- No Deal: Trade under World Trade Organisation (WTO) rules. The UK-EU trade relationship is the same as with the rest of the world. This scenario would be a major change for existing business models, causing economic disruption.
- MFTA (Multilateral Free Trade Agreements): Individual free trade agreements (FTA) with the EU-27 nations, with other nations also having FTAs with the EU-27, and new FTAs with countries not previously traded with. This scenario assumes a broadly similar EU trade relationship as currently in place, enabling potential impacts of greater world market exposure to be examined.

The scenarios were intended to explore vulnerabilities by covering a range of possible outcomes which might contribute to the final Brexit trade deal. More details in Supplementary Section S1, which also outlines the rationale for predicted change in each livestock system. Evidence used by the SWG included scenario analysis from the FAPRI-UK Model (Davis et al., 2017), and an impact assessment focussing on Wales' most significant agricultural systems (AHDB, 2017).

Based on the SWG report and associated evidence, Welsh Government provided projections of market demand for animal products for each trading scenario, which they further extrapolated to our "Brexit scenarios" of estimated changes in animal numbers in Wales, using available evidence, expert judgement and cross-checking with stakeholder groups and the SWG (Stebbings, 2018, 2019).

2.2. Mapping of livestock systems and land use change

To produce a baseline, we use farm scale agricultural survey data on livestock numbers and economic turnover (See Supplementary Section S2) to produce a map of farm type based on dominant economic activity. Land use changes are modelled for farm type transitions for livestock farms assigned to the following types: dairy; sheep; beef, Mixed Grazing; Various Grazing; Lowland Mixed Grazing. Farms in each classification are assigned average stocking densities and land use composition for farms in that class, according to data from the Welsh Govenrment 2017 June Agricultural Survey to provide a comprehensive picture of grazing livestock farm practice in Wales for a "baseline" year (2017) against which the Brexit scenarios are compared. Using these baseline characteristics, the land area required to change farm type to accommodate grazing livestock animal numbers in response to each Brexit scenario can be determined. Changes are also modelled for pigs and poultry, but due to the nature of these enterprises land area requirements are not considered.

We predict the spatial patterns of land use change using capacity-based decision trees with clearly stated rules, developed in collaboration with Welsh Government, to ensure an understandable, acceptable approach which is easily communicated to policymakers and accounts for physical constraints to agriculture (Supplementary Section 3).

All changes in livestock are accounted for in each transition, for both the farm being replaced and the farm being created, on an area basis using the average livestock composition and stocking density of the farm types involved.

2.3. Opportunities for new land uses: woodland planting

For farms potentially changing to non-agricultural uses in a given Brexit scenario, there are opportunities for alternative uses. New woodland creation on this land was tested here, in line with Welsh national goals at the time, of planting 100,000 ha of new woodland (Warren-Thomas and Henderson, 2017). To do this, we modelled woodland planting up to this target as a final step in each scenario, planting trees on farms with more than 10 ha potentially available, selecting farms with the highest Agricultural Land Classification (ALC) first. Land availability was identified based on farms coming out of agricultural use under that scenario, and intermediate restrictions associated with the Glastir Woodland Creation Rules (GWC-Wales, 2018; full lists of these restrictions are provided in Supplementary Section 4).

2.4. Environmental impact models

Appropriate environmental indicator variables were chosen in consultation with stakeholders and end-users: agricultural GHG emissions (nitrous oxide and methane); air quality and human health (ammonia emissions as precursors to particulate matter); water quality (pollutant loads of nitrogen, phosphorous and sediment to water bodies); biodiversity (bird species abundance); and woodland GHG mitigation (GHG balance of woodland planting on land out of agriculture). Industry standard environmental impact models are used. The models are all well-tested and have been developed and applied at the national scale. We ensured that model input data and assumptions were consistent (except where different input variables were required) so that our results represent a cohesive scenario. More detailed descriptions of the models and their application here are provided in Supplementary Section 5.

Agricultural pollutants of nitrous oxide and methane emissions, ammonia emissions, and runoff of nitrate-nitrogen (N), phosphorus (P), and suspended sediments (SS) are modelled using Farmscoper (Farm Scale Optimisation of Pollutant Emission Reductions; Gooday et al. (2014)). These pollutants are modelled based on land use and management, using coefficients derived from more complex process based modelling. Farmscoper is applied at the field level across all of Wales using average management and stocking characteristics of the assigned farm type and size, and spatial data on climate and soils.

Changes in bird species abundance were modelled using bird models developed by the British Trust for Ornithology (BTO). These apply generalised linear models with Poisson error structures derived from modelled relationships between bird abundance (captured with the BTO/JNCC/RSPB Breeding Bird Survey (BBS)) and land use in 1 km squares. Results are presented for species listed as: Woodland ($n = 25$), Farmland ($n = 9$), Water and wetland ($n = 5$), other ($n = 15$).

The potential for GHG mitigation from new woodland is evaluated using the Forest Research model CARBINE (Forest Research, 2019), for five combinations of forest and management type, accounting for climatic zones, current land use, soil type, yield class, species and management. The Ecological Site Classification (ESC) model (Pyatt et al., 2001) is applied across Wales at a resolution of 250 m to identify the most productive species for each forest type and management type. These data are then extracted to land parcels mapped for new woodland planting under the relevant scenarios. The outputs from CARBINE include annual estimates of changes in carbon stocks (rates of carbon sequestration) in forest soils, litter, tree biomass and harvested wood products, and GHG emissions from management. These are summed to produce a value for net within-sector GHG mitigation benefit. Estimates of the potential for wood products to displace GHG-intensive non-wood materials and energy sources were also calculated. These GHG cross-sector mitigation benefits were outside of the scope of this study, and were therefore considered separately to the within-sector GHG balance, in order to maintain consistent system boundaries (since the GHGs associated with exporting agriculture cannot be included in the analysis). However, their inclusion here enables some consideration of what the cross-sector impacts might look like.

3. Results

3.1. Potential changes in the livestock systems in Wales

The net changes in agricultural land use and labour for each Grazing Livestock System under each Brexit scenario are shown in Table 1, and spatial patterns of farm type change mapped in Fig. 1. These changes are based on the projected changes in trade (Supplementary Section 1), modelled spatially using capacity-based decision trees (Supplementary Section 3).

The EU Deal only affected a small area of farmland (3%), with much larger areas affected under No Deal scenario (17%) and MFTA (15%). For all three scenarios, the sheep system makes up the majority of farmland with potential for changing to non-agricultural uses.

The EU Deal involves relatively small changes in animal numbers, with increases in dairy, pork and poultry and small declines in sheep and beef numbers. Land used for expansion of dairy led to reduced numbers of beef livestock, so it was necessary to model a small increase in beef farms in order to match projected livestock numbers.

The No Deal scenario has much greater increases in dairy, pork and poultry, a small increase in beef and a large decrease in sheep numbers. The MFTA scenario shows a decrease in animal numbers for all systems; projected reduction in sheep is the same as the No Deal scenario, but this scenario has no opportunity for converting to other (expanding) systems (see Supplementary Table S1).

The spatial distribution of potential new pork and poultry units (Supplementary Fig. S2) reflects the dependence of the systems on transport links for feed delivery, linkages to the meat system across the border in England, and access to specialised abattoirs and meat processing facilities.

3.2. Potential impacts on environmental quality and jobs

Potential changes in air pollution (ammonia) and national diffuse

Table 1
Potential changes in agricultural land use (or commercial units) and agricultural labour (as FTE) in each Livestock System in Wales as a result of the three Brexit scenarios, the total areas affected (ha), and the proportion each represents of baseline farmland of all types in Wales (1,686,733 ha).

	EU Deal		No Deal		MFTA	
Grazing Livestock Systems						
	Area, ha	FTE	Area, ha	FTE	Area, ha	FTE
Dairy	+15,674	+632	+86,786	+3499	−3939	−159
Beef	+3581	+53	+73,341	+1048	0	0
Sheep	−41,197	−1097	−204,012	−5432	−169,550	−4517
Grazers	−15,489	−412	−74,373	−1980	−85,803	−2284
	Area, ha (% of baseline farmland)		Area, ha (% of baseline farmland)		Area, ha (% of baseline farmland)	
Area changed to new system	19,348 (1.1%)		166,334 (9.9%)		0 (0%)	
Total area out of agricultural use	37,430 (2.2%)		118,258 (7.0%)		259,292 (15.4%)	
Area possible woodland planting (under intermediate restrictions)	7215 (0.4%)		31,171 (1.8%)		98,343 (5.8%)	
Total area affected by scenario	56,779 (3.4%)		284,592 (16.9%)		259,292 (15.4%)	
Commercial Pork and poultry Systems						
	Units	FTE	Units	FTE	Units	FTE
Pork	+ 8	+ 16	+ 28	+ 168	0	0
Poultry	+ 31	+ 116	+ 50	+ 190	−1	−4
Total	+ 39	+ 132	+ 78	+ 358	−1	−4
All Livestock Systems						
		FTE		FTE		FTE
Total		−692		−2507		−6963

pollution to waterbodies (N, P, SS) and agricultural GHG are shown in Fig. 2a,b,c,d,e. All scenarios led to predicted decrease in soil loss, agricultural GHG and jobs; other impacts varied in direction of change. Transitions between livestock systems have a mixed impact on agricultural pollution, whilst land coming out of agriculture reduces emissions. Changes are small for all pollutants in the EU Deal scenario, whereas the No Deal scenario produces large increases for some pollutants (NH_3 and N loads), and the MFTA scenario produces large declines of all pollutants. The changes in livestock numbers lead to reduced SS and agricultural GHG emissions for all three scenarios. Total potential agricultural labour requirement declines under all scenarios, although there are within system increases under the EU Deal and No Deal scenarios (Table 1, Fig. 2e,f).

Although the MFTA scenario affects a similar land area to No Deal, the contraction across all systems produces much greater reductions in environmental impacts of agriculture and a large loss of agricultural jobs across all livestock systems in Wales (Table 1, Fig. 2e,f).

To consider potential trade-offs and co-benefits of environmental and labour impacts for each Brexit scenario, these are plotted as percentage change from baseline (Fig. 2e). This illustrates that for the No Deal scenario, total agricultural ammonia emissions and N load are predicted to increase alongside losses of agricultural jobs.

There was significant spatial variation in the impacts of each scenario, as illustrated by the example for N load to waterbodies (Fig. 3). Baseline status is important, for example areas with high baseline N load in the south west may be more likely to suffer from water quality issues if loading increases, as predicted for these regions under EU Deal and No Deal scenarios. Spatial patterns of impacts are most important for outcomes where effects are felt locally e.g. jobs and air and water pollution (See Supplementary Section 5 for maps for other outcomes).

3.3. Potential opportunities for new woodland planting

In our simulations, 7215, 31,272 and 98,343 ha of woodland are planted in the EU deal, no deal and MFTA respectively (Table 1); only under the MFTA scenario is the 100,000 ha target close to being reached, due to restrictions on where woodland can be planted applied as per current schemes (see Supplementary Section 4). The additional benefit of new woodland planting could be significant, in spite of the relatively smaller area planted in our scenario (20–40% of land coming out of agricultural use).

A comparison of GHG mitigation from conifers managed under low impact silvicultural systems (LISS) with avoided agricultural GHG emissions across the Brexit scenarios (Fig. 4a) indicates that within-sector GHG mitigation from woodland is greater than avoided agricultural emissions for No Deal, but avoided emissions are higher for the other two scenarios. Modelled agricultural GHG mitigation for the EU deal and MFTA scenarios remain higher than woodland GHG mitigation even once cross-sector woodland GHG offsetting is considered, due largely to the smaller area modelled. It must be noted that these cross-sector GHG offsetting opportunities in construction and energy are not directly comparable to agricultural GHG savings modelled here.

Comparison of different woodland options shows that within-sector GHG mitigation in broadleaf woodlands managed with no thinning or felling is equivalent to conifers managed as LISS (Fig. 4b), with the latter having additional potential for cross-sector GHG mitigation. The remaining three planting options result in smaller within-sector GHG mitigation, whereas once cross-sector benefits are considered, conifers managed with thinning and felling perform better than broadleaf.

3.4. Potential biodiversity impacts on birds

Response is highly variable across the 54 bird species modelled, with increases in abundance for some species and decreases for others (Fig. 5). For farmland species, the range of change in species abundance is − 5% (MFTA) to + 31% (No Deal); for woodland species − 26% (MFTA) to + 13% (No Deal); for wetland and water species − 14% to + 70% (both No Deal); for other species − 12% to + 55% (both No Deal). Variation reflects the differing habitat needs of modelled species.

4. Discussion

There is a pressing need for rapid, adaptable modelling approaches to support policy development against a background of dynamic changes in environmental and political conditions. This study demonstrates how modelling the potential effects of post-Brexit trade agreements on agricultural and environmental systems in Wales, explicitly assuming no change in current policy and regulations, can identify agricultural systems and environmental outcomes that are most directly at initial risk from external change. Understanding the relationships between changes in trade and changes in employment and in environmental impacts of agriculture, will support planning of policy and regulations to mitigate environmental risks and to support communities.

This work has had significant impact nationally, providing evidence to Welsh and UK governments as to the potential scale of changes to agriculture, environment and jobs under the different Brexit deals. Welsh Government has used this work to influence the UK Government at the Ministerial Quadrilateral meeting (a meeting of the four UK

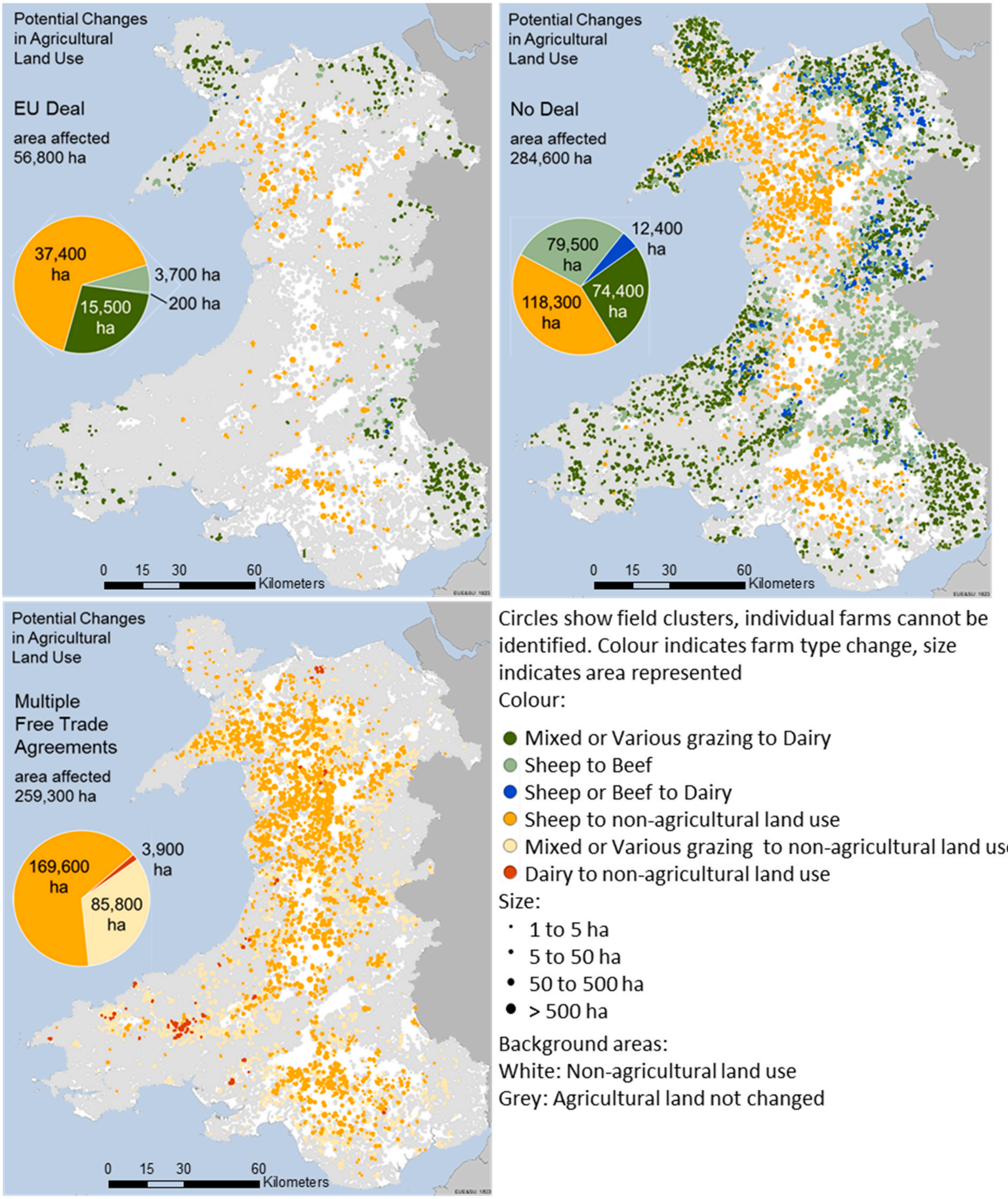

Fig. 1. Potential agricultural land use change in Wales for the three Brexit trade scenarios. Farms that have potential for land conversion and are geographically close to each other have been combined into circles proportional to their combined area, such that individual farms cannot be identified. Grey areas are agricultural land not changing under a scenario.

administrations, Ministers for Agriculture and Environment). The evidence Wales was able to present helped persuade the Defra Minister at the time to lobby the Department for International Trade for some tariff protection for UK agriculture.

4.1. Scenarios of agricultural sector changes

The Welsh sheep sector is most at risk, with issues around carcass balance and seasonality of markets and production. Projected contractions would be highly detrimental to rural livelihoods and culture. The Welsh dairy and beef systems are less vulnerable as the UK is a net importer of dairy and red meat products, and trade restrictions on imports could provide opportunities for expansion in Wales. Conversely, increase in imports from countries with lower production costs could reduce the domestic market for UK products. Whilst this hierarchy of sectoral risk is consistent across the scenarios, there was a large variation in the scale of predicted change between scenarios (e.g. from 2% to 15% of land area coming out of agricultural use), which highlights the

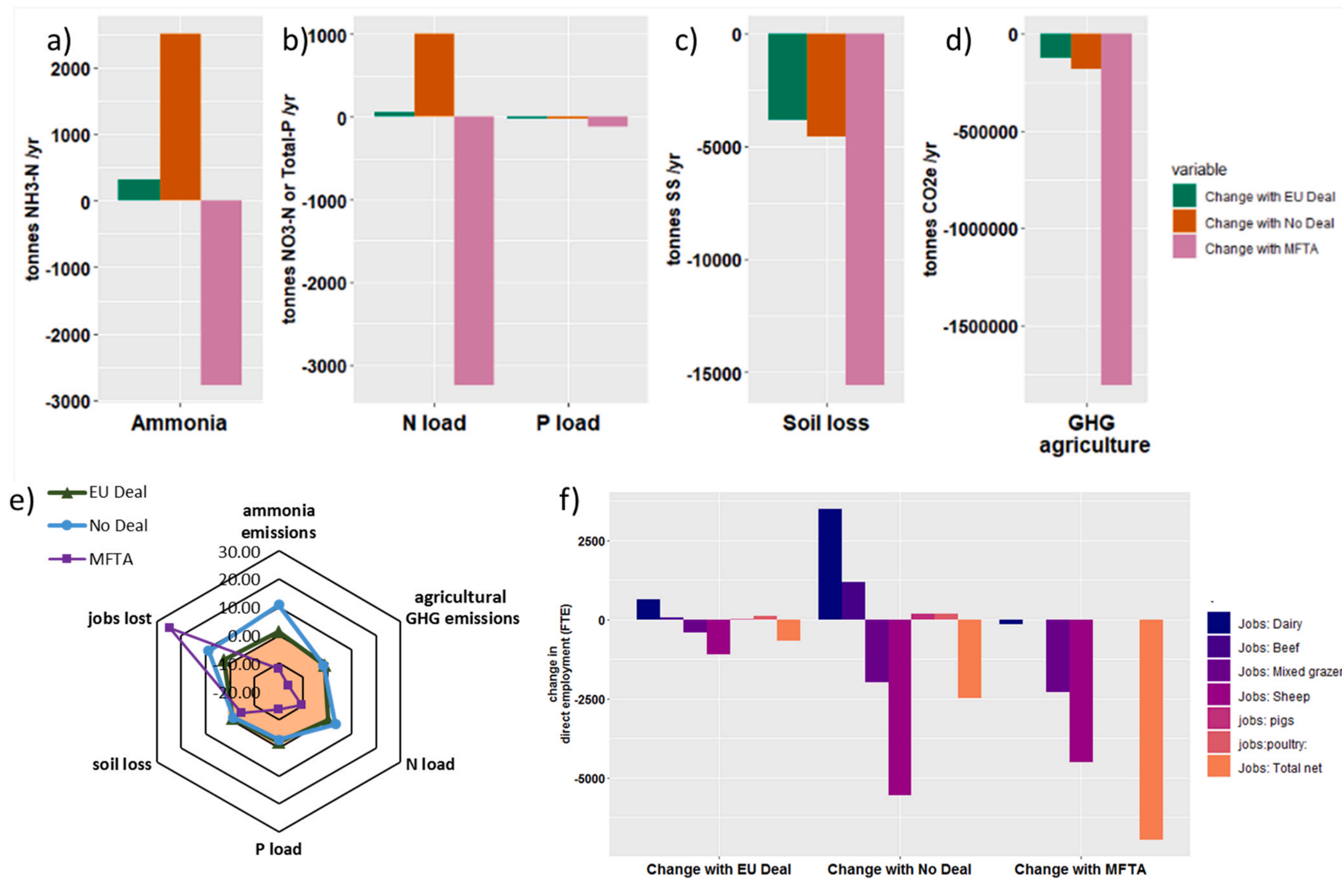

Fig. 2. National impacts of potential agricultural land use change in Wales resulting from each of the three Brexit scenarios on: air quality (Ammonia: agricultural ammonia emissions); water quality (N load- runoff of nitrate nitrogen (N); P load- total phosphorous (P) from fertilizer, and soil loss- as suspended sediment (SS) from farm activities); GHG agriculture- emissions (nitrous oxide and methane) from animals, fertilizer and soil; direct agricultural employment- as full time employees (FTE). Fig. 2a-d) show physical units. Fig. 2e) shows data expressed as percentages of baseline (2017) values. Values inside the central shaded area represent positive outcomes (environmental improvement or job increases); values in the outer white area indicate negative outcome. Fig. 2f) shows changes in jobs as FTE, with a breakdown by farm type.

importance of the final trade deal. The modelled trajectories for the agricultural systems correspond with the evidence used to develop the scenarios, and are broadly in line with other projections (e.g. van Berkum et al., 2016; Bradley and Hill, 2017; Hubbard et al., 2018).

Explicit spatial modelling of outcomes enables us to confirm that current agricultural capacity in Wales can support the potential livestock sector expansions in the Brexit scenarios. The approach gives improved understanding of potential changes, by representing transitions between systems alongside sector contraction. For example, we showed that, due to other transitions, the creation of new beef farms was predicted for the EU Deal in spite of the small decrease in beef livestock.

Work elsewhere using very different methodologies supports the spatial patterns modelled here for land coming out of agriculture. For example, Manzoor et al. (2021) predict a similar pattern of upland land abandonment and loss of sheep farming under similar economic scenarios, based on spatial patterns of past trajectories of land use change in Wales. Similarly, using famer studies and past trajectories in Europe, Arnott et al. (2019) suggest that upland sheep and cattle farming on poor quality land will be most susceptible to land abandonment due to reduced subsidies.

4.2. Predicted changes in jobs and environmental quality

As well as highlighting the scale of risk to agricultural jobs in Wales following Brexit, our findings illustrate the potential for large gains in jobs from transitions between systems even as total agricultural jobs decline, and the need to account for all sectoral transitions to understand these.

Variation in environmental impacts between systems and scenarios enables some broad generalisations, which should help to anticipate the impacts of the finalised Brexit deal, and provide transferable insights. For example, expansion of dairy (and potentially beef) is likely to increase ammonia; but reducing sheep whilst increasing these may still lead to net improvement for some impacts, particularly phosphorus, sediment and GHG emissions.

The large range shown in Fig. 2 for each outcome illustrates the uncertainty associated with not knowing the finalised Brexit deal, and highlights the challenges of preparing for the impacts of dramatic change, under political uncertainty.

4.3. Importance of spatial patterns of change for progress towards SDG

Because net change at the national scale does not always reflect local trends, examining spatial patterns can identify regions with potential for serious local problems. Understanding and anticipating spatial patterns helps governments to plan where social support or environmental protections such as an enhanced regulatory floor may be needed.

Small net change in agricultural jobs may mask large shifts in job opportunities between regions or agricultural systems. Fig. 2f shows that most jobs were lost in sheep farming with most new jobs created in dairy, whilst Supplementary Fig. S5 shows most losses predicted in north western and central parts of Wales. The jobs in new livestock systems may not be accessible to those currently employed in the old sector due to lack of expertise or interest, or proximity to the newly created jobs.

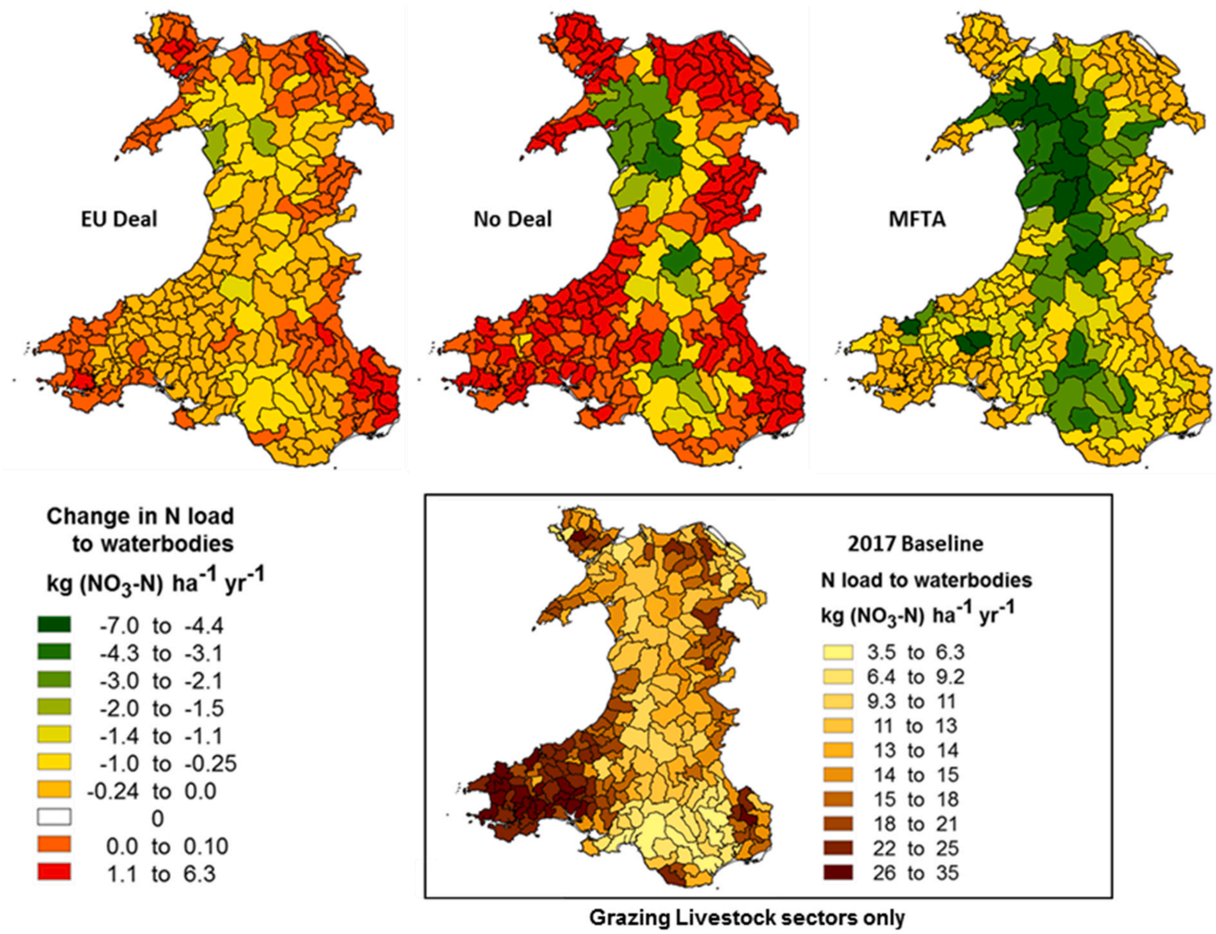

Fig. 3. Spatial patterns of potential changes in agricultural N load to waterbodies for the Brexit scenarios. Changes are relative to 2017 baseline values (inset). Mapped results from individual farm fields are aggregated to the Welsh Agricultural Small Areas, each of which contains 100–200 farms, such that individual farms cannot be identified. Loadings are expressed as annual values per ha for each Agricultural Small Area.

This could result in larger potential national losses in farm labour if the re-located jobs cannot be filled. Spatial data can be compared with maps of other socio-economic indicators revealing potential conflicts or unexpected socio-economic opportunities, increasing the value of modelling outputs to policy planning. This is important for SDG 10, to "Reduce inequality within (and among) countries".

Similarly, relatively minor net environmental changes at the national scale may mask local exceedance of regulatory thresholds. For example, a risk of deterioration in water quality status is modelled for 51 waterbodies under the No Deal scenario, violating commitments to the Water Framework Directive, even though the net national change is small. Fig. 3 shows that loading of N is already highest in the south western parts of Wales, and these were predicted larger increases in N under EU Deal and No Deal. Similarly for P, increases under no deal occur primarily in parts of the country with high baseline load, see Fig. S4. This has implications for SDG 15, which includes objectives to conserve and restore inland freshwater ecosystems and their services. Spatial outputs thus provide evidence of where interventions may need to be targeted to avoid exceedance of regulatory thresholds.

Increases in ammonia emissions under the EU Deal and No Deal scenarios are more severe in some areas with high baseline ammonia emissions. This has implications for human health (as important precursors for formation of particulates e.g. PM2.5) and progress towards SDG 3 "Ensure healthy lives and promote well-being for all at all ages". There are also implications for eutrophication, particularly in Special Areas of Conservation, which in wales largely (92%) already exceed the recommended atmospheric ammonia concentrations (Hallsworth et al., 2010). This relates to SDG 15, which includes objectives to protect terrestrial ecosystems and halt biodiversity loss. By predicting patterns of risk, our findings can help to spatially target environmental protections and mitigation measures to improve agricultural practice and thus support progress towards these and other SDG.

4.4. Integrated assessment of impacts

Loss of agricultural jobs might always be expected to correlate with reduced agricultural pollution. However our analysis reveals that shifts between livestock systems, in particular expansion of dairy combined with larger contractions for sheep, can lead to increases for some pollutants alongside job losses. This was seen nationally in the No Deal scenario and regionally in the EU Deal and No Deal scenarios (See Supplementary for regional summaries across Wales).

Deconstructing cross-indicator responses to the scenarios can also identify options for post-Brexit natural resource management. For example these findings suggest that per hectare planted the GHG benefits of woodland may be greater than GHG mitigation of avoided agricultural emissions, but suitability of land may limit realisation of this potential. This highlights the opportunity for policy interventions to improve outcomes from the Brexit scenarios; if suitable incentives could be developed for woodland planting on agricultural land, this could drive the spatial pattern of agricultural system contraction to maximise area of new woodland. Such comparisons of benefits are often lacking in the early stages of policy planning.

There is further complexity in the comparison, since avoided

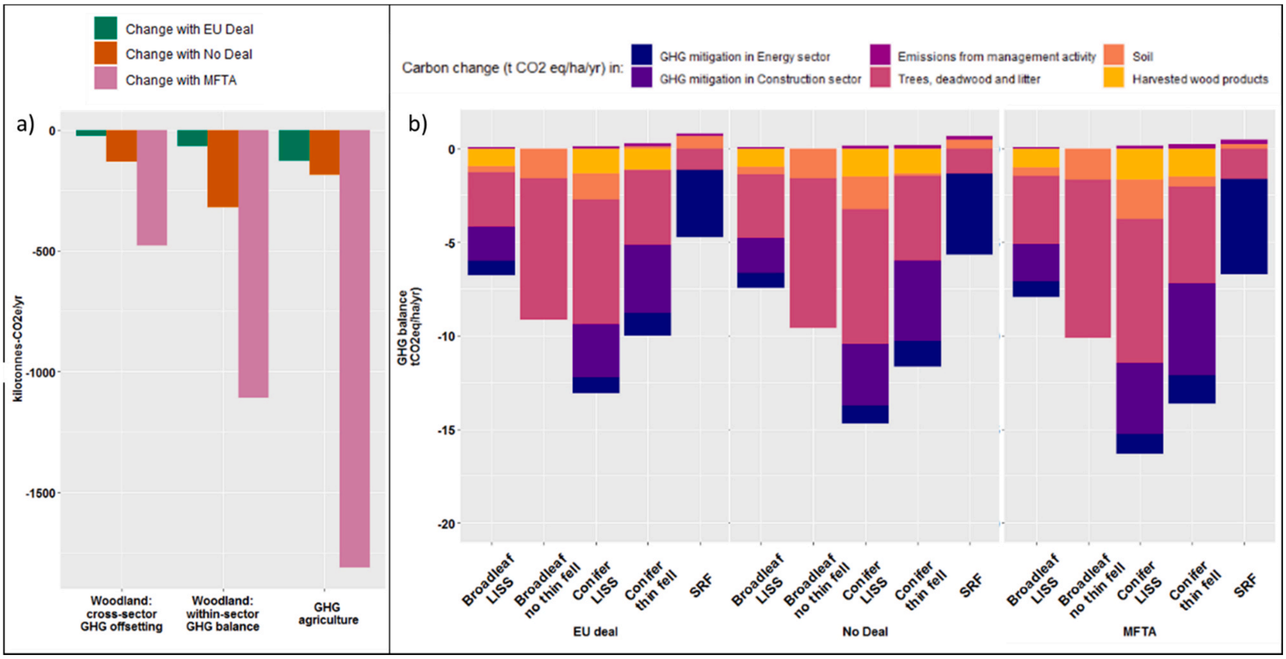

Fig. 4. Modelled GHG mitigation from woodland planting on farms coming out of agriculture, with over 10 ha satisfying intermediate GWC restrictions (See supplementary Section 4), planted up to the 100 Kha target. This creates approx. potential new woodland areas of: EU deal 7 Kha; No deal 31 Kha; MFTA98 Kha. a) Comparison of potential avoided agricultural GHG emissions and potential woodland GHG mitigation from conifers with low impact silviculture systems for the three Brexit scenarios. b) Variation in GHG mitigation for woodland type and management option. Data are shown for within-sector GHG balance (emissions from management activity, change in carbon in trees deadwood and litter, soils and harvested wood products) and cross-sector GHG offsetting (GHG mitigation in energy and construction sectors). Note that to maintain consistent system boundaries, the cross-sector impacts of woodland should not be compared directly to the agricultural GHG balance, but are shown here only to allow consideration of how they may affect the overall picture.

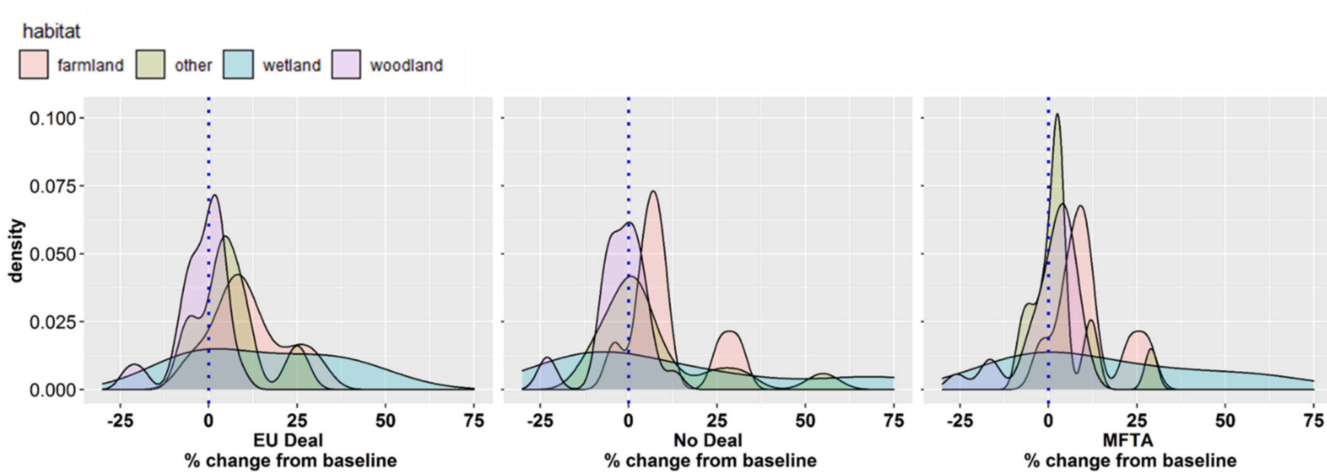

Fig. 5. Density plots to show potential change in abundance of bird species. Where "density" is the proportion of species with a given % change in abundance between baseline and the scenario indicated. Plots show the distribution of change in abundance for different species, with species split by habitat type to assess whether birds exploiting different habitat types may be affected differently.

livestock GHG emissions can be immediately realized, whereas woodland GHG mitigation rates are slower and depend on cumulative woodland growth (for simplicity values shown here are averaged over 100 years). Our system boundaries do not capture the whole picture, since the cross-sector GHG impacts of woodland are likely to be beneficial (avoided emissions from energy and construction) whereas externalities from agricultural contraction may be detrimental (exporting production may increase emissions elsewhere).

Avoided environmental impacts of agriculture may be exported, since these scenarios are driven by changes in trade and not dietary change affecting global demand. Exported impacts might be more or less severe in other locations depending on land management practices, soils climate, existing habitats and biodiversity (e.g. cutting rain forests for animal grazing). In general, agriculture in the tropics can have three times the carbon emissions for the same amount of production (West et al., 2010).

Exporting lamb production from Wales may increase global GHG emissions, since a review found median Global Warming Potential (GWP) of 24 kg CO2e/kg bone free meat for the UK, 33 elsewhere in the EU, and a global average of 26. Conversely, UK beef production has a GWP of 27, comparable to their reported world average (27) and higher than elsewhere in the EU (25) (Clune et al., 2017). (Note that this study found considerable variation around these median figures, depending on study assumptions and methods). Export of environmental degradation would undermine apparent progress towards SDG 13 “Take urgent action to combat climate change and its impact”, and is a violation of Wales’ Well-being of Future Generations Act (Welsh Government, 2015). Our analysis makes no accounting of potential global impacts of changes outside of Wales.

4.5. New woodlands

The ambition for large areas of woodland planting in Wales, with a focus on carbon sequestration to help achieve net zero CO_2 emissions targets (across all sectors of the economy, see: (Committee on Climate Change, 2019)), must be balanced against the land use loss to other systems (including agriculture), the risks to sensitive habitats or species and potential disturbance of cultural features in the landscape (see GWC restrictions, Supplementary Section 4). Restricting the area available for woodland planting by physical constraints, and sensitivities as applied in the Glastir Woodland Creation scheme e.g. peat soils and designated land had a large impact on potential woodland creation here. The area of woodland planted could be increased (up to 71% of land) if Sensitivities were ignored or may be restricted by further Guidance restrictions down to 5% (see Supplementary Section 4). The implications for balancing climate mitigation with environmental sensitivities is significant.

Potential GHG benefit for new woodland also varied significantly between woodland types and management systems. Modelled within-sector benefits can be ranked, in descending order: 1) conifers with low impact silviculture systems (LISS); 2) native broadleaf with no thinning or felling; 3) conifers with thinning and clear felling; 4) native broadleaf with LISS; and 5) short rotation forestry. If cross-sector mitigation were accounted for, conifers with thinning and clear felling have greater GHG benefits than native broadleaf with no thinning or felling. These rankings may not apply at individual sites because local variations in growing conditions favour different forest types or management systems. The highest national GHG benefits may be achieved by differential planting strategies optimizing for local conditions. It is worth noting that the biodiversity benefits of these woodland types would not follow the same hierarchy, hence the relative importance of these issues must be considered in decision-making. This illustrates how targeting improvements in multiple, sometimes conflicting, objectives inevitably leads to trade offs (Kuhmonen, 2018; Liu et al., 2018), since even planting and managing woodland may have conflicts between climate benefits under SDG 13, biodiversity benefits under SDG 15 and the need for food production under SDG 2 (zero hunger).

4.6. Biodiversity

Agricultural land use change, removal of land from agricultural use and new woodland planting all affect the biodiversity of Welsh landscape in multiple ways and at multiple taxonomic levels. All land-use changes are likely to benefit some species and to have negative effects on others. It is a limitation of the study that here, biodiversity impacts are considered via just a single group of organisms. However, birds are commonly used as biodiversity indicators because they are high in their food chain (so should be sensitive to gross changes in other elements of biodiversity at lower trophic levels) and are known to be sensitive to landscape changes in agricultural areas. Farmland birds are a main metric of the EU’s Common Monitoring and Evaluation Framework (CMEF; Butler et al., 2010) for European Rural Development Programs.

For birds, the variable impact of scenarios on species abundance is due to the range of species considered, which utilise different habitat types, and thus responded according to specific habitat increases or decreases. For countries like the UK, where much of biodiversity is well-adapted to agricultural systems, this will include some negative responses to land being taken out of agricultural production. Thus there are likely to be winners and losers in any scenario, which highlights the complexity of work towards SDG, by identifying conflicts within SDG 15 objectives to halt biodiversity loss. SDG 15.5 refers to protection for threatened species, and points to the need for explicit consideration of specific species of interest (due to e.g. Red List status), alongside biodiversity in the round assessments. Unsurprisingly, the response was also mixed for these important species; three red-listed farmland species and three or four red-listed generalist species increased in abundance under all scenarios. Conversely, three red-listed woodland species were predicted to decline under EU deal and no deal, and two red-listed woodland species and one red-listed generalist were predicted to decline under the MFTA.

4.7. Rapid adaptive modelling for policy support

Compromises are often necessary in policy applications, where the idealised application of complex models and science is often limited by the chaotic nature of policy development (Adelle et al., 2012). Integration across disciplines is infrequent in modelling for policy assessment; a recent review found the vast majority of studies assess economic indicators, 72% assess environmental indicators (of which few account for a diverse range of indicators), and only 37% assess social indicators (Reidsma et al., 2018). Whilst the benefits of fully integrated modelling, e.g. to account for feedbacks and interdependencies between drivers and outcomes (Harrison et al., 2016) have previously been shown, the development of these creates long lead in times, and political realities here required a rapid response to frame major opportunities and risks.

Rapid, adaptive modelling using more informal model linkages, as demonstrated here, can provide timely input to policy, accounting for a diverse range of outcomes. However, it is crucial to follow appropriate guidelines to support appropriate use. Here we follow the UK government’s “Guidance on Producing Quality Analysis for Government” (Treasury, 2015), which requires transparency of assumptions and limitations to facilitate interpretation of outcomes. The evidence chain and documentation should make it clear which outputs may be affected by any inaccuracies in these assumptions. Since time constraints prevented modelling of uncertainty and sensitivity for the individual scenarios, communication of these assumptions was crucial to ensure appropriate interpretation of findings.

It is a central aspect of the work that the speed of modelling required for policy discussions did not allow for uncertainty or sensitivity analysis around the assumptions driving the pattern of land use change and impact models. Whilst the scope for concern around singular interpretation of modelling outputs has been clearly illustrated by recent public health modelling (e.g. Begley, 2020), the level of confidence in modelling outputs need only be sufficient to justify the decisions which it is used to support. Furthermore, the largest unknown in this instance was the Brexit trade deal itself; relative to the scale of the variation in outcomes between the scenarios, the uncertainty within each scenario is unlikely to be significant in policy terms. Critically, the scenario modelling here provides an estimate of the how the magnitude and direction of impacts could vary depending on the deal, with enough confidence to inform Welsh Government that a) the final deal will have ramifications for agriculture and the environment and b) protections may be needed for both to mitigate risk. Although we cannot expect to predict transitions at farm level accurately, given the range of physical, economic and social factors at play, the overall pattern of simulated farm transitions is in line with expectations from work elsewhere (Arnott et al., 2019; Manzoor et al., 2021). This provides a sufficient level of confidence with which to state that the impacts would be spatially variable, with greater contraction of agriculture likely in the uplands, and with some trade deals risking increased agricultural pollution in areas already more intensively farmed. The confidence in these predictions is sufficient to warrant exploration of policy options to support agriculture and rural communities through the transition, and to mitigate environmental risks. Further modelling and a range of other evidence sources will support this process.

Frequent communication with Welsh Government, stakeholders and end users throughout this project resulted in confidence in, and acceptance of, the findings at a time when prolonged debate about assumptions and outcomes could delay critical planning and decision making. Stakeholder confidence is important to governments when using outcomes of modelling to support policy planning and development. Modelling outputs must also be used alongside other sources of evidence, to reduce the risk of impacts from uncertainty, and ensure that decision makers have access to a range of information.

The planned shift of UK agricultural policy towards more sustainable land management for delivery of 'public goods for public money' (Defra, 2018; Welsh Government, 2018b, 2019) could support progress towards SDG. However, the public goods trade-offs identified here (e.g. around woodland planting) illustrate the complexity of thinking required to target progress on all SDG simultaneously, given the need to achieve all goals, which is central to the SDG agenda (Mann et al., 2018). It has been noted (e.g. Arnott et al., 2019) that the funding required to meet this challenge would be significant, and there is now a need to prioritise public goods alongside funding new economic challenges introduced by the Covid 19 pandemic. Additionally, the social and legal implications of moving from a system of area-based payments to a spatially targeted approach must be considered (Reed et al., 2014).

5. Conclusions

By working collaboratively, and linking existing tools, the approach was able to provide useful input in a timely manner to support policy and planning towards multiple SDG objectives, in an environment of rapid change. The large variation between scenarios in impacts on agricultural systems, environmental outcomes and jobs, highlights the importance of trade negotiations.

Agricultural changes can produce net loss of jobs and increase in pollution simultaneously, at regional and national levels. It is crucial to consider spatial variation in likely impacts of change where effects are felt locally (e.g. jobs and air and water pollution), and how these interact with exiting patterns of environmental condition and social prosperity. To support planning, the spatial patterns can be used to identify where the regulatory floor may need to be enhanced, due to risk of increases in agricultural emissions in already polluted areas, and where social safety nets may be required, due to risk of agricultural job losses.

Displaced agriculture is not accounted for here, but may be expected to have worse implications for GHG and biodiversity (West et al., 2010; Searchinger et al., 2018). Any positive environmental outcomes for Wales must be considered alongside this risk.

The findings of this study can thus support Welsh government in developing programmes to manage the Brexit transition proactively, and to develop policy options for re-targeting rural funding and tailoring environmental legislation to Welsh objectives, creating improvements for multiple outcomes for securing the future of Welsh farming, and supporting Wales' commitment to SDG.

CRediT authorship contribution statement

Amy Thomas: Writing – original draft, Writing – review & editing, Methodology, Software, Formal analysis, Visualization. **Jack Cosby:** Conceptualization, Formal analysis, Writing – review & editing. **Richard Gooday:** Software, Formal analysis, Writing – review & editing. **Hester Lyons:** Formal analysis. **Gavin Siriwardena:** Software, Formal analysis, Writing – review & editing. **Esther Kettel:** Formal analysis. **Robert Matthews:** Software, Formal analysis, Writing – review & editing. **Kate Beauchamp:** Software, Formal analysis, Writing – review & editing. **Michal Petr:** Software, Formal analysis. **Bridget Emmett:** Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2021.08.009.

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