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Research article

Cattle production strategies to deliver protein with less land and lower environmental impact

Daniel Henn[a,b,*], Colm Duffy[b,1], James Humphreys[c], James Gibbons[d], Kenneth A. Byrne[e], David Styles[a,b]

[a] Bernal Institute, School of Engineering, University of Limerick, Limerick, Ireland
[b] Ryan Institute, School of Biological & Chemical Sciences, University of Galway, Galway, Ireland
[c] Animal and Grassland Research and Innovation Centre, Teagasc, Moorepark, Fermoy, Ireland
[d] School of Natural Sciences, Bangor University, Bangor, Wales, UK
[e] Department of Biological Sciences, School of Natural Sciences, University of Limerick, Limerick, Ireland

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ABSTRACT

Global land resources are over-exploited and natural habitats are declining, often driven by expanding livestock production. In Ireland, pastureland for grazing cattle and sheep account for circa 60% of terrestrial land use. The agriculture, forestry and other land use sector (AFOLU) is responsible for 44% of national greenhouse gas (GHG) emissions. A new Grassland Animal response Model (*GLAM)* was developed to relate livestock-cohort grass and feed requirements to farm-grassland system areas, enhancing environmental assessment of prospective AFOLU configurations. Although land conversion targets are often well-defined, they tend to lack a clear definition of where land sparing can occur. Through analyses of 10 scenarios of milk and beef production and management strategies, we found that displacing beef cows with dairy cows can increase national protein output while sparing up to 0.75 million ha (18%) of grassland (albeit with a minor increase in overseas land requirement for additional concentrate feed). Reducing slaughter age, increasing exports of male dairy calves and increasing grassland use efficiency on beef farms each achieved between 0.19 and 0.32 million ha of land sparing. Sexed semen to achieve more favourable male-female birth ratios had a minor impact. GHG emissions, ammonia emissions and nutrient leaching were only reduced substantially when overall cattle numbers declined, confirming the need for cattle reductions to achieve environmental objectives. Nonetheless, application of *GLAM* shows potential for improved grass and cattle management to spare good quality land suitable for productive forestry and wetland restoration. This change is urgently needed to generate scalable carbon dioxide removals from the land sector in Ireland, and globally.

1. Introduction

Land resources are increasingly over-exploited due to a growing global population and demand for resource-intensive, high-impact foods. Economic growth has driven expansion of agricultural production at the expense of the environment and the depletion of natural resources (IPCC et al., 2019a; Sandker et al., 2017; Searchinger et al., 2023). Grassland-based ruminant livestock production is an important part of Ireland's economy and a major land use. In 2020, 59% of land cover was classified as grasslands, mostly used for livestock (cattle and sheep) production (CSO, 2023). Wetlands, forests and cropland accounted for 17%, 11% and 10%, respectively. The agricultural sector is the second largest national GHG emission source (23 Mt CO_2e in 2021), primarily due to intensive livestock production systems (Duffy et al., 2023). Unlike the majority of European countries, Ireland's land use, land use change and forestry (LULUCF) sector is a source of emissions (7.3 Mt CO_2e in 2021) with annual emissions from grassland on organic soils surpassing carbon sequestration in forests and mineral soils under grassland (Duffy et al., 2023).

As one of the 196 countries signing the Paris Agreement, Ireland has committed to reaching climate neutrality across all sectors by 2050 (Government of Ireland, 2021; UNFCCC, 2015). The agriculture,

* Corresponding author. Bernal Institute, School of Engineering, University of Limerick, Limerick V94 T9PX, Ireland.
E-mail address: daniel.henn@ul.ie (D. Henn).
[1] These authors contributed equally to this work.

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forestry and other land use (AFOLU) sector in Ireland is responsible for 44% of national greenhouse gas (GHG) emissions. Achieving new zero GHG emissions will require substantial changes in land use into carbon sinks such as forestry or wetlands (Haughey et al., 2023; Lanigan et al., 2023). A successful implementation of these measures will necessitate the large-scale transformation of the current, grassland-dominated, land configuration in Ireland to build synergies between food production, carbon dioxide removals, fossil-free energy production, water quality improvements and biodiversity enhancements (Bishop et al., 2024; Gorman et al., 2023; Roe et al., 2019).

Despite the urgent need and political targets to reduce environmental impacts and spare land, clearly defined pathways to meeting these objectives are lacking on the national and international scale. In this study, we aim to quantify the land sparing potential of ruminant livestock production strategies in Ireland alongside their impacts on livestock numbers, protein production from cattle, concentrate feed requirements, and environmental quality indicators (GHG and ammonia emissions, N and P nutrient leaching to water bodies). These livestock production strategies require a design that enables the investigation of how protein production can be combined with lower environmental footprints of livestock production that can be radically decoupled from past livestock herd and land structures, enabling more detailed exploration of specific changes in herd dynamics and grassland management. We aim to investigate five unique shifts in grassland-based livestock production strategies as follows:

(1) A continuation of the trend towards more dairy cows and fewer beef cows in Ireland. Recent modelling has shown a slight increase in GHG emissions until 2030 under a business-as-usual regime with a shift in cow composition (EPA, 2022). Producing a larger proportion of beef from the dairy sector instead of the suckler beef herd has shown potential to reduce GHG emissions (Soteriades et al., 2019; van Selm et al., 2021).
(2) A reduction of mean slaughter ages of cattle kept for beef production. This reduces life-cycle emissions while lowering cattle numbers in older age cohorts (Lanigan et al., 2023; Mazzetto et al., 2015).
(3) Maximisation of male dairy calf export to minimise their environmental impacts and land use within the Irish national inventory boundary. Alternatively, a minimisation of male dairy calf exports to maximise national protein production.
(4) The introduction of sexed semen to alter male-female birth ratios of dairy cows towards female dairy-progeny, thus reducing the number of surplus male (non-crossbred) dairy calves. This was found to be a cost-effective mitigation measure at farm-level (Eory et al., 2014; Holden and Butler, 2018).
(5) Improving grassland use efficiency (GUE) on beef farms, which is substantially lower compared with dairy farms in Ireland (Duffy et al., 2022b).

2. Materials and methods

2.1. Disaggregated cattle herd representation

The *COHORTS* model represents the national cattle herd structure as 21 cohorts (Fig. 1): three in the adult stage (dairy cows, beef cows, and bulls) and 18 in the pre-adult stage (pure dairy cattle (DxD), dairy-beef crossbreeds (DxB), and pure beef cattle (BxB), each male and female, and each in age groups <1 year, 1–2 years, and >2 years) (Henn et al., 2023a). Pre-adult cohorts in the scenarios are determined based on herd coefficients that are derived from dairy and beef cow numbers. This genetic classification allows for a differentiation between DxD and DxB, based on dairy cow numbers, and BxB, based on beef cow numbers. For scenarios, a three-year mean (2018–2020) of herd coefficients was used to reduce the impact of outliers for any given year. The *COHORTS* model was validated for the period 2006–2020 in terms of total cattle numbers, beef production and GHG emissions stemming from enteric fermentation (Henn et al., 2023a). Sheep numbers were based on data from the National Inventory Report and reclassified according to the sheep flock structure of the GOBLIN land-balance model, including a differentiation into upland and lowland herds (Duffy et al., 2022b, 2023).

Energy requirements and environmental impacts (GHG emissions, ammonia emissions, N and P leaching) from cattle and sheep were calculated in the life cycle assessment sub-model within GOBLIN, based on IPCC Tier 2 methodology and equations 10.2 to 10.34 (Duffy et al., 2023; IPCC, 2019b; IPCC, 2006). Annual milk production was obtained from Eurostat (2022) and protein content was assumed to be 3.5% (CSO, 2023). Total beef output was calculated according to Henn et al. (2023a) based on cattle in the 1–2 year old cohorts. Protein content of beef was

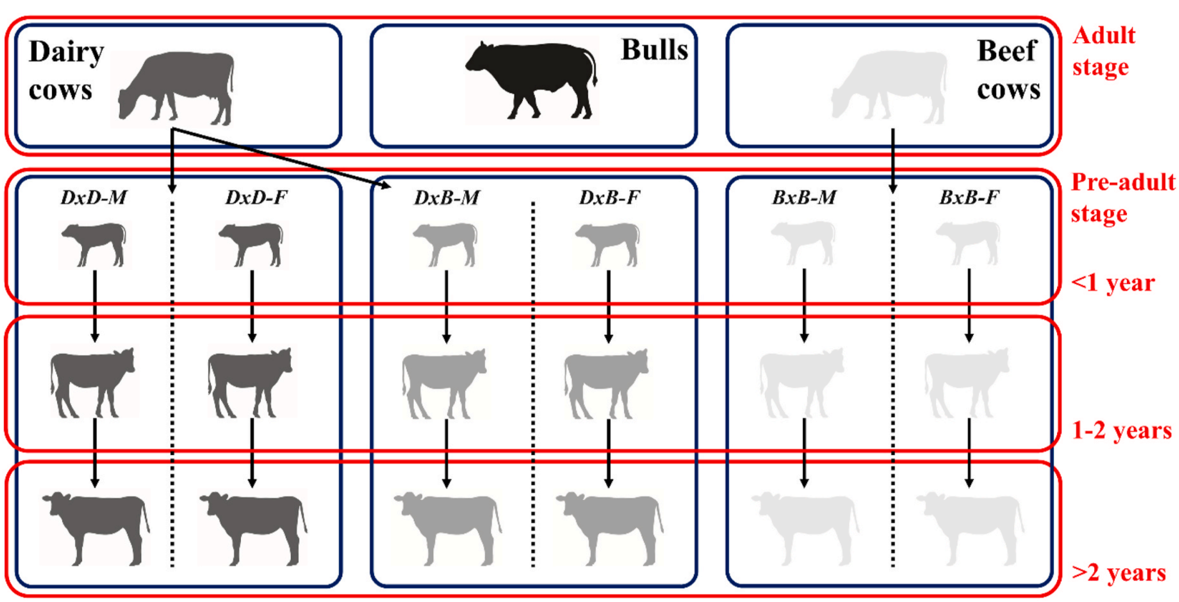

Fig. 1. Overview of the 21 cattle cohorts contained within the *COHORTS* model: three in the adult stage and 18 in the pre-adult stage. Bulls for breeding were not distinguished between dairy and beef genetics. Pre-adult cohorts were divided according to age, gender and genetic classification into three groups: DxD (pure dairy cattle), DxB (dairy-beef crossbreeds) and BxB (pure beef cattle), according to the structure adapted from Henn et al. (2023a).

estimated at 23% (AMCTB, 2014; Greenfield and Southgate, 2003).

The GOBLIN model assumes three different sectors of livestock production: dairy, beef and sheep. Dairy farms are specialised in milk production and contain dairy cows, DxD cattle <1 year, and DxD heifers. Beef farms specialise in either rearing or fattening of cattle for beef production, and contain beef cows, bulls, DxD male cattle >1 year, DxB cattle and BxB cattle. In terms of Ireland's National Farm Survey (NFS) farm definitions, "cattle rearing" and "cattle other" farms are combined within our definition of the beef sector and, when applicable, mean values of the two farm types were used. Sheep farms are specialised in sheep production and contain all sheep cohorts.

2.2. GrassLand Animal response model (GLAM)

Grassland is the main source of feed for the vast majority of Irish ruminant livestock (cattle herd and sheep flock). Dairy cow diets consist of over 80% grazed grass and grass-silage, while the proportion in beef cattle and sheep diets are typically higher (O'Brien et al., 2018; O'Mara et al., 2021). The purpose of the grassland model within GOBLIN is to determine the total grassland area needed to provide dry matter feed requirements from grassland for the aggregated national dairy cattle herd (dairy sector), beef cattle herd (beef sector) and sheep flock (sheep sector) after concentrate feed intake is accounted for. Total concentrate feed requirements for all cohorts are based on aggregation from O'Mara (2006). Dairy cow concentrate feed requirements were adjusted to reflect increased milk production and resulted in 2.97 kg day^{-1}, a substantially larger intake than beef cows (0.84 kg day^{-1}), bulls (0.65 kg day^{-1}), cattle <1 year of age (1 kg day^{-1}) and cattle >1 year of age (0 kg day^{-1}) (Duffy et al., 2022b).

The NFS and NFS fertiliser survey distribute grassland into four types depending on management: pasture, silage, hay and rough grazing (Dillon et al., 2018, 2022). In the GrassLand Animal response Model (*GLAM*), total areas of each of these four grassland types were allocated across the three ruminant livestock sectors outlined above, resulting in a total of twelve grassland use categories. Based on inorganic and organic fertiliser inputs to each grassland use category, mean dry matter production was determined utilising yield response functions developed by Finneran et al. (2012). Inorganic fertiliser inputs to each grassland use category were derived for the period 2005–2015 from the NFS fertiliser survey and extrapolated until 2020 utilising national fertiliser inputs (Dillon et al., 2018).

Organic fertilisation rates were based on the LCA sub-model in GOBLIN (Duffy et al., 2022b), which utilises IPCC Tier 2 methodology to determine spreading rates of excretion from livestock (IPCC, 2006). We assume that only ruminant livestock manure is spread on grassland, and application occurs only on pasture and silage areas within each livestock sector and there is no nitrogen trading between sectors. In addition, a soil yield penalty is applied, which lowers the mean yield on grassland use categories within each livestock sector depending on soil groups. The NFS defines three soil groups according to agricultural suitability (I, II, and III, with I being the most productive) and provides mean distributions of each soil group per farm type (Dillon et al., 2022).

Previously calculated dry matter feed requirements per animal are upscaled to represent all cohorts present within each sector depending on average livestock numbers per farm type (Dillon et al., 2022). Dry matter feed requirements depend on Irish grass nutritive value, most

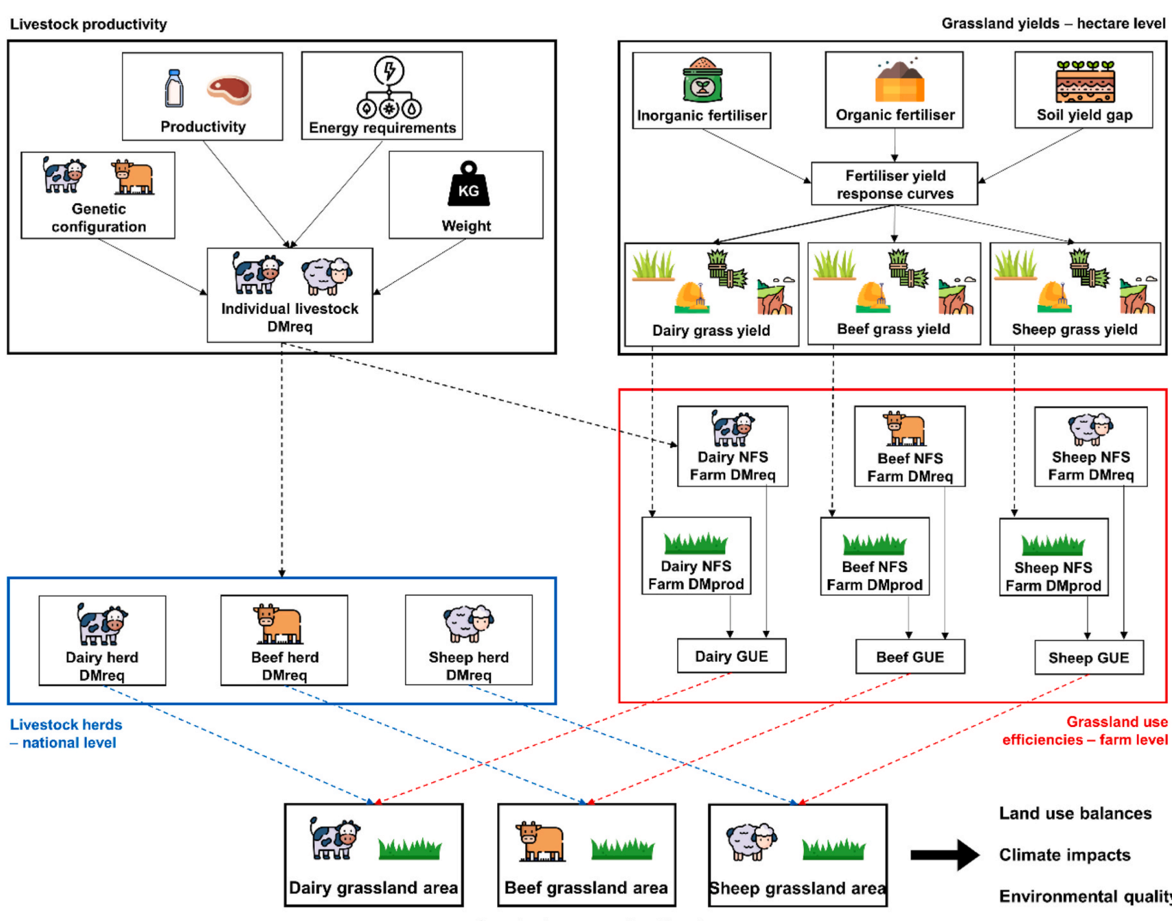

Fig. 2. Structure of *GLAM* as grassland sub-model within the GOBLIN model; total grassland areas of the three livestock sectors (centre) are determined based on data inputs for livestock productivity, grass yields on a per *hectare* level, grassland use efficiencies (GUEs) by average farm type based on the National Farm Survey (Dillon et al., 2022) and dry matter requirements on a national level; DMreq = dry matter requirements, DMprod = dry matter produced.

importantly dry matter digestibility (70%), crude protein content (18.5%), and gross energy (18.5 MJ kg^{-1} DM), and energy demand of livestock for maintenance, activity, weight gain, pregnancy and lactation (IPCC, 2006). Based on the average size and grassland type composition per farm type defined by the NFS (Dillon et al., 2022), dry matter production per farm type was determined using the previously determined average grass yields within each livestock sector. Mean grassland use efficiencies (GUEs) of the three sectors were determined by dividing dry matter requirements by dry matter production (Fig. 2). These GUEs were scaled up and assumed to represent each livestock sector at the scale of national grassland area.

On a national level, total dry matter requirements of each farm type were calculated based on the previously outlined distribution of cohorts between the three livestock sectors. Total grassland areas per farm type were determined by combining the hectare level grass yields from each grassland type (GT), livestock sector (LS) specific GUEs and national level dry matter requirements depending on the different cohorts (C). This resulted in a total of 252 sub-equations as outlined in Equation (1):

$$Total\ grassland\ area = \frac{Dry\ matter\ requirements_{C1\ to\ C21}}{Grass\ yield_{GT1\ to\ GT4} * GUE_{LS1\ to\ LS3}} \quad (1)$$

The developed total grassland areas were used for validation of *GLAM* against national grassland areas from CSO (2023) over the timeframe 2005 to 2015.

2.3. Scenario development and rationale

A baseline scenario was established that represents agricultural activity in Ireland for 2020. Cow numbers were based on the mean numbers of the June and December surveys from CSO in 2020 (CSO, 2023). Where available, real values for the year 2020 were used for baseline scenario setup. When aggregation or extrapolation were necessary, mean values from 2018 to 2020 were used to lower bias from interannual variability yet remain close to the baseline year. Pre-adult cattle herds were compiled based on the *COHORTS* model (Henn et al., 2023a). Herd coefficients, mean slaughter age and weight gain, export rates and fertiliser application rates were based on mean values between 2018 and 2020. The proportion of male DxD calves exported within the first six weeks after birth averaged 30% between 2012 and 2020 (DAFM, 2022). Grassland use efficiencies of each farm type were based on 2015 levels modelled within GOBLIN, unless manually changed as specified scenario inputs.

The 2020 baseline scenario (Sc1) was developed to compare with Scenarios 2–10 (Table 1). These nine scenarios can be classified into five groups of measures that investigate individual impact of changing (1) cow numbers and genetic composition, (2) slaughter age, (3) proportion of DxD male calves exported, (4) using sexed semen with altered male-to-female birth ratios, and (5) improved grassland use efficiency on beef farms. The last two scenarios (9&10) combine measures from the five groups. In all scenarios, a constant milk production of 14.95 L cow^{-1} day^{-1}, 2020 inorganic fertiliser application rates for each grassland use category, and sheep numbers were based on numbers in 2020 and were assumed to remain constant in the analyses (Dillon et al., 2018; Eurostat, 2022).

Purposefully, the scenarios were designed to be extremely ambitious in relation to current projections or national emission mitigation objectives between 2020 and 2030. This was done to assess what can be achieved through national scale implementation of measures without constraint from current policy recommendations. This implies that not all of the scenarios examined reflect expected or desired outcomes from a policy perspective. Instead, they provide estimates of the magnitude of the effectiveness of each investigated scenario. For each scenario, nine key characteristics and impacts were investigated: (1) total cattle numbers, (2) protein output, (3) concentrate feed utilisation, (4) inorganic N fertiliser application, (5) agricultural GHG emissions, (6) ammonia emissions, (7) N leaching from agricultural soils, (8) P runoff/leaching from agricultural soils, and (9) grassland area in use for grazing livestock. National grassland area is the all-encompassing boundary for this study serving as the interface for external imports (for example concentrated feed produced on cropland in Ireland or elsewhere) and exports (export of calves to livestock farms outside of Ireland). Within the grassland boundary, productivity and other different herd management strategies have an immediate impact on grassland area. To simplify the display of the nine key characteristics, results are provided as "scores". A positive score indicates a positive impact on the respective production, environmental or land balancing indicator, while a negative score represents a negative impact. Therefore, an increase in protein output or a decrease across all other characteristics represent a positive score. Scenarios are time insensitive, meaning that the outlined results are independent from the time required for their implementation.

The land sparing potential of each scenario was determined in relation to the grassland area of the 2020 baseline scenario. Greater herbage production per ha for livestock feed compared with the baseline translates into land being available for other uses. On the other hand, higher demand for herbage or feed translates into a requirement for additional grassland for herbage production and thus land use change. Depending on the livestock sector from which land is spared, the average soil group distribution within the sector determines the distribution of spared land

Table 1
Scenario description and inputs, including: dairy and beef cow numbers [000 head], mean slaughter age [days], export percentage of male DxD calves at calf stage within six weeks of birth (average between 2012 and 2020) (DAFM, 2022), sexed semen utilisation, and grassland use efficiency [%] on dairy and beef farms according to GOBLIN calculation (Duffy et al., 2022b).

Scenario	Description	Dairy cows	Beef cows	Mean slaughter age	DxD_m export rate	Sexed semen	Grass use efficiency (dairy/beef)
Units		million head	million head	days	%	✓/×	%
1	2020 Baseline	1.56	0.92	795	30	×	73/55
Dairy specialisation scenarios							
2	Strong dairy increase	2.00	0.47	795	30	×	73/55
3	Very strong dairy increase	2.25	0	795	30	×	73/55
Slaughter age efficiency							
4	90-day reduction	1.56	0.92	705	30	×	73/55
Export scenarios							
5	DxD_m export minimised	1.56	0.92	795	0	×	73/55
6	DxD_m export maximised	1.56	0.92	795	100	×	73/55
Sexed semen scenarios							
7	DxD: 25% M, 75% F DxB/BxB: 75% M, 25% F	1.56	0.92	795	30	✓	73/55
Grassland Use Efficiency							
8	Beef farm improvement by 10%	1.56	0.92	795	30	×	73/65
Combined scenarios							
9	Combination of Sc. 1,4,6,7,8	1.56	0.92	705	30	✓	73/65
10	Combination of Sc. 3,4,6,7,8	2.25	0	705	30	✓	73/65

per soil group. Changing concentrate feed requirements were also calculated in relation to the 2020 baseline scenario. An average, dairy concentrate feed composition for Irish dairy cows was adapted from O'Brien et al. (2012). Using the Ecoinvent v.3.9 cut-off LCA database (Wernet et al., 2016), and accounting for global average land requirements for production of specific feed components, we determined the mean land requirements of feed. Land use change due to lower or higher concentrate feed requirements was assumed to take place outside of Ireland, where about 80% of the concentrate feed components are produced (O'Brien et al., 2012).

Scenario (Sc) 2 and Sc3 investigate a specialisation of the Irish agricultural sector towards dairy production. This trend started in 2011 with the removal of EU milk quotas and was driven by the profitability of pasture-based dairy production (Henn et al., 2023b). This trend is expected to continue in coming years (Donnellan et al., 2018; EPA, 2022). In Sc2, total adult cow numbers remain consistent, but their distribution is altered strongly towards two million dairy cows and 470, 000 beef cows. In Sc3, overall cow numbers are reduced by 9% to 2.25 million, although all of them are dairy cows.

One of the central targets for GHG emission mitigation in Ireland is the reduction of mean slaughter ages of cattle to at least 24 months by 2030 (DECC, 2023). This requires a reduction of circa 70 days from the 2020 baseline of 795 days. This would represent a steep acceleration in productivity, considering that mean slaughter age was reduced by no more than 50 days between 2010 and 2020 (Henn et al., 2023a; ICBF, 2022). We go a step further in Sc4, which involves a 90-day reduction in mean slaughter age of cattle kept for beef production, (i.e. excluding bulls used for breeding, dairy cows and beef cows).

Sc5 and Sc6 are concerned with export rates of male DxD calves. Due to their slow daily weight gain compared with DxB and BxB cattle, they are often considered as a by-product of dairy production and are less profitable for beef production (Rutherford et al., 2021). However, from a global, environmental efficiency perspective, their use is important as they support additional (downstream) beef production from dairy systems, with smaller carbon and environmental footprints compared with specialised BxB beef production (Soteriades et al., 2019). Sc6 examines minimising national environmental impacts by exporting of all male DxD calves. On the other hand, there are animal welfare concerns about the live export of calves from Ireland to continental Europe (Boyle et al., 2022; Mee, 2020; Mee and Boyle, 2020). This could result in stricter requirements for the care of calves during transport or a ban of live exports altogether, and is examined in Sc5.

Sexed semen in dairy and beef cattle herds provide the opportunity to alter the ratio between born male and female calves, allowing the displacement of the consistent surplus of male DxD calves (Holden and Butler, 2018). In beef herds, male DxB and BxB cattle accumulate weight faster than females (ICBF, 2022). However, there are well-known problems with conception rates that might negate economic advantages of sexed semen (Holden and Butler, 2018; Oikawa et al., 2019). In Ireland, conception rates of sexed semen are between 16 and 18% lower than conventional semen (Teagasc, 2023), which can mean a somewhat more protracted breeding to achieve the same rates of pregnancy season where sexed semen is used. Furthermore, we assume that technical improvements in the future can bridge this gap and conception rates remain unchanged. In Sc7, we assume that birth ratios are skewed from current ratios, almost exactly 50% male and female for all three genetic classes (DxD, DxB, and BxB), towards 75% female and 25% male for DxD cattle. Nevertheless, we assume that female DxD births remain constant and male DxD births are lower and instead replaced by a larger number of DxB births. Total offspring numbers from dairy cows remain unchanged. In addition, a DxB birth ratio of 75% male and 25% female is assumed.

Between 2005 and 2015, grassland occupied by the dairy sector has consistently shown a 15–20% higher GUE compared with grassland used by the beef sector. In 2015, GUE was 73% within the dairy sector, 55% within the beef sector and 52% within the sheep sector (Duffy et al., 2022b). In Sc8, the effects of a 10% increase in GUE across grassland of the beef sector are investigated, i.e. closing the gap towards the dairy sector by half.

In Sc9 and Sc10, the effects of mean slaughter age reduction, male DxD calf export maximisation, sexed semen and GUE improvements are combined. Cow numbers and deriving cattle numbers in pre-adult cohorts are based on 2020 (Sc9) or Sc3 (Sc10).

3. Results

3.1. Cattle numbers and structure

In 2020, the baseline scenario (Sc1) contains total cattle numbers of 6.8 million. Dairy expansion scenarios 2 and 3 resulted in a changing composition of offspring towards larger proportions of DxD and DxB cattle (Fig. 3). This resulted in lower cattle numbers in Sc3, where the herd decreased by 9% due to lower cow numbers and subsequently smaller pre-adult cohorts. A mean slaughter age reduction (Sc4) led to 5% lower cattle numbers due to shrinking cohorts of cattle over two years old. Sc5 and Sc6 directly impact DxD pre-adult cohorts and increased total cattle numbers by 4% or decreased them by 8%, respectively. The implementation of sexed semen showed a small effect on total cattle numbers but altered the composition of pre-adult cohorts, mostly from DxD towards DxB. Improved grassland use efficiency had no effect on cattle numbers (Sc8). Combined scenarios 9&10 both lowered total cattle numbers, especially Sc10, which resulted in 5.7 million cattle, the lowest value across scenarios. Genetic distributions in Sc10 are strongly altered towards dairy cows and 68% DxB in pre-adult cohorts.

3.2. Scenario impacts

In Sc1, total bovine protein production comprises 67% from milk and 33% from beef. Sc2 and Sc3 produce 18% and 24% more bovine protein in aggregate, respectively (Fig. 4). This is achieved by larger milk outputs which offset lower beef outputs. The proportion of protein that is supplied by milk rises to 73% in Sc2 and 78% in Sc3. However, replacing beef cows with dairy cows incurs a trade-off by increasing concentrate feed requirements (a dairy cow is typically fed 3.5 times more concentrate feed than a beef cow, annually). In Sc2, slightly lower inorganic fertiliser use was recorded, while the environmental impact remained similar across the investigated impact categories (GHG and NH_3 emissions, N and P nutrient leaching). In Sc3, fertiliser inputs were reduced by circa 15%, which resulted in an improvement of around 10% across all environmental impact categories. This coincided with the 10% reduction in total cattle numbers for Sc3 (Fig. 3). Reduced fertiliser inputs are mainly a direct result of land sparing from agricultural production, depending on the livestock sector it is spared from. Sc4 showed

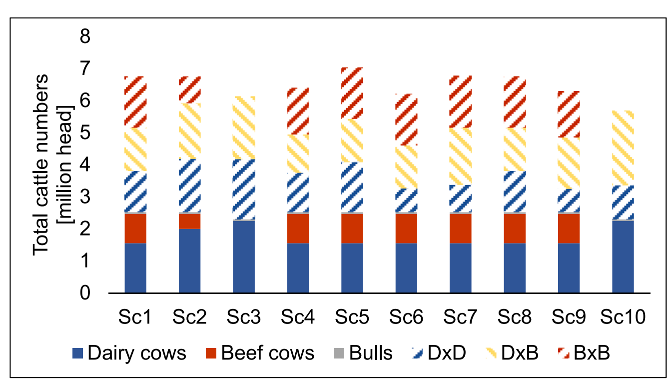

Fig. 3. Total cattle numbers [million head] in Scenarios (Sc) 1 to 10 outlined in Table 1, and distributed into adult cohorts (dairy cows, beef cows and bulls) and pre-adult cohorts grouped by genetics (DxD, DxB and BxB).

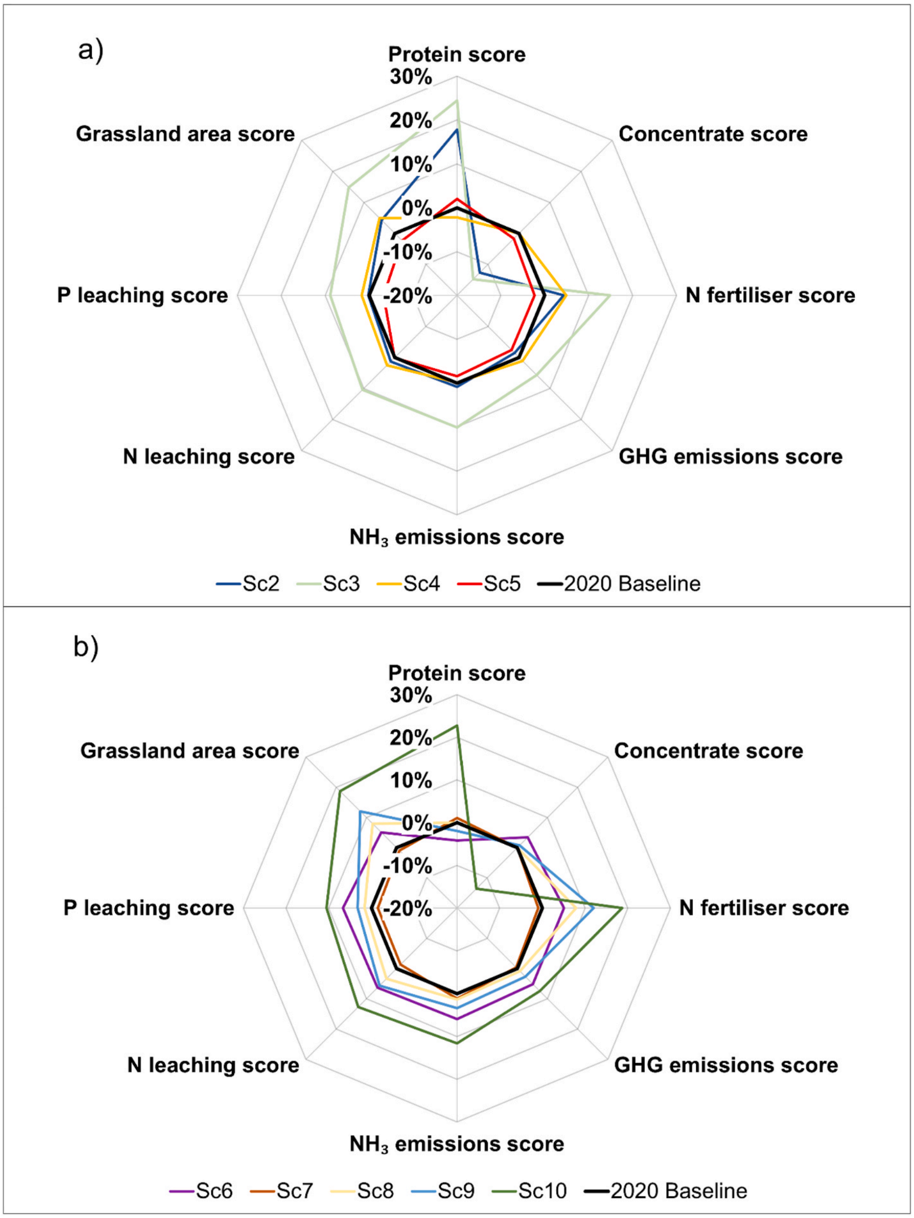

Fig. 4. Radar plot of modelling results from a) Baseline (Sc1) + Sc2 to Sc5 and b) Baseline (Sc1) + Sc6 to Sc10 (Table 1). Investigated results are provided as scores, where positive scores indicate proportional improvement compared to Sc1 (i.e. increase in protein output; decrease in concentrate and N fertiliser input, reduced emissions of GHGs or NH_3 to air, or N and P to water).

very small changes relative to the baseline across environmental impact categories, while protein output and fertiliser application were slightly reduced. Similarly small impacts were observed in Sc7, from the introduction of sexed semen. Sc5 led to slightly more protein production at the expense of larger concentrate feed requirements and environmental impacts, while Sc6 resulted in the opposite. Higher GUE on beef farms (Sc8) lowered inorganic fertiliser applications and environmental impacts, specifically NH_3 and nutrient leaching. Sc9 lowered protein production slightly while concentrate requirements remained stable and all other impact categories were reduced by around 5%. Sc10 showed the largest impact – protein output is increased by 23% at the expense of 14% larger concentrate feed requirement, whilst fertiliser applications and environmental impacts are reduced by 8–13%.

3.3. Total grassland requirements and spared land

The 2020 baseline scenario entailed a grassland area of 4.01 million ha (Fig. 5). Apart from Sc5 and Sc7, where area increased very slightly, all scenarios resulted in grassland sparing opportunities within Ireland. The largest grassland sparing opportunities were found in Sc3 and Sc10, coinciding with the largest reductions in cattle numbers. In these scenarios, 0.6 and 0.75 million ha, respectively, were spared from current grassland use. Consequently, around 15–20% of current grassland areas could be spared, while total protein output would be increased substantially. However, concentrate feed requirements increased for these two scenarios, and resulted in non-Irish land use change of 102 kha and 94 kha, reflecting 17% and 12%, respectively, of grassland area directly spared within Ireland. No significant non-Irish land area was spared globally across the other scenarios, apart from in Sc6 where less concentrate feed was required due to the prompt export of all male DxD calves (in this case, global land sparing would only take place if calves are slaughtered for veal soon after export). Otherwise, global feed requirements would remain stable and are solely displaced from Ireland to the export country. Across all scenarios, between 88% and 93% of land

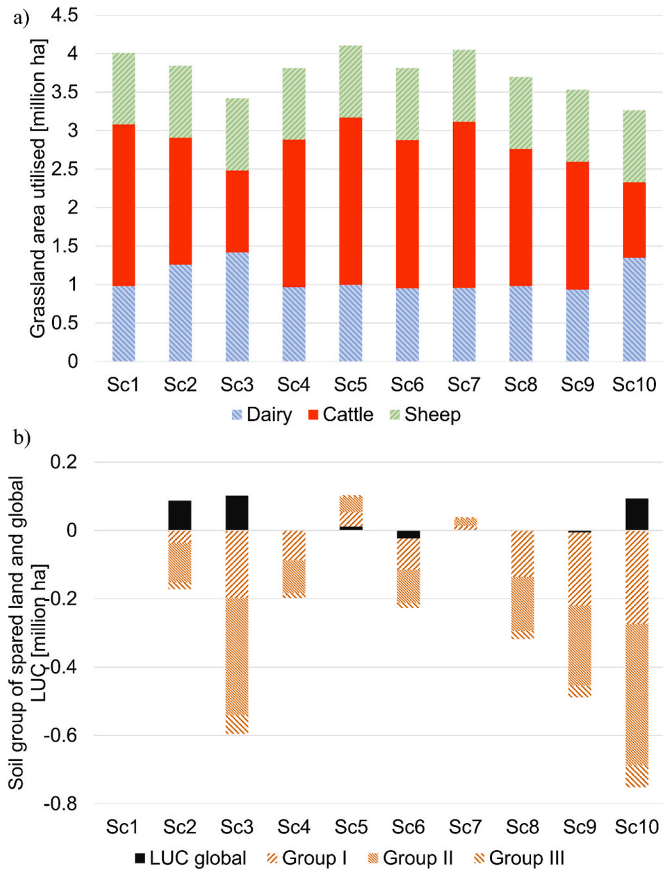

Fig. 5. (a) Grassland area [million ha] per livestock sector (dairy, cattle and sheep) in Scenarios 1 to 10 and (b) spared grassland per soil group I to III in Ireland [million ha], defined by the NFS according to their productivity (Dillon et al., 2022), and land use change (LUC) outside of Ireland due to varying concentrate feed requirements (negative values indicate land sparing compared to Sc1, positive values indicate additional land requirements).

use change in Ireland occurred on soils of groups I and II, the most productive soil classifications (Fig. 5).

4. Discussion

4.1. Modelling approach

The new *GLAM* sub-model within GOBLIN is primarily based on yield response functions that determine grass production and the underlying productivity of grassland resources. Therefore, the model is easily adaptable to different response functions and databases that may become available to increase the accuracy of predicting grass productivity, such as PastureBase in Ireland (O'Donovan et al., 2022). It could also be adapted to represent different sward compositions, such as grass-clover or multi species swards which have the potential to provide large herbage yields while improving environmental quality (Baker et al., 2023; Herron et al., 2021; Yan et al., 2013). Combined with type of grassland management specific data on fertiliser inputs, these allow for a greater level of differentiation between grasslands within each livestock sector in terms of productivities and area-based emissions. The distribution of livestock cohorts onto varying farm types provides the foundation of modelling herd dynamics, and their grass feed and land area requirements. At present, the model contains three different livestock sectors with a total of twelve unique grassland use categories, which is a vast improvement on previous GOBLIN model resolution (Duffy et al., 2022b). In future studies, there is great potential to further improve the structure and implement “mixed livestock” systems with lower degrees of specialisation into the model. In addition, further distribution according to performance or intensity spreads within farm types could enable testing of measures to close gaps between high- and low-performance farms of similar typologies (Buckley and Donnellan, 2022). Livestock intensity could be used as a proxy to differentiate between conventional and organic production systems, which are growing in importance and typically operate under nitrogen and livestock stocking rate limitations. This will further improve the utility of bio-physical modelling by elucidating a wider range of interventions across prospective herd compositions. This is especially relevant in Ireland, where herd composition and farm dynamics have changed substantially over the past decade and a further increase in dairy cows is expected due to high profitability gaps between farm systems (Donnellan et al., 2018; EPA, 2022).

To meet future climate and other environmental targets in Ireland, large-scale land sparing from grasslands is a necessity (Gorman et al., 2023; Haughey et al., 2023). This will require models to support informed decision-making around effective strategies involving appropriate land uses in relation to farm and grassland types and soil categories. Scenarios presented here outline large-scale potential for land sparing on a national level, even where total bovine protein output remains constant or increases. The next step is spatial determination of where these can be implemented based on current agricultural systems, soils, climate and other specific regional factors. The modelled changes in livestock systems would entail significant structural changes to Ireland's agriculture sector, including the exit, merger and conversion of many farms. One important caveat about realising the land sparing potential indicated by biophysical modelling is the economic pull that could be exerted by more productive livestock systems towards expansion of production. To realise environmental benefits from land sparing, a robust policy framework will be required to promote diversification of spared land and prevent further intensification through additional cattle stocking (particularly dairy). Such intensification would also be likely to have consequences for animal welfare and biodiversity (Carter et al., 2023; Stafford and Gregory, 2008).

4.2. Climate and environmental impact

Presented scenarios indicate that substantial reductions in agricultural GHG emissions will be difficult to achieve through the evaluated measures, without significant reductions in overall cattle numbers. Sc3, Sc6 and Sc10 were the only scenarios that reduced GHG emissions by 5% or more, Sc10 representing the largest reduction of 7.5%. Notably, these three were the only scenarios that included larger reductions in total cattle numbers, between 8 and 15%. This indicates that total cattle numbers are a more important driver of agricultural emissions compared with other herd dynamics or compositions. While dairy cows have larger GHG emission factors per head, a larger proportion of their offspring is exported, and the remaining offspring are less emission intensive compared to those from beef cattle. However, in scenarios with larger dairy cow populations, an increase in protein production was achieved due to much larger milk outputs and comparatively small losses of beef production. Dairy specialisation is likely to further reduce the average carbon footprint per litre of milk produced in Ireland. More broadly (at global scale), dairy specialisation may come at the risk of increasing beef carbon footprints due to lower dairy-beef outputs driving a shift towards more specialised beef production with a larger carbon footprint, unless beef demand is dramatically reduced (Soteriades et al., 2019). Meanwhile, the indirect emissions effects of displacing beef production systems overseas are unclear and could be either positive or negative. Ultimately, whilst herd reductions may become a necessity to meet environmental targets, and the much less profitable beef sector is more likely to shrink first, scenarios evaluated here highlight how a reduction in total cattle numbers does not necessarily mean a reduction in total protein output. Protein production is used as proxy for the economic growth of the Irish agricultural sector that was achieved since 2011, closely linked with livestock production, particularly from the dairy sector (Fitzgerald, 2019). Often it is also associated with Ireland's contribution to global food security. However, close to 80% of agri-food export value was generated in the EU-27 countries, UK and United States in 2022 (DAFM, 2023), countries where protein availability is well-established.

All scenarios fall far short of the 2030 national target to reduce GHG emissions by 25% compared with 2018 values (Government of Ireland, 2021). Therefore, there remains an urgent need for rapid implementation of additional mitigation measures to reduce agricultural emissions, as proposed by Lanigan et al. (2023) and the Irish Climate Action Plan (DECC, 2023). Strategies defined in the evaluated scenarios appear much more important for land sparing, supporting GHG emission mitigation within the LULUCF sector, than for direct emission reductions in the agricultural sector. In reality, farmers manage most land, and the sectors are closely intertwined; indeed, the agricultural and LULUCF sectors may be accounted for as a combined Agriculture, Forestry and Other Land Use (AFOLU) sector in the future (European Parliament, 2023; Herold et al., 2021). Outlined structural changes need to go hand in hand with effective farm-scale mitigation measures to lower agricultural emissions while turning the land use sector from an annual source of carbon into a sink.

As part of the European Green Deal, the EU has targets to reduce nutrient losses by 50% and inorganic fertiliser use by 20% (European Commission, 2019). The majority of investigated scenarios have a positive impact on both of these targets, especially reducing inorganic fertiliser application. Sc3 and Sc10 reduce inorganic N fertiliser application by over 15% (Fig. 4), almost entirely achieving the outlined target without further measures. However, N and P leaching are far less effectively mitigated in all of the scenarios in this study, achieving a maximum reduction of 15% in Sc10. From 2030 onwards, Ireland is obliged to reduce ammonia emissions to 113.6 kt annual emissions according to the EU emission ceiling directive (EPA, 2021; Hyde et al., 2021), a 12.3% reduction in relation to the 2020 baseline situation. Sc3 and Sc10 reduce NH_3 emissions by 10.1% and 11.6% respectively, indicating that the outlined scenarios can contribute substantially to meeting ammonia reduction targets.

The sexed semen strategy implemented in scenarios 7, 9 and 10 resulted in very small effects on all evaluated impact categories, only providing isolated benefits in combination with drawbacks for other attributes, e.g. lower environmental impact but also lower protein production (from beef). Whilst increasing the birth ratio of DxD cattle towards female replacement heifers for dairy production may reduce the environmental impact of dairy farms on a farm level, less protein is produced on a national level. As outlined in the context of dairy specialisation, maintaining protein production levels would require additional beef production from BxB cattle, mitigating any farm-level environmental benefits. Hence, when combined with challenges such as reduced conception rates, our results suggest that sexed semen offers little meaningful potential for improvement of environmental quality or land sparing on a national level.

4.3. Land sparing and soil quality

The investigated scenarios outline pathways to reduce grassland areas needed for cattle by up to 0.75 million ha, circa 20% of all Irish grassland. Depending on accounting method and net-zero target definition (and which sectors are included), projections outline that between 0.5 and 1 million ha will be needed for afforestation and wetland restoration to meet 2050 targets and create sufficient carbon sequestration to offset livestock and other agricultural emissions (Duffy et al., 2022a; Haughey et al., 2023).

At least 88% of spared land was found to be on soil groups I and II, depending on scenario. These are the most productive soils, not only for agriculture, but also for biomass production in forests (Duffy et al., 2020). This is crucial in terms of the potential for CDR from new forests established on these soils. A comparatively small proportion of soils is within group III. A significant gap in knowledge is the distribution of drained organic soils across the three soil groups. Identifying where these are located is crucial to develop strategies for preferential land sparing and appropriate management, including wetland restoration, enhanced soil carbon storage and afforestation. This is especially important given that past afforestation on organic soils within soil group III means is contributing to a rapidly declining carbon sink within Irish forests. Forests planted on organic soils may even be a net source of GHG emissions according to recently revised emission factors for organic soils under forest (Jovani-Sancho et al., 2021), outlining the importance of sparing good quality land for afforestation measures. A major barrier to implementation of nature-based solutions on such land could be the willingness of farmers to diversify this land out of food production. There are a variety of concerns among farmers about forest conversion, especially the perceived loss of value of the land and the irreversibility of the conversion due to current regulations (Vidyaratne et al., 2020). Overcoming such barriers may require a restructuring of current afforestation policies to enhance economic benefits and increase flexibility (Ryan et al., 2022).

In scenarios with increased dairy cow numbers, a growing demand for concentrate feed was observed. This resulted in land use requirements outside Ireland that were not further specified on the global market. Additional global land use requirements were modest compared to land sparing opportunities within Ireland under the investigated scenarios, representing 10–50% of spared national areas. The overall GHG balance that would result from the land use change outside and inside Ireland will be strongly case dependent on previous land use in countries where feed components are produced and subsequent use of converted grasslands in Ireland. Further studies are required to investigate possible outcomes.

4.4. Limitations

Environmental and land modelling is subject to substantial uncertainties. GOBLIN validation methods were outlined in detail by Duffy et al. (2022b). *GLAM* was validated within GOBLIN over the time period from 2005 to 2015 against total national grassland areas from CSO (2023) and achieved less than 2% mean difference over this timeframe (Figure Appendix A.1).

For this work, scenario development was based purely on the national cattle herd and interactions between dairy and beef sectors and area requirements and their effect on important characteristics and environmental impacts. According to GOBLIN, approximately 20% of Irish grasslands are used for sheep production (Duffy et al., 2022b), and different sheep flock strategies, production levels and management practices should certainly be investigated in future scenarios.

An important next step will be to model pathways towards national climate neutrality based on the investigated scenarios. This will require the development of land use strategies to determine how remaining grassland and spared land are managed, including the addition of measures from the LULUCF sector like afforestation (of various tree species, yield classes and management regimes) and wetland restoration.

5. Conclusions

The development of *GLAM* enables a more dynamic and higher resolution modelling of prospective national grassland-based livestock herds, land management practises and associated land requirements. Scenarios that increased dairy cow numbers at the expense of beef cow numbers, especially when combined with overall herd reductions, slaughter age reduction, increased male dairy calf exports and GUE improvements, showed tremendous potential on the Irish national scale to spare high-quality land from agricultural use. Meanwhile, limiting the export of male dairy calves and implementation of sexed semen had adverse or small impacts. The explored scenarios could provide a significant contribution to meeting ammonia reduction targets but offered limited progress towards meeting agricultural GHG emissions and nutrient leaching reduction targets. Previously studied farm-scale mitigation measures not explicitly modelled here, and/or reductions in animal protein output, may be needed to meet those targets.

Substantial land use diversification will be required to achieve climate neutrality across the agricultural and LULUCF sector by mid-century and to meet biodiversity targets. This study demonstrates an important potential contribution from modified cattle production strategies. Realising potential environmental benefits will require integration with technical emission abatement measures and appropriate land use strategy via coordinated policies pertaining to agriculture, land use and environmental protection.

CRediT authorship contribution statement

Daniel Henn: Conceptualization, Methodology, Validation, Writing – original draft. **Colm Duffy:** Methodology, Software, Validation, Writing – review & editing. **James Humphreys:** Conceptualization, Funding acquisition, Writing – review & editing. **James Gibbons:** Writing – review & editing. **Kenneth A. Byrne:** Writing – review & editing. **David Styles:** Methodology, Supervision, 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.

Data availability

Data will be made available on request.

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Appendix

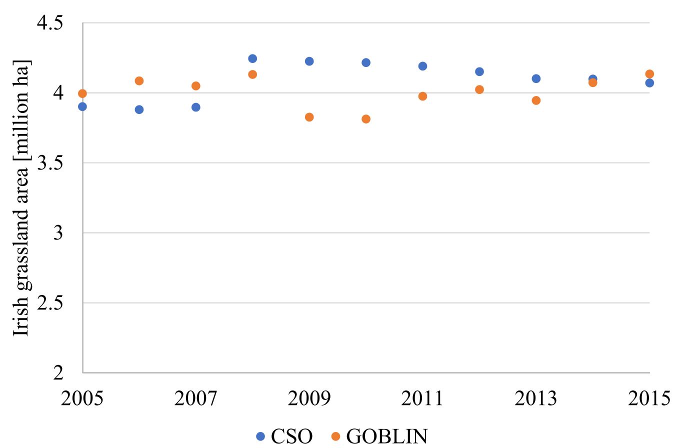

Fig. A.1. Time series between 2005 and 2015 displaying Irish grassland area (containing pasture, silage, hay and rough grazing) from CSO (2023) and GOBLIN (Duffy et al., 2022b)

References

AMCTB, 2014. Meat and poultry nitrogen factors. Anal. Methods 6, 4493–4495.

Baker, S., Lynch, M.B., Godwin, F., Boland, T.M., Kelly, A.K., Evans, A.C.O., Murphy, P.N. C., Sheridan, H., 2023. Multispecies swards outperform perennial ryegrass under intensive beef grazing. Agric. Ecosyst. Environ. 345, 108335 https://doi.org/10.1016/j.agee.2022.108335.

Bishop, G., Duffy, C., Prudhomme, R., Cowie, A., O'Donoghue, C., Cain, M., Lanigan, G. J., Styles, D., 2024. Defining National "Net Zero" Goals is Critical for Food and Land Use Policy. Commun. Earth Environ. 5, 104. https://doi.org/10.1038/s43247-024-01275-0.

Boyle, L., Conneely, M., Kennedy, E., O'Connell, N., O'Driscoll, K., Earley, B., 2022. Animal welfare research – progress to date and future prospects. Ir. J. Agric. Food Res. 61, 87–108.

Buckley, C., Donnellan, T., 2022. National Farm Survey - 2021 Sustainability Report. Athenry, Ireland.

Carter, A., Henchion, M., Hynds, P., Markiewicz-Keszycka, M., Mooney, S., O'Brien, D., 2023. Pro-environmental diversification of pasture-based dairy and beef production in Ireland, the United Kingdom and New Zealand: a scoping review of impacts and challenges. Renew. Agric. Food Syst. 38, e5. https://doi.org/10.1017/S1742170522000382.

CSO, 2023. Central Statistics Office - Databases [WWW Document]. URL. https://data.cso.ie/. (Accessed 27 April 2023).

DAFM, 2023. Tract Factsheet Full Year 2022 [WWW Document]. URL. https://assets.gov.ie/221990/eeb9bffd-8863-4d37-899f-a6d34d9f3fa7.pdf.

DAFM, 2022. AIM Bovine Statistics Reports.

DECC, 2023. Climate Action Plan 2023. CAP23.

Dillon, E., Buckley, C., Moran, B., Lennon, J., Wall, D., 2018. Teagasc National Farm Survey - Fertilizer Use Survey 2005-2015.

Dillon, E., Donnellan, T., Moran, B., Lennon, J., 2022. Teagasc National Farm Survey 2021.

Donnellan, T., Hanrahan, K., Lanigan, G., 2018. Future Scenarios for Irish Agriculture: Implications for Greenhouse Gas and Ammonia Emissions.

Duffy, C., O'Donoghue, C., Ryan, M., Styles, D., Spillane, C., 2020. Afforestation: replacing livestock emissions with carbon sequestration. J. Environ. Manag. 264, 1–15. https://doi.org/10.1016/j.jenvman.2020.110523.

Duffy, C., Prudhomme, R., Duffy, B., Gibbons, J., Iannetta, P.P.M., O'Donoghue, C., Ryan, M., Styles, D., 2022a. Randomized national land management strategies for net-zero emissions. Nat. Sustain. https://doi.org/10.1038/s41893-022-00946-0.

Duffy, C., Prudhomme, R., Duffy, B., Gibbons, J., O'Donoghue, C., Ryan, M., Styles, D., 2022b. GOBLIN version 1.0: a land balance model to identify national agriculture and land use pathways to climate neutrality via backcasting. Geosci. Model Dev. (GMD) 15, 2239–2264. https://doi.org/10.5194/gmd-15-2239-2022.

Duffy, P., Black, K., Fahey, D., Hyde, B., Kehoe, A., Kent, T., MacFarlane, B., Monaghan, S., Murphy, J., Ponzi, J., Ryan, A.M., 2023. Ireland's National Inventory Report 2023 Greenhouse Gas Emission 1990-2021.

Eory, V., MacLeod, M., Shrestha, S., Roberts, D.J., 2014. Linking an economic and a life-cycle analysis biophysical model to support agricultural greenhouse gas mitigation policy. Ger. J. Agric. Econ. 63, 133–142.

EPA, 2022. Ireland's Greenhouse Gas Emissions Projections 2021-2040.

EPA, 2021. Ireland's Air Pollutant Emissions 1990-2030.

European Commission, 2019. The European green deal. Eur. Community 53, 24. https://doi.org/10.1017/CBO9781107415324.004.

European Parliament, 2023. Regulation (EU) 2023/839 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out the targets of the Member States for 2030, and [WWW Document]. URL. http://data.europa.eu/eli/reg/2023/839/oj.
Eurostat, 2022. Eurostat Database [WWW Document]. URL. https://ec.europa.eu/eurostat/data/database. (Accessed 18 May 2023).
Finneran, E., Crosson, P., O'Kiely, P., Shalloo, L., Forristal, D., Wallace, M., 2012. Stochastic simulation of the cost of home-produced feeds for ruminant livestock systems. J. Agric. Sci. 150, 123–139. https://doi.org/10.1017/S002185961100061X.
Fitzgerald, C., 2019. Dairy in the Irish economy. Irish Dairy. Grow. Sustain. 46–48.
Gorman, C.E., Torsney, A., Gaughran, A., McKeon, C.M., Farrell, C.A., White, C., Donohue, I., Stout, J.C., Buckley, Y.M., 2023. Reconciling climate action with the need for biodiversity protection, restoration and rehabilitation. Sci. Total Environ. 857, 159316 https://doi.org/10.1016/j.scitotenv.2022.159316.
Government of Ireland, 2021. Climate Action Plan 2021: Securing Our Future.
Greenfield, H., Southgate, D.A.T., 2003. Food Composition Data: Production, Management, and Use. FAO.
Haughey, E., Styles, D., Saunders, M., Benneth Coady, R., Moran, J., 2023. Land Use Review: Fluxes, Scenarios and Capacity, Evidence Synthesis Report: 3. Johnstown Castle, Ireland.
Henn, D., Humphreys, J., Duffy, C., Gibbons, J., Styles, D., 2023a. Improved representation of cattle herd dynamics for bio-physical modelling of pathways to a climate neutral land sector. Agric. Syst. 212, 103772 https://doi.org/10.1016/j.agsy.2023.103772.
Henn, D., Humphreys, J., Gibbons, J., Styles, D., 2023b. Land use and environmental quality in Ireland over two decades of contrasting agricultural trends. Biol. Environ. 123B, 39–53. https://doi.org/10.1353/bae.2023.0001.
Herold, A., Boettcher, H., Gores, S., Urrutia, C., 2021. 2030 Climate Target: Review of LULUCF Regulation [WWW Document]. URL. https://www.europarl.europa.eu/cmsdata/233827/Background_paper_LULUCF_Regulation_2030_Climate_target.pdf.
Herron, J., Hennessy, D., Curran, T.P., Moloney, A., O'Brien, D., 2021. The simulated environmental impact of incorporating white clover into pasture-based dairy production systems. J. Dairy Sci. 104, 7902–7918. https://doi.org/10.3168/jds.2020-19077.
Holden, S.A., Butler, S.T., 2018. Review: applications and benefits of sexed semen in dairy and beef herds. Animal 12, s97–s103. https://doi.org/10.1017/S1751731118000721.
Hyde, B., Duffy, P., Ryan, A.M., Murphy, J., Fahey, D., Monaghan, S., Kehoe, A., 2021. Ireland's Informative Inventory Report 2021: Air Pollutant Emissions in Ireland 1990-2019. Johnstown Castle, Ireland.
ICBF, 2022. Irish Cattle Slaughter Database 2006 to 2021.
IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds) Published: IGES, Japan.
IPCC, 2019a. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson, V. (Eds.), Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge Univ. Press, Cambridge, UK New York, NY, USA. https://doi.org/10.1017/9781009157988. Delmot [WWW Document].
IPCC, 2019b. In: Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S. (Eds.), 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.
Jovani-Sancho, A.J., Cummins, T., Byrne, K.A., 2021. Soil carbon balance of afforested peatlands in the maritime temperate climatic zone. Global Change Biol. 27, 3681–3698. https://doi.org/10.1111/gcb.15654.
Lanigan, G., Black, K., Donnellan, T., Crosson, P., Beausang, C., Hanrahan, K., Buckley, C., Lahart, B., Herron, J., Redmond, J., Shalloo, L., Krol, D., Forrestal, P., Farrelly, N., O'Brien, D., Lenehan, J.J., Hennessy, M., O'Donovan, M., Wall, D., O'Sullivan, L., O'Dwyer, T., Dineen, M., Waters, S., NiFlahartha, N., Houlihan, T., Murphy, P., Spink, J., Dillon, P., Upton, J., Richards, K., 2023. MACC 2023: an Updated Analysis of the Greenhouse Gas Abatement Potential of the Irish Agriculture and Land-Use Sectors between 2021 and 2030. Oak Park, Carlow, Ireland.
Mazzetto, A.M., Feigl, B.J., Schils, R.L.M., Cerri, C.E.P., Cerri, C.C., 2015. Improved pasture and herd management to reduce greenhouse gas emissions from a Brazilian beef production system. Livest. Sci. 175, 101–112. https://doi.org/10.1016/j.livsci.2015.02.014.
Mee, J.F., 2020. Denormalizing poor dairy youngstock management: dealing with "farm-blindness.". J. Anim. Sci. 98, 140–149. https://doi.org/10.1093/jas/skaa137.
Mee, J.F., Boyle, L.A., 2020. Assessing whether dairy cow welfare is "better" in pasture-based than in confinement-based management systems. N. Z. Vet. J. 68, 168–177. https://doi.org/10.1080/00480169.2020.1721034.
O'Brien, D., Moran, B., Shalloo, L., 2018. A national methodology to quantify the diet of grazing dairy cows. J. Dairy Sci. 101, 8595–8604. https://doi.org/10.3168/jds.2017-13604.
O'Brien, D., Shalloo, L., Patton, J., Buckley, F., Grainger, C., Wallace, M., 2012. A life cycle assessment of seasonal grass-based and confinement dairy farms. Agric. Syst. 107, 33–46. https://doi.org/10.1016/j.agsy.2011.11.004.
O'Donovan, M., Dillon, P., Conaghan, P., Hennessy, D., 2022. Irish Grassland Research — main achievements and advancements in the past 60 yrs and where to progress to next. Ir. J. Agric. Food Res. https://doi.org/10.15212/ijafr-2020-0152.
O'Mara, F., 2006. Climate Change: Development of Emission Factors for the Irish Cattle Herd.
O'Mara, F., Richards, K.G., Shalloo, L., Donnellan, T., Finn, J.A., Lanigan, G., 2021. Sustainability of ruminant livestock production in Ireland. Anim. Front. 11, 32–43. https://doi.org/10.1093/af/vfab037.
Oikawa, K., Yamazaki, T., Yamaguchi, S., Abe, H., Bai, H., Takahashi, M., Kawahara, M., 2019. Effects of use of conventional and sexed semen on the conception rate in heifers: a comparison study. Theriogenology 135, 33–37. https://doi.org/10.1016/j.theriogenology.2019.06.012.
Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs, G.-J., Popp, A., Sánchez, M.J.S., Sanderman, J., Smith, P., Stehfest, E., Lawrence, D., 2019. Contribution of the land sector to a 1.5 °C world. Nat. Clim. Change 9, 817–828. https://doi.org/10.1038/s41558-019-0591-9.
Rutherford, N.H., Lively, F.O., Arnott, G., 2021. A review of beef production systems for the sustainable use of surplus male dairy-origin calves within the UK. Front. Vet. Sci.
Ryan, M., O'Donoghue, C., Hynes, S., Jin, Y., 2022. Understanding planting preferences – a case-study of the afforestation choices of farmers in Ireland. Land Use Pol. 115, 105982 https://doi.org/10.1016/j.landusepol.2022.105982.
Sandker, M., Finegold, Y., D'Annunzio, R., Lindquist, E., 2017. Global deforestation patterns: comparing recent and past forest loss processes through a spatially explicit analysis. Int. For. Rev. 19, 350–368.
Searchinger, T., Peng, L., Zionts, J., Waite, R., 2023. The Global Land Squeeze: Managing the Growing Competition for Land. https://doi.org/10.46830/wrirpt.20.00042 [WWW Document].
Soteriades, A.D., Foskolos, A., Styles, D., Gibbons, J.M., 2019. Diversification not specialization reduces global and local environmental burdens from livestock production. Environ. Int. 132, 1–15. https://doi.org/10.1016/j.envint.2019.05.031.
Stafford, K.J., Gregory, N.G., 2008. Implications of intensification of pastoral animal production on animal welfare. N. Z. Vet. J. 56, 274–280. https://doi.org/10.1080/00480169.2008.36847.
Teagasc, 2023. Sexed Semen [WWW Document]. URL. https://www.teagasc.ie/animals/dairy/breeding–genetics/sexed-semen/.
UNFCCC, 2015. Paris agreement on climate change, united nations framework convention on climate change, UNFCC: adoption of the Paris agreement. In: 21st Conference of the Parties. Paris, United Nations, 12 December 2015.
van Selm, B., de Boer, I.J.M., Ledgard, S.F., van Middelaar, C.E., 2021. Reducing greenhouse gas emissions of New Zealand beef through better integration of dairy and beef production. Agric. Syst. 186, 102936 https://doi.org/10.1016/j.agsy.2020.102936.
Vidyaratne, H., Vij, A., Regan, C.M., 2020. A socio-economic exploration of landholder motivations to participate in afforestation programs in the Republic of Ireland: the role of irreversibility, inheritance and bequest value. Land Use Pol. 99, 104987 https://doi.org/10.1016/j.landusepol.2020.104987.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.
Yan, M.J., Humphreys, J., Holden, N.M., 2013. The carbon footprint of pasture-based milk production: can white clover make a difference? J. Dairy Sci. 96, 857–865. https://doi.org/10.3168/jds.2012-5904.