Exploring Fodder Availability for Beef and Dairy Farming in the light of Future Change

Simon Willcock
Scotland's Rural College (SRUC)

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Abstract

Scotland, while rich in natural resources, is sensitive to the impacts of future change. To ensure the resilience of Scotland's ecosystems, we need all sectors of society to contribute to the protection of ecosystem services for multiple benefits. Here, we focus on identifying and understanding multiple benefits and trade-offs surrounding the Scottish beef and dairy industries, placing specific emphasis on how can we identify resilience to future climatic and dietary changes up to the year 2050. We produced a holistic framework characterising the dairy and beef farming systems, as well as identifying the key fodder and feed inputs. To determine the resilience of these inputs, we ran the CLIMSAVE model for Scotland (http://www.climsave.eu/iap). Our results show that most crops associated with the beef and dairy industry will likely increase in total production due to both increases in yield and crop area as a result of climate change. Socio-economic variables (e.g. demand for beef) seem to have much less impact on the model results. Finally, we highlight trade-offs and synergies with other ecosystem services. Whilst we can expect the win-win of increases in food production and biodiversity, notable trade-offs are anticipated, including decreases in stored carbon and timber production, as well as increases in the amounts of pesticides, fertilisers and nitrate leaching. Decision-making to maximise future resilience will be most effective given full knowledge of the ecosystem service benefits and dis-benefits derived from the beef and dairy systems.

Introduction

Society derives many benefits or ecosystem services from the natural environment (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2011). However, socio-economic and climatic pressures are negatively impacting the state of these natural resources and thus the benefits derived by society at sub-national, national and global scales (Holman et al. 2008; Harrison et al. 2013; Rounsevell et al. 2006) and so many of these services are known to be in decline (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2011). Debate surrounds the relative importance of future drivers of change (i.e. climate change vs. socio-economic change (Holman et al. 2005; Rounsevell & Reay 2009)), partly as a result of numerous compounding and interacting factors that link different sectors. Managing ecosystems to avoid exceeding planetary boundaries will inevitably involve trade-offs and synergies between different ecosystem services and sectors. Maximising one benefit (e.g. provision of food) may be traded-off against another (e.g. carbon storage), resulting in potential conflict due to competing demands and pressures. These trade-offs may be exacerbated by future change (i.e. climate change). Thus, decision-making will be most effective given full knowledge of the ecosystem service benefits derived from a system.

The value of ecosystem service information depends increasingly on our ability to link it in a coherent way to other pieces of information (e.g. economic, social) so as to enhance its value and support holistic, evidence-based decision-making. This need is strongly felt in empirical science but also public and private bodies. The challenge in meeting this need is that information (data) is produced within different communities each with their own point of view and technical knowledge, following different data lifecycles, and usually heavily oriented to the purposes for which they were produced (e.g. farm-scale data produced by farm managers may not be available to support landscape-scale decision-making by local authorities). Fulfilling societal demand for multiple benefits from land requires a change from the previous focus on single assets as failing to take a holistic approach could possibly result in erroneous policy recommendations (Skourtos et al. 2015).

Scotland is rich in natural resources and associated ecosystem services, but potentially sensitive to the impacts of future change. For example, much of the agriculture and biodiversity within the country is located at the margins of their climate suitability (Brown et al. 2011; Trivedi et al. 2008). The Scottish Government's Economic Strategy highlights the importance of investing in natural capital to deliver opportunities for all, but whilst Scotland has plentiful natural resources, we are exceeding planetary limits for some. Scotland's ecological footprint has been calculated to be 5.4 ha capita^{-1}, more than twice the equitable global distribution (Chambers et al. 2004). As such, Scotland is having a disproportionately large negative impact on GHG emissions, nitrogen and phosphorus flows in the landscape and ocean, contribution to ozone depletion, and air pollution (Sayers et al. 2014). Moreover, in a recent analysis of the 'Scottish doughnut', large inequalities in wealth distribution also meant that several social indicators, such as unemployment, fuel poverty, and food unaffordability, scored low, despite average wealth being relatively high (Sayers et al. 2014).

Adaptation represents an important opportunity for Scotland to reduce the adverse impacts and to exploit the beneficial opportunities to the advantage of Scottish society (Scottish Government 2009). The challenge is to ensure that Scotland continues to be a prosperous country, but with more equitable distribution of this prosperity, and that its natural assets are enhanced rather than degraded (Jackson 2009). Within RESAS Theme 1 we have identified that, to reach a situation where Scotland's natural assets are enhanced, we need all sectors of society to contribute to the protection of ecosystem services for multiple benefits. This led to the formulation of four research questions:

- RQ1. How do Scotland's natural assets function, how healthy are they, what are their trends, and what are 'safe' limits to their sustainable use?
- RQ2. How resilient are Scotland's natural assets to climate change and other risks (invasive non-native species, pollution, etc.), and what are the key interventions to make them more resilient or to protect them from further harm?
- RQ3. What are the key ecosystem benefits we derive from Scotland's natural assets, how are they distributed, how are they related to one another, are our natural assets declining as socio-economic capital increases, and how do we manage trade-offs between them?
- RQ4. How can we improve the management of our natural assets to support sustainable land-based industries and vibrant communities, how can we improve existing instruments, and what other instruments could be applied to support social and economic entitlements and a just distribution of outcomes? Did literature review to create conceptual framework of the supply chain.

This research focuses on identifying and understanding multiple benefits and trade-offs (RQ3), placing specific emphasis on how can we identify resilient interventions for multiple benefits (RQ2). Under RD 1.4.2, we outlined three objectives:

- Objective 1.4.2a: Identification of gaps in the current delivery of multiple benefits.
- Objective 1.4.2b Identification of opportunities to increase multiple benefits through new and existing delivery mechanisms.
- Objective 1.4.2c Option appraisals to demonstrate resilience of natural assets under different trajectories.

We will address these objectives for beef and dairy farming systems within Scotland, considering climate change as well as socio-economic changes.

Within these objectives, this report uses the CLIMSAV model explore the impact of climate and dietary scenarios on the production of crops that contribute feed and fodder to beef and dairy industries. Findings are intended to be explorative in nature and provide a first basis for discussion on the future availability of crucial inputs into beef and dairy production.

The report also provides a conceptualisation of the beef supply chain, describing linkages between individual elements and makes proposals for operationalizing parts of the chain within existing model frameworks.

Method

Both dairy and beef farming systems have been characterised into numerous frameworks, focussing on different aspects of the Agrifood sector - from producers to consumers. For example, the livestock industry in Scotland has been characterised at least three times recently, focussing separately on food and drink production, carbon emissions and disease transmission (Scottish Government 2008; Thomson 2008; Sheane et al. 2011). However, to identify resilient interventions for multiple benefits, it is necessary to integrate existing systems frameworks of the farming system to produce a holistic framework capable of capturing multiple ecosystem services. First, we undertook a systematic literature review to produce a holistic framework for the Scottish beef and dairy farming system, enabling multiple aspects of the natural capital to be modelled under a variety of scenarios.

It is then necessary to 'set the scene' in which this framework can occur. Fodder availability is a major input into the Scottish beef and dairy farming system; thus, we evaluated potential changes in fodder availability under future change (e.g. climate change) using the freely available CLIMSAVE Integrated Assessment Platform (IAP) that integrates participatory scenario development and quantitative modelling (http://www.climsave.eu/iap (Holman et al. 2016)). The CLIMSAVE IAP is an interactive, exploratory web-based modelling tool to enable stakeholders to improve their understanding of impacts, adaptation responses and vulnerability under uncertain futures. Two versions of the CLIMSAVE IAP are available: one for Europe and one for Scotland (see Holman et al. (2013) for further information). This report utilises the Scottish version and so sets a holistic scope covering multiple land uses, including:

- Urban: the Regional Urban Growth (RUG) meta-model consists of a look-up table of artificial surfaces per grid cell derived from running the original RUG model with all possible combinations of platform input values.
- Forest: MetaGOTILWA+ is an artificial neural network (ANNs) that emulates the performance of the GOTILWA+ model.
- Flooding: the Coastal Fluvial Flood (CFFlood) meta-model is a simplified process-based model that identifies the area at risk of flooding based on topography, relative sea-level rise or change in peak river flow and the estimated Standard of Protection of flood defences. Flood damages for residential properties (both contents and structure) are calculated based on urban areas and people at risk of flooding, flood water depths and gross domestic product.
- Water: the WaterGAP meta-model (WGMM) uses look-up tables of 3D response surfaces to reproduce the outputs of the WaterGAP3 model run at a 5′ × 5′ resolution for about 100 spatial units (single large river basins or clusters of smaller, neighbouring river basins with similar hydro-geographic properties) larger than 10,000 km2.
- Crops: the crop yield meta-models use ANNs, trained on simulated outputs of the ROIMPEL model, combined with temperature thresholds to prevent crops growing in unsuitable territories.
- Rural land allocation: the SFARMOD meta-model uses a series of regression equations to simulate the behaviour of the full SFARMOD-LP model, using SFARMOD-LP outputs from 20,000 randomly selected sets of input data that fully cover the parameter input space. Up to 10 iterations based on profitability and food demand determine the final land allocation and food production.
- Biodiversity: SPECIES uses an ensemble of ANNs, utilising climate and soil moisture variables, to characterise bioclimatic suitability envelopes.

All meta-models have previously been satisfactorily validated (see Holman and Harrison (2011) for the full details of each model and its validation). A simplified flow diagram of the linkages between the models is shown in Figure 1.

We ran the models at a resolution of 5 km × 5 km to ensure consistency with climate data. The climate data used was the United Kingdom Climate Projections or UKCP09 scenarios as these provide the greatest spatial and temporal detail for Scotland (Murphy et al. 2009). They are probabilistic projections for three SRES emissions scenarios (A1FI—high emissions, A1b—medium and B1—low) based on ensembles of climate model projections consisting of multiple variants of the UK Met Office climate model, as well as climate models from other centres. Thus, we modelled the impact of each scenario (low, medium and high emissions) for the year 2050, comparing this to a socio-economic shift in the preference for beef and lamb by maintaining present day demand, but also increasing or decreasing this demand by 50%.

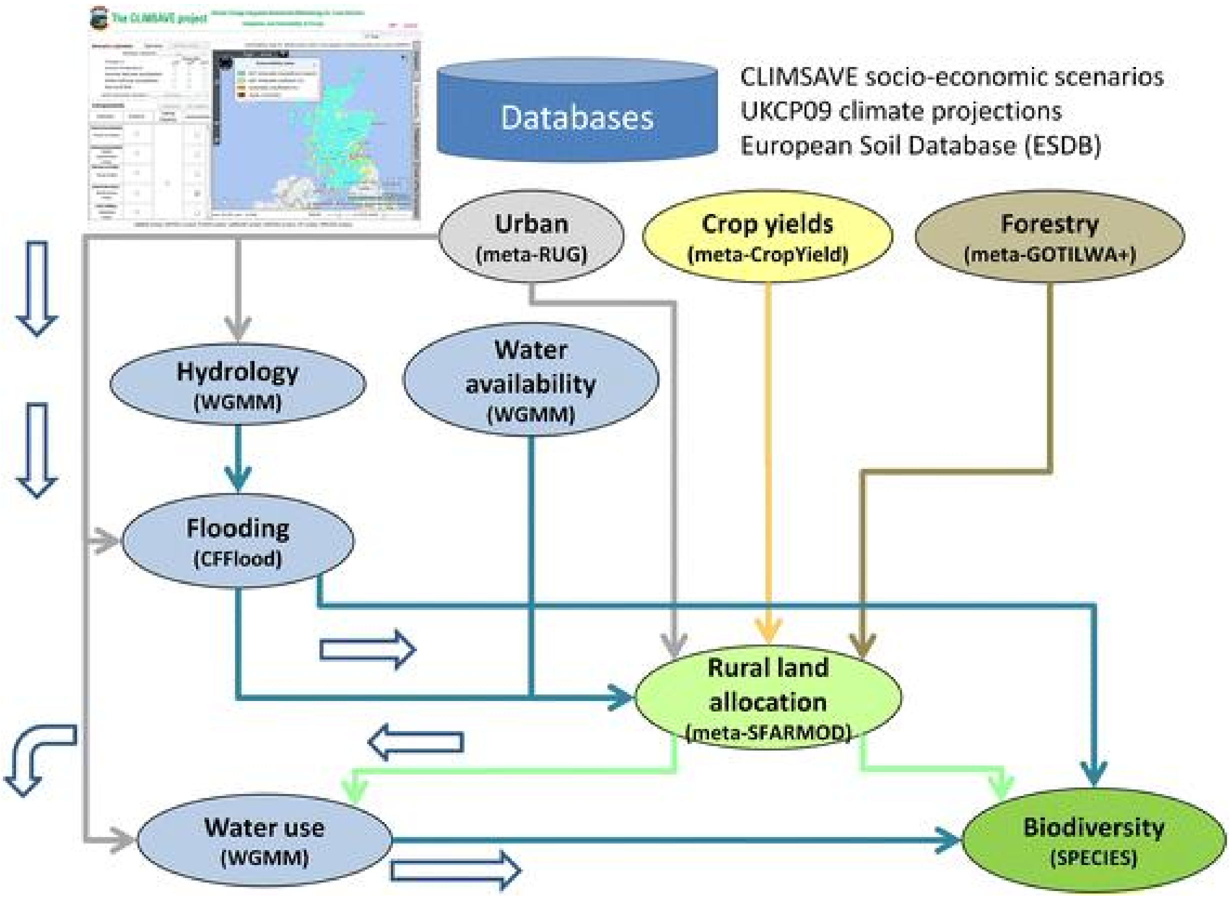

Figure 1 – A diagrammatic representation of the CLIMSAVE model (Holman et al. 2016)

Outputs were produced for both sector-based impact indicators and ecosystem services (covering a range of provisioning, regulating and cultural services) in order to link climate change impacts to human well-being. For this report, a subset of 9 indictors covering the range of sectors and important ecosystem functions and services have been analysed for the whole of Scotland:

- Agricultural production – the yield per hectare, total farmed area and total production of crops known to input into beef and dairy value chains. The crops to be investigated were determined via systematic literature review.
- Potential carbon stock – the aboveground carbon stored within each grid cell (t ha^{-1}).
- Potential Soil Organic Matter – the organic matter held within the soil within each grid cell (t ha^{-1}), providing an indicator of soil fertility.
- Timber Production – the timber production within each grid cell (t ha^{-1}).
- Irrigation usage – the amount of irrigation water required within each grid cell (million m^3).
- Fertiliser usage – the amount of fertiliser required within each grid cell (kgN ha^{-1}).
- Pesticide usage – the number of pesticide doses required within each grid cell (ha^{-1}).
- Nitrate loses – the amount of nitrate leaching from each grid cell (kgN ha^{-1}).
- Shannon Biodiversity Index – a measure of the species richness within each grid cell.

Results

Our systematic review of the literature resulted in production of a framework for describing beef and dairy life stock value chains (Figure 2). Further review of the literature identified that the crop inputs into our framework were dominated by wheat, barley, potatoes, maize and grass, and so these crops

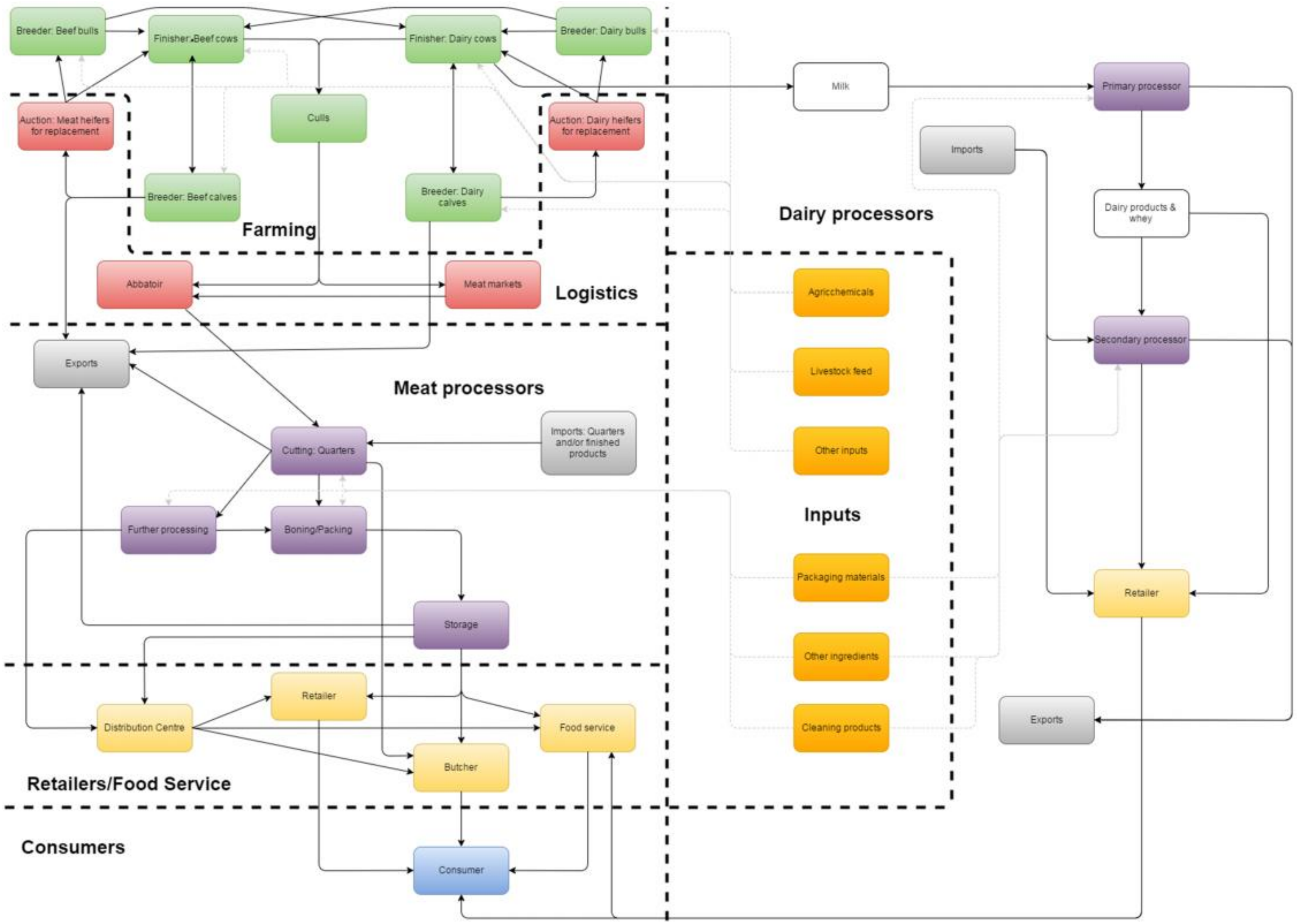

Figure 2 –Framework for modelling dairy and beef supply chains.

were included in the model runs (Table 1). The model results then show that yield of most of these crops is expected to increase 1-4% under climate change (Figure 3), accompanied by increases in crop area (particularly for spring barley; Figure 4) and resultant increases in total production (Figure 5; Appendix 1).

Table 1 – Feed and fodder inputs into the beef and dairy system for Scotland and Census Year 2015 (Scottish Government 2016)

Crop	Total use (000's t)	Animal feed (000's t)	Percentage of feed designated for cattle (%)
Wheat	902	364	15
Barley	1952.2	1371.9	85
Potatoes	1031.1	87.8	80
Forage maize	55840	55840	100
Grass		~100%	66

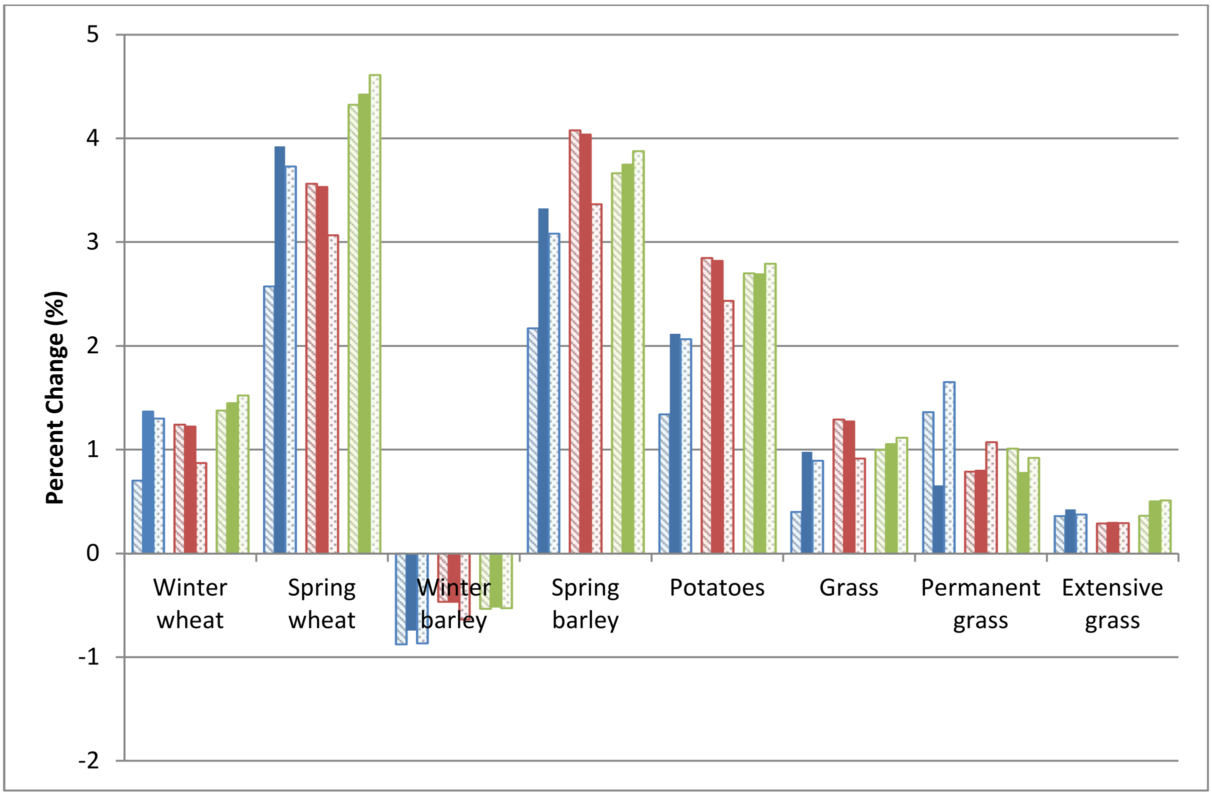

Figure 3 – Percent changes in yield per hectare for selected crops in Scotland between 2015 and 2050 for low (blue), medium (red) and high (green) emissions scenarios and for present day beef demand (solid fill), as well as with beef demand reduced (striped fill) and increased (dotted fill) by 50%

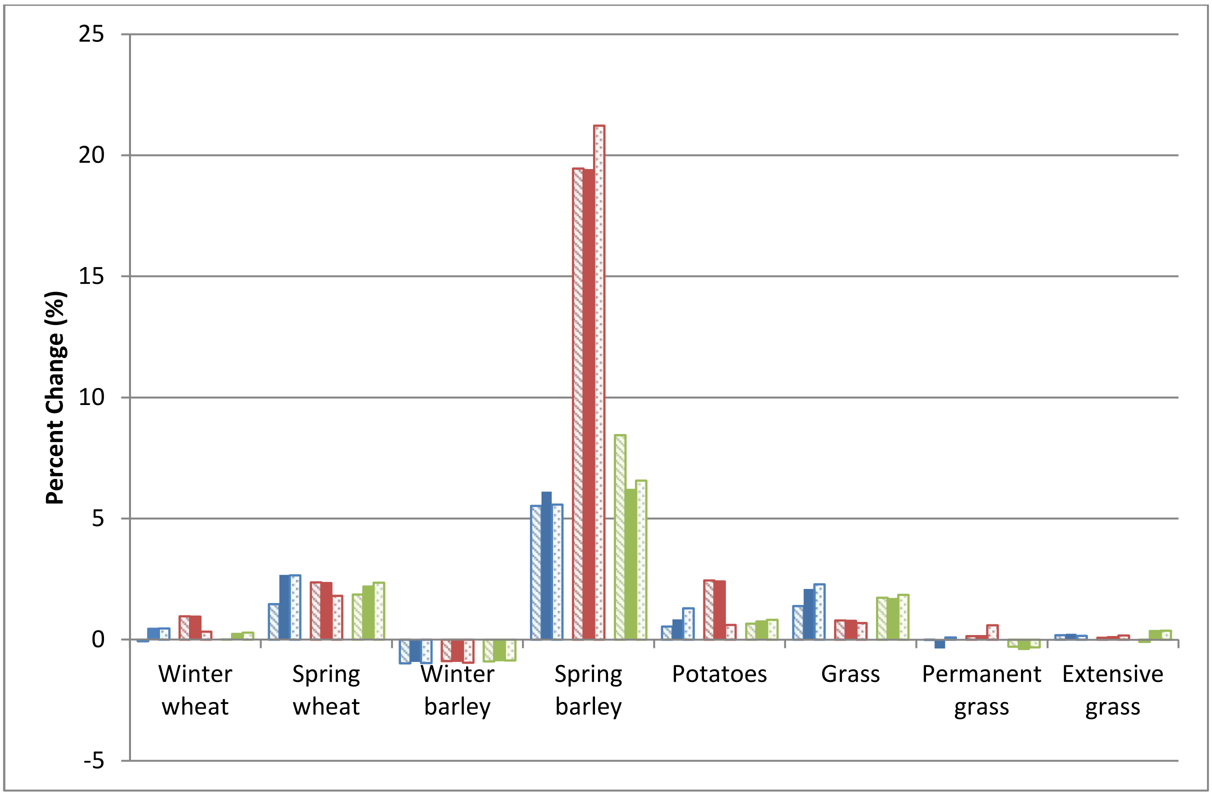

Figure 4 - Percent changes in crop area for selected crops in Scotland between 2015 and 2050 for low (blue), medium (red) and high (green) emissions scenarios and for present day beef demand (solid fill), as well as with beef demand reduced (striped fill) and increased (dotted fill) by 50%

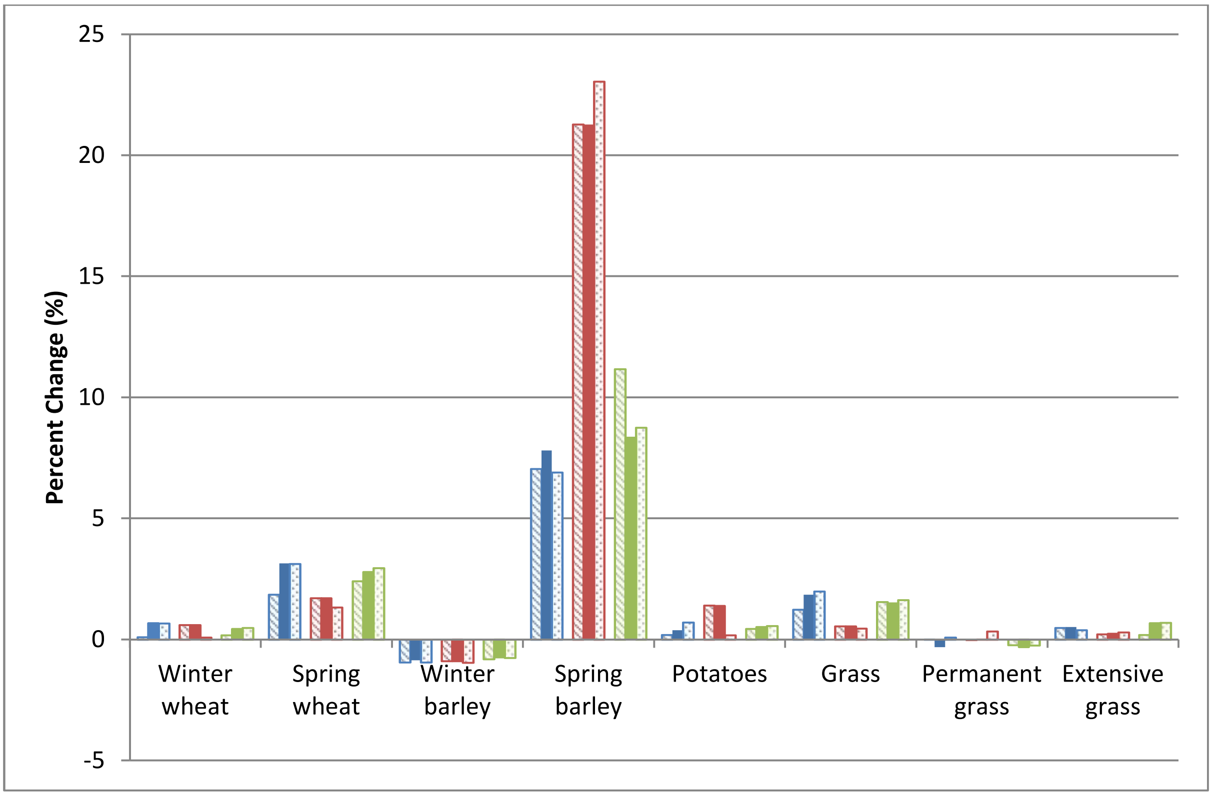

Figure 5 - Percent changes in total crop production for selected crops in Scotland between 2015 and 2050 for low (blue), medium (red) and high (green) emissions scenarios and for present day beef demand (solid fill), as well as with beef demand reduced (striped fill) and increased (dotted fill) by 50%

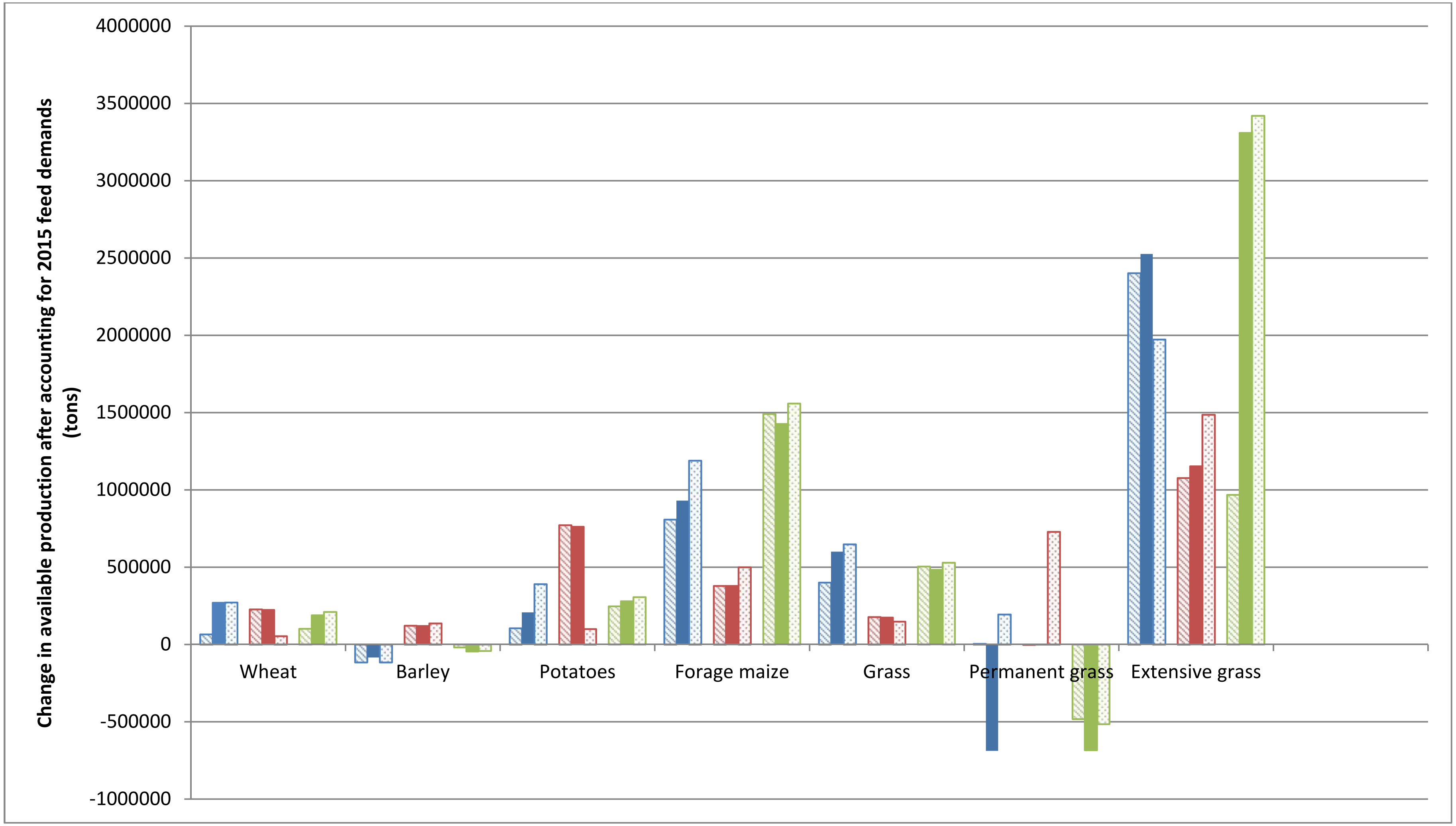

Figure 6 - Change in available production in 2050 after accounting for 2015 feed demands and calibrating the model to match present day (2015) production in Scotland for low (blue), medium (red) and high (green) emissions scenarios and for present day beef demand (solid fill), as well as with beef demand reduced (striped fill) and increased (dotted fill) by 50%. For most feed and fodder sources, future conditions show an increase in availability when related to 2015 supply.

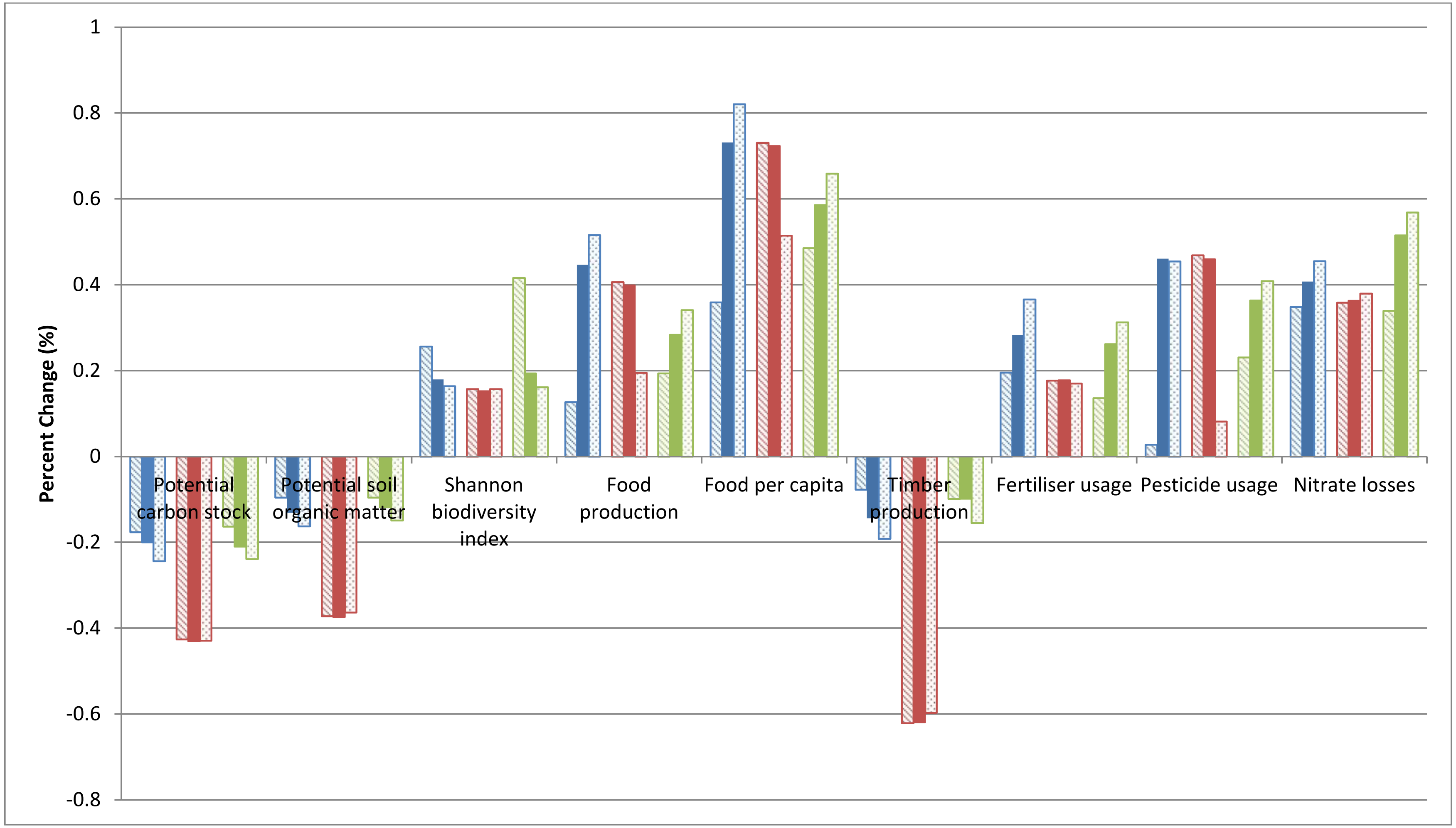

Figure 7 - - Percent changes selected ecosystem services between 2015 and 2050 in Scotland for low (blue), medium (red) and high (green) emissions scenarios and for present day beef demand (solid fill), as well as with beef demand reduced (striped fill) and increased (dotted fill) by 50%

Discussion

The model results are somewhat encouraging for the resilience of the beef and dairy industries in Scotland. Yield per hectare for the majority of crops investigated are expected to increase by between 1 and 4 % over the next 30 years (Figure 3). The anticipated yield increase is in line with current scientific understanding. Crop yields across northern Europe are expected to increase as result of climate change (Alexandrov et al. 2002; Ewert et al. 2005; Audsley et al. 2006; Olesen et al. 2007; Richter & Semenov 2005). In C_3 crops (including rice, soybeans and wheat), increases in atmospheric CO_2 concentrations result in increases in net photosynthesis because RuBisCO is not saturated under present day conditions. In theory, at 25°C, an increase in atmospheric CO_2 from the present-day value of 380 ppm to that of 550 ppm, projected for the year 2050, would increase C_3 photosynthesis by 38% (Long et al. 2004); this effect is termed CO_2 fertilisation. In contrast, in C_4 crops (such as maize and sorghum), CO_2 is concentrated to three to six times atmospheric concentrations before being exposed to (von Caemmerer & Furbank 2003). This concentration is sufficient to saturate RuBisCO and in theory would prevent any increase in CO_2 uptake increasing atmospheric concentrations; however, an indirect increase in the efficiency of water use via reduction in stomatal conductance may still increase yield (Long et al. 2004). On average, free-air concentration enrichment (FACE) experiments show lower increases in the yield of C_3 crops in elevated CO_2 concentrations than the theorised value. For example, at 25 °C, a CO_2 increase to 550 ppm theoretically results in a 38% increase in photosynthetic rate, FACE experiments show increases of 20 % for the daily integral of photosynthetic CO2 uptake, 17 % for total biomass, and just 13 % for yield (Long et al. 2006). Further yield increases may be gain from other aspects of climate change, e.g. temperature increases. With anticipated adaptation, yields simulated under a 2 °C temperature increase may result in yield increase of between 7 and 15 % as a result of increased metabolic rates (Challinor et al. 2014). However, whilst mean yields are expected to increase, it is likely that the inter-annual variability in yields will also increase, although less in known about this (Challinor et al. 2014).

As well as yield increases, the model results anticipate increases in crop area for several crops, particularly for spring barley (Figure 4), and a decrease in winter barley crop area. Areas within Scotland that currently have a marginal climate will likely become more suitable for crop growth and thus provide the opportunity for agricultural expansion (Olesen et al. 2011). This trend is expected across northern Europe as a whole. Increases in yield and expansion of climatically suitable areas in northern Europe are expected to reinforce the current trends of intensification of agriculture in northern and western Europe and extensification and abandonment in the Mediterranean and south-eastern parts of Europe (which will see increase in water shortage and extreme weather events) (Bindi & Olesen 2011). Whilst the yield increases are significant, it is the increase in crop area that drives the overall pattern in increased total production (Figure 5). As a result, Scotland will have an excess of feed and fodder under climate change when compared to present day conditions, enabling for increases in beef and dairy production or export to other sectors and/or nations (Figure 6).

An exception to the trends detailed above is winter barley. Winter barley is an extremely important fodder crop for the beef and dairy sector (Table 1), but the impacts of climate change are expected to be negative (Figure 3-5). Whilst higher temperatures in Scotland are expected to enable use of late maturing cultivars, thus extending the growth duration, and the damage during winter and risk of frost damage are expected to be lower, an increase in pest herbivory combined with increased winter rainfall and soil saturation is anticipated to have an overall negative effect (Olesen et al. 2011).

Overall, the climate change scenarios had a much larger impact on the indicator variables than the socio-economic scenarios (Figures 3-7). This result potential has two interpretations; either future changes in climatic conditions are more important than socio-economic changes for the beef and dairy sector (Holman et al. 2005; Rounsevell & Reay 2009), or the CLIMSAVE model underestimates the importance of socio-economic feedbacks and impacts. Future work undertaken will determine the relative impact of climatic and socio-economic variables with greater certainty (see Further Work).

In summary, the overall net impact of the variables investigated here on the beef and dairy industry are positive. However, there are notably both trade-offs and synergies with other sectors (Figure 7). In general, agricultural ecosystems, which provide food and forage essential to human wellbeing, rely on services provided by natural ecosystems; including pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling and hydrological services. Whilst agricultural ecosystems produce a variety of ecosystem services (such as regulation of soil and water quality, carbon sequestration, support for biodiversity and cultural services), they can also be the be the source of numerous disservices (including loss of wildlife habitat, nutrient runoff, sedimentation of waterways, greenhouse gas emissions, and pesticide poisoning of humans and non-target species) (Power 2010). The model results suggest that, whilst we can expect a win-win (both food production and biodiversity in Scotland are likely to increase by 2050), notable trade-offs are anticipated, including decreases in stored carbon and timber production, as well as increases in the usage of pesticides and fertilisers and associate nitrate leaching (Figure 7). Future work should evaluate the synergies and trade-offs indicated here in terms of spatial scale, temporal scale and reversibility.

Note that due to the nature of the CLIMSAVE model, it is not possible to interrogate the results to understand the combination of processes that lead to these results. To obtain such information, process-based models would need to be integrated (as outlined in the next section of the report).

Further work

The modelling activities undertaken as part of this investigation focus on the production of fodder for the Scottish beef and dairy industry. However, further work could improve the utility of the findings. Most notably, future work under RESAS 1.4.2 may expand this study in two distinct ways:

1. **Follow the increased fodder availability down the value chain** – Whilst this study suggests an increase in fodder availability within Scotland by 2050, it currently requires conjecture and extrapolation to anticipate the impact of this on cattle numbers, farm-related businesses and consumers. Future work could provide insight into the impacts on the beef and dairy value chains using the framework outlined at the beginning of this study (Figure 2).
   The first steps towards integrating models to build the framework shown in Figure 2 have already begun. Models representing the 'Farming' section of the framework have been reviewed for suitability by ranking model availability alongside ability of the model estimate multiple ecosystem services, resulting in the selection of the internationally acclaimed Global Livestock Environmental Assessment Model (GLEAM; http://www.fao.org/gleam/resources/en/).
   GLEAM was developed to address the need for a comprehensive tool to evaluate the environmental impacts of the livestock sector and to support stakeholders in their efforts towards more sustainable practices than ensure the livelihood of producers and mitigates the environmental burdens. GLEAM is a modelling framework based on a Life Cycle Assessment method that covers the 11 main livestock commodities at global scale, namely meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. GLEAM is built on five modules reproducing the main stages of livestock production: the herd module, the manure module, the feed module, the system module and the allocation module (Figure 8).
2. **Production of disaggregated results** – For ease of reporting, the results presented here have been aggregated to national summaries, however the models were run at a 5 km × 5 km spatial resolution. Hence, the results can be spatially and temporally disaggregated, highlighting trade-offs and synergies at a sub-national scale and across years. Further work could also disaggregate the beneficiaries by unpacking the beef and dairy sector in accordance with the framework provided in Figure 2, providing more insight into anticipated 'winners' and 'losers' as a result of future climatic and socio-economic change. For example, following on from the extension of CLIMSAVE via integration with GLEAM, the cattle biomass

modelled could be followed through to auction markets, abattoirs, hide traders, wholesale meat markets, by-product processors and consumers. The eFoodChainMap (https://www.emap.org.uk/map.aspx?sid=1) provides spatial data on the location of infrastructure vital to the beef and dairy industries. Future work could use the ARtificial Intelligence for Ecosystem Services (ARIES) software to integrate CLIMSAVE with both GLEAM and the eFoodChainMap data, producing a dynamic agent-based model describing the entire beef and dairy value chain (Figure 2) and fulfilling all the objectives of 1.4.2 (see Appendix 2 for further information).

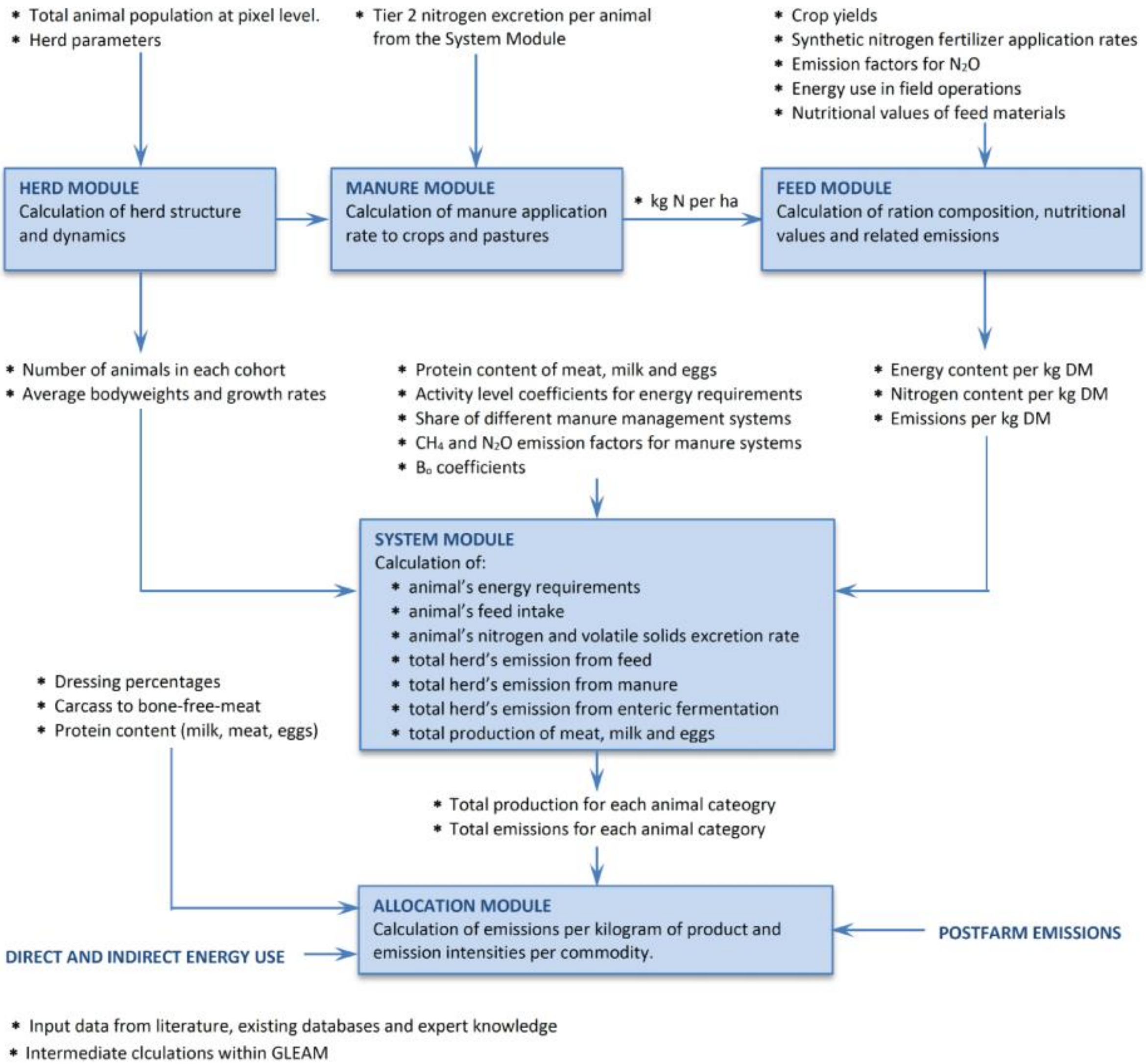

Figure 8 – An overview of the Global Livestock Environmental Assessment Model (GLEAM; (FAO 2016)).

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Appendix 1 – Selected CLIMSAVE outputs for Scotland

Model Run	Baseline	Baseline & 50% less beef demand	Baseline & 50% more beef demand	Low emission	Low emission & 50% less beef demand	Low emission & 50% more beef demand	Medium emission	Medium emission & 50% less beef	Medium emission & 50% more	High emission	High emission & 50% less beef demand	High emission & 50% more beef demand
Winter wheat (t/ha)	2511	2511	2511	2949	2663	2663	2626	2626	2626	2908	2908	2908
Spring wheat (t/ha)	2436	2436	2436	2835	2559	2559	2497	2497	2497	2728	2728	2728
Winter barley (t/ha)	1357	1357	1357	1599	1443	1443	1436	1436	1436	1441	1441	1441
Spring barley (t/ha)	2637	2637	2637	3045	2749	2749	2686	2686	2686	2889	2889	2889
Potatoes (t/ha)	1736	1736	1736	2027	1830	1830	1816	1816	1816	1867	1867	1867
Forage maize (t/ha)	1482	1482	1482	1810	1634	1634	1583	1583	1583	1642	1642	1642
Grass (t/ha)	1478	1478	1478	1819	1652	1652	1576	1576	1576	1684	1684	1684
Permanent grass (t/ha)	1482	1482	1482	1806	1630	1630	1582	1582	1582	1633	1633	1633
Extensive grass (t/ha)	1810	1810	1810	2165	1954	1954	1915	1915	1915	2031	2031	2031
Winter wheat area (ha)	269642	269642	276733	348093	336323	336323	337459	337459	337459	352727	352276	352648
Spring wheat area (ha)	271127	271127	282654	313931	313948	313948	310443	310443	310443	314107	314105	314105
Winter barley area (ha)	272409	272409	272409	303271	303288	303288	294831	294831	294831	305124	305124	305124
Spring barley area (ha)	282266	282266	309866	350977	350986	350986	348972	348972	348972	354091	354086	354086
Potatoes area (ha)	292938	292938	292938	308669	308683	308683	306652	306652	306652	306219	306217	306218
Forage maize area (ha)	272544	272544	271267	301177	301194	301194	293676	293676	293676	303156	303156	303156
Grass area (ha)	210043	210043	210043	314938	217306	217292	220035	220036	220025	278632	277188	278366
Permanent grass area (ha)	265788	265788	265788	293788	293802	293802	286800	286800	286800	294680	294680	294680
Extensive grass area (ha)	268708	268708	268708	297466	297480	297480	290169	290169	290169	299425	299425	299425
Winter wheat (t)	309293	309293	309293	362943	362964	362961	332484	332484	332484	364635	434664	436265
Spring wheat (t)	145567	145567	154498	229777	244815	244808	198992	199022	169753	244428	243067	244300
Winter barley (t)	155549	155549	186754	326532	353340	353324	259694	259755	188009	349291	346498	349028
Spring barley (t)	138084	138084	138084	161649	161650	161650	161565	161565	161565	172220	172220	172220
Potatoes (t)	144183	144183	144183	165182	165180	165180	164051	164051	164051	174709	174709	174709
Forage maize (t)	129771	129771	127796	284746	284739	284739	249404	249404	249404	307537	307537	307537
Grass (t)	268631	268631	268631	309460	309458	309458	290790	290790	290790	312086	312086	312086
Permanent grass (t)	269417	269417	269417	297597	297591	297591	290294	290294	290294	299449	299449	299449
Extensive grass (t)	274634	274634	274634	337800	337794	337794	300480	300480	318944	341491	341491	341491
Potential Carbon stock (t/ha)	1461	1461	1461	1787	1613	1613	1567	1567	1567	1620	1620	1620
Potential Soil Organic matter (t/ha)	1438	1438	1438	1763	1592	1592	1550	1550	1550	1598	1598	1598
Areas of coastal grazing marsh (ha)	265051	265051	265051	291077	291074	291074	284381	284381	284381	292098	292098	292098
Shannon Biodiversity index	1082	1082	1082	1259	1136	1136	1161	1161	1161	1239	1239	1239
Food production (TJ)	264263	264263	264263	275505	275506	275506	274512	274512	274512	276931	276931	276931
Food per capita (kcal/day)	2237	2237	2237	2554	2305	2305	2285	2285	2285	2458	2458	2458
Timber production (Mt)	431829	431829	431829	459935	459950	459950	487449	487449	487449	446603	446596	446597
Irrigation usage (mill. mÂ³)	327718	327718	327718	357358	357358	357358	339192	339192	339197	368901	368901	368901
Fertiliser usage (kgN/ha)	1636	1636	1636	1983	1790	1790	1716	1716	1716	1820	1820	1820
Pesticide usage (dose/ha)	1486	1486	1541	1879	1706	1706	1591	1591	1591	1725	1725	1725
Nitrate losses (kgN/ha)	1501	1501	1540	1826	1694	1694	1602	1602	1602	1715	1715	1715

Appendix 2 – Model integration in k.LAB and ARIES

Managing ecosystems to avoid exceeding planetary boundaries will inevitably involve trade-offs and synergies between different ecosystem services. Maximising one benefit (e.g. provision of food) may be traded-off against another (e.g. carbon storage), resulting in potential conflict due to competing demands and pressures. These trade-offs may be exacerbated by drivers of change (i.e. climate change). Thus, decision-making will be most effective given full knowledge of the ecosystem service benefits derived from a system. The value of ecosystem service information depends increasingly on our ability to link it in a coherent way to other pieces of information (e.g. economic, social) so as to enhance its value and support holistic, evidence-based decision-making. This need is strongly felt in empirical science but also public and private bodies. The challenge in meeting this need is that information (data) is produced within different communities each with their own point of view and technical knowledge, following different data lifecycle, and usually heavily oriented to the purposes for which they were produced (e.g. farm-scale data produced by farm managers may not be available to support landscape-scale decision-making by local authorities).

Whole fields (bioinformatics, ecoinformatics, geoinformatics) emphasise reusability and integration of data artifacts and models. For example, reusability, versatility, reproducibility, extensibility, availability, and interpretability were identified as requirements for sustainability science knowledge structuring (Kumazawa et al. 2009). In recent years, the vision of a semantic web (Berners-Lee et al. 2001) has determined an emphasis on formal semantics as a strategy for the integration of diverse, independently developed and curated resources. The development and use of ontologies (i.e. logical theories accounting for the *intended meaning* of a formal vocabulary: Guarino (1998)) has become commonplace in attempts to describe the semantics of data and model assets for purposes of integration and reuse (e.g. Villa et al (2009), Porter et al (2014)). While the ultimate goal of practical and widespread model integration remains far from achieved, research and progress in semantics-mediated integration have been significant. Here, we focus on one example of model integration software, the k.LAB knowledge modelling environment (http://www.integratedmodelling.org/).

k.LAB is a software platform designed to integrate models via the use of well-defined scientific concepts. The software gives access to an integrated network of web-accessible models, catalogued and related across scientific disciplines through semantics. k.LAB provides a user-friendly means to query the network, seeking information about a concept of interest. The system links natural science (e.g., process-based models) and human behaviour (e.g., agent-based models) effortlessly and resolves differences in units or scale automatically, enabling outputs to support complex, interdisciplinary decisions. Behind the scenes, an artificially intelligent engine assembles the best possible workflow to compute outputs that describe the concept of interest to the modeller or decision maker. This deductive process builds a decision tree to resolve the principal concept to the most suitable data or model and in turn resolves any other concepts required by the data or models chosen at each step, seamlessly linking models to provide holistic outputs that support real-world decision-making. The technology and corresponding k.LAB software are not specific to ecosystem services (i.e., they can be applied to other integrated modelling problems), however the utilisation of k.LAB to holistically model beef and dairy farming systems to monitor multiple ecosystem services has numerous advantages:

- Modellers can build on others' work by connecting to the k.LAB network, providing automated access to a growing library of interoperable data and models shared by others. The semantics specified using the k.IM language ensures that the information available on the network has exactly the same meaning to the original developers as for you.
- Researchers can develop models and annotate your data in the k.IM language, which integrates existing data and models and allows creation of new ones. The language completely describes each dataset or model's semantics, allowing it to exist independently on a network node, and to be used and reused based solely on the meaning

of its associated semantics. In other words, k.LAB enables new levels of modularity and interoperability between independently developed data and models.

- Decision-makers will soon be able to connect to modelling engines through the k.EXPLORER, an interface that enables a two-step modelling workflow (set a context and observe a concept). With minimal training, running many sophisticated models will become a simple matter of searching and observing a concept over a context – a user workflow that closely resembles the familiar ways we use the Internet today.

The most visible application of k.LAB has been the ARtificial Intelligence for Ecosystem Services (ARIES; http://aries.integratedmodelling.org/) project, a suite of state-of-the-art ecosystem services models aimed at supporting science-based decision-making. ARIES, while young, stands out as the first real-world tool for social-environmental systems modelling, using knowledge and models built independently by many actors and endorsed by the scientific community to produce holistic outputs, making evidence-based environmental decision making easier and more effective. Some example uses for ARIES are listed in Table A2.

Table A2 – Example uses of the ARtificial Intelligence for Ecosystem Services (ARIES) modelling platform.

ARIES use	Sample questions	Spatial scale
Spatial mapping and quantification of ecosystem services	- What ecosystem services (ES) are being provided and where on the landscape are they provided? - Where are the beneficiaries of ES located?	Local to National
Spatial economic valuation of ecosystem services	- What is the economic value of the ES being provided, and how is this value distributed in space? - What compensation amounts should be required to compensate for environmental damage?	Local to National
Natural capital accounting	- How are the provision, use, and flows of ecosystem services changing over time? - How do these services contribute to specific economic sectors – both within and beyond estimates already included in Gross Domestic Product?	Local to National
Optimization of payment schemes for Ecosystem Services (PES)	- Where is it best to invest in payment schemes for ES so as to optimize investment? - What type of PES scheme is the most effective given the nature of the services of interest? - How are opportunity costs distributed in space? How are probabilities of land conversion distributed in space?	Watershed to Regional
Conservation planning	- Where is it most efficient and cost-effective to invest in conservation for the combined provision of biodiversity and important ES?	Local, watershed, regional
Spatial policy planning	- What policy tools (payments, penalties, property rights, persuasion and prescription) are likely to be most effective for the maintenance of ES and the minimization of environmental impact?	Local, watershed, regional
Forecasting of change in ES provision	- How is land use or climate change likely to affect the provisioning and value of ES?	Local, watershed, regional

The ARIES project develops and maintains a large-scale cyberinfrastructure (computer infrastructure for data and linked socio-environmental modelling services distributed over the internet) that is designed for collaborative modelling. The system is semantic – underpinned by ontologies that allow proper integration of concepts used in models developed by any user. Using an integrated approach, models are housed in a distributed repository, with their compatibility maintained by semantics. This allows the assembly of models from different paradigms, including system dynamics, agent-based models, Bayesian networks, GIS algorithms, analytical models, look-up tables, and multi-criteria analysis. The system includes artificial intelligence-based heuristics to select best models based on their appropriateness for the spatiotemporal context of interest – a context-aware modelling environment. This approach enables networked collaboration, where scientists can share inter-operable data and models in a cloud-based environment. Modellers add models and datasets to the network and they automatically become available to other modellers, with access privileges controlled by the contributors of each dataset and model.

Agent-based models built in the ARIES platform benefit from interconnection to a large library of modelling components. Over the last four years, the library of process-based models have been built into ARIES, focusing on food security, water availability, and other provisioning ecosystem services critical to human well-being and food security (http://espa-assets.org/). Notably, global ecological process-based models for biomass and water are relevant to the proposed work (Figure A1). The biomass model is a semantically enabled rewrite of the well-established LPJ-GUESS model (Smith et al. 2001). This model can simulate the process of growth of natural and crop vegetation in great detail, and can be used to assess carbon sequestration and biomass production in forests and croplands, as well as other land uses. ARIES also contains a fully-distributed, surface water flow model quantifies water supply, based on weather station data accessed from global repositories. Both models are spatially and temporally explicit and can run in any geographical context of the globe using data from their respective global repositories, though they benefit from the addition of site-specific data that will improve their accuracy.

ARIES combines dynamic models enabling the tracking of provision, use, and flows of ecosystem services ranging from physical flows (e.g., water, food) to cultural ecosystem services (e.g., viewsheds, recreation; Bagstad et al. 2013). It would be possible to develop agent-based models within ARIES of the local socio-economic and cultural activities taking place in the beef and dairy industry within Scotland (e.g., land use in agricultural activity, point-source outputs for industrial activity, cultural and recreational amenities provided in a landscape), and their spatial flows

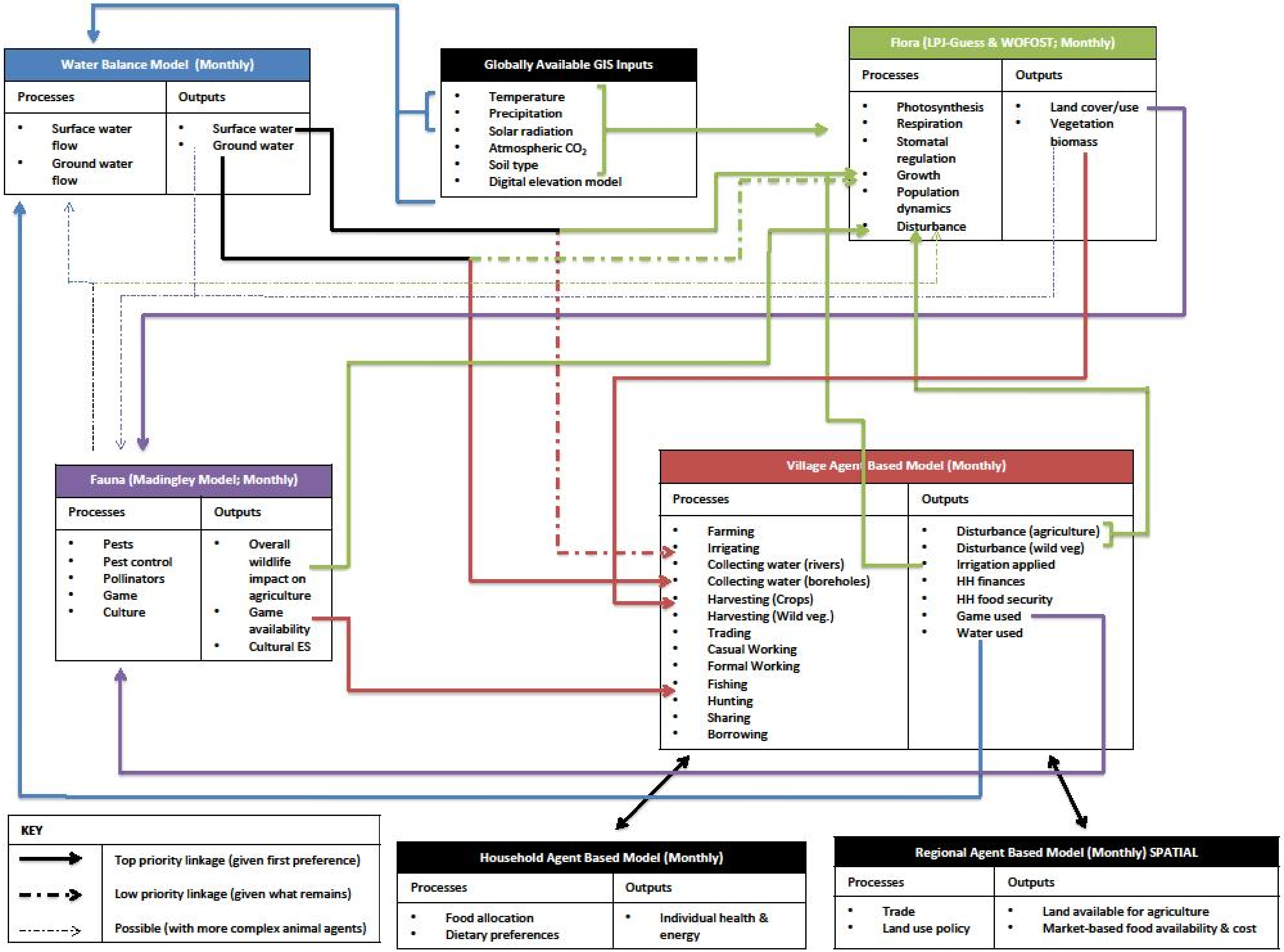

Figure A1 – The existing modelling framework within the ARtificial Intelligence for Ecosystem Services (ARIES) modelling platform.