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1. Extended Data

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Supplementary Information	Yes	supplementary_materials.pdf	Supplementary figure 1
Reporting Summary	Yes		

Peer Review Information	No	*OFFICE USE ONLY*

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Supplementary Data	1	Scenario_input.csv	Original scenario generation for modelling sample

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Randomised national land management strategies for net-zero emissions

Colm Duffy[(1,7)], Remi Prudhomme[2], Brian Duffy[6], James Gibbons[3], Pietro P. M. Iannetta[7], Cathal O'Donoghue[4], Mary Ryan[5], David Styles[1]

[1]Bernal Institute, School of Engineering, University of Limerick, Ireland
[2]CIRAD Département Environments et sociétés, Montpellier, Languedoc-Roussillon, France
[3]School of Natural Sciences, Bangor University, Bangor, Wales, UK
[4]National University of Ireland Galway Policy Lab, University Road, Galway, H91 REW4, Ireland
[5]Rural Economy & Development Programme, Teagasc, Athenry, Co. Galway, Ireland
[6]Independent Researcher
[7]Ecological Sciences, The James Hutton Institute, Dundee, United Kingdom

Correspondence to: Colm Duffy (Colm.Duffy@hutton.ac.uk)

Abstract

Global scenario modelling for climate stabilisation lacks national resolution, particularly for the agriculture, forestry and other land use (AFOLU) sector, impeding effective national climate policy making. We generate 850 randomised scenarios of activity combinations for Ireland's AFOLU sector in the year 2050 and evaluate associated greenhouse gas (GHG) fluxes to the year 2100. Using a GWP_{100} "net-zero" GHG definition, 146 scenarios achieve AFOLU climate neutrality and 38 contribute to national neutrality (a significant AFOLU sink) by 2050. Just one scenario contributes to national climate neutrality through to 2100, reflecting future declines in CO_2 removals by new forests (excluding potential downstream mitigation). In the absence of technical solutions to dramatically reduce the emissions intensity of bovine production, national milk and beef output will need to be significantly curtailed to achieve net-zero emissions. Active carbon dioxide removal on destocked land, via organic soil rewetting and ambitious afforestation, could moderate output declines in milk and beef production, reducing international carbon leakage risks.

Keywords: climate policy; biophysical model; LULUCF; food security; scenario analysis

Main Text

The recent IPCC[1] AR6 report has left no doubt about the scale of the global climate challenge facing humanity. Every region of the globe is projected to experience concurrent and multiple changes in climate impact-drivers (climate system conditions that affect an element of society or ecosystems). Limiting future warming to a specific level will require, at least, reaching "net-zero" CO_2 emissions along with "strong, rapid and sustained" reductions in CH_4 and other greenhouse gas (GHG) emissions[1]. The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement[2] emphasises that we must reach peak GHG emissions as quickly as possible, with parties striving to achieve a balance between anthropogenic emissions and removals. There is an urgent need to identify pathways to "net-zero GHG emissions" at national scale across all countries.

Globally, the Agriculture Forestry and Other Land Use (AFOLU) sector is both a major emissions source and sink due to agricultural production and land use, land use change & forestry (LULUCF) activities. Smith et al[3] states that the AFOLU sector is responsible for almost one quarter of all anthropogenic emissions, but has vast potential for mitigation. However, there are significant institutional, policy coordination and implementation issues that impede realisation of this mitigation potential[3]. A lack of high-resolution information on the range of AFOLU configurations compatible with climate neutrality, food production and delivery of other services constitutes a major barrier to effective climate action.

Global Integrated Assessment Models (IAMs) are essential tools that underpin global climate science and policy[4,5]. IAMs include important assumptions in relation to resources, technologies, population dynamics and mitigation policy[4]. Inevitably, national context and landscape detail is lost in such global modelling. Scenario development tools that can assess relatively large (national) scale scenarios, whilst preserving important agricultural practices and landscape detail, are needed to inform effective national climate policy. Current national climate neutrality plans have been criticised for lacking detail and being vague in the definition of neutrality[6]. The development of detailed national climate neutrality plans appropriate to the Paris Agreement will require high-resolution integrated modelling of national emissions sources and sinks.

The objective of this paper is to elaborate and interpret independently generated scenarios depicting AFOLU transition pathways that comply with net-zero GHG emission constraints at the national and sectoral level by 2050. This is done utilising a national biophysical AFOLU model, "GOBLIN" (General Overview for a Back-casting approach of Livestock INtensification)[7], and Ireland as a case study country owing to a dichotomy between expansion plans for a comparatively efficient agri-food sector and climate policy objectives[8]. GOBLIN integrates randomly varied key parameters determining GHG fluxes in the land sector, utilising a methodology consistent with Ireland's UNFCCC reporting[9] to account for major AFOLU sources and sinks (Fig. 1).

Country Context

Irish agriculture emits 20.5 Tg CO2 eq. annually, 34% of national GHG emissions[9], of which 92% originates from cattle (beef and milk production), 4% from sheep and 2% from other livestock[9]. In addition, roughly 9 Tg of CO_2 eq. are emitted per annum from drained organic soils and 2 Tg CO_2 eq. from exploited wetlands, while Irish grassland mineral soils and forests remove 2 and 5 Tg of CO_2 eq. per annum, respectively[9]. As such, Ireland's LULUCF sector is a net emissions source of over 4 Tg CO_2 eq. annually. Meanwhile, Ireland's Climate Action

Bill[11] sets a target for 51% reduction in national emissions by 2030. As such, Ireland's AFOLU sector has a key role to play in terms of both emissions reduction and Carbon Dioxide Removal (CDR).

CO_2 is the most important gas in relation to climate change. However, CH_4 has a significant warming impact[12]. Though it is acknowledged that CH_4 has a relatively short life-span in the atmosphere (9 – 12 years in the troposphere), Saunois et al[12] emphasise that CH_4 remains a potent GHG and large reductions in CH_4 emissions will be critical to stabilise the climate[1]. CH_4 accounts for circa 67% of Ireland's agricultural GHG emissions, with over 12 Tg year^{-1} originating from enteric fermentation, and LULUCF emissions of CH_4 could increase if organic soils are rewetted to reduce CO_2 emissions[13]. The future shape of climate neutrality in Ireland's AFOLU sector, and the amount of beef and milk that can be produced within associated emission constraints, is thus particularly sensitive to the method of CH_4 accounting in terms of warming equivalent[14,15].Given the transformative nature of climate neutrality solutions, and associated socio-economic, political, and cultural implications (resistance), it is crucial that development of climate neutrality scenarios is undertaken in a transparently objective manner. Here, randomised scenario generation in GOBLIN is combined with filtering of scenarios according to emissions profiles compatibility with a " net-zero GHG emission" definition of climate neutrality[16,17], in line with Ireland's national carbon budgets approach[8]. From here on, for the purpose of brevity, "climate neutrality" is taken to represent net-zero GHG emission. Randomised scenarios reduce the risk of (model) user preconceptions (bias) constraining identification of prospective pathways to climate neutrality by 2050, and beyond.

Results

Activity inputs to the model were randomly varied utilising a Latin hypercube model[10] between predefined floor and ceiling values (Table 1) to generate 850 scenarios (see Duffy et al.[7] for full list and definitions of scenario parameter inputs). Randomised scenarios were then classified as: (i) failed to meet neutrality (N-Z-Fail), net flux > 2.5 Tg CO_2e; (ii) achieved AFOLU neutrality (N-Z-AFOLU), net flux ≤ 2.5 Tg CO_2e, ≥ –2.5 Tg CO_2e; (iii) and contributing to national neutrality (N-Z-National), net flux ≤ –2.5 Tg CO_2e. National neutrality scenarios are those that exceed AFOLU neutrality by a margin sufficient to offset 5-10% of non-AFOLU national emissions in 2020[9] – i.e. capable of balancing out a plausible level of residual emissions from energy-related activities in a future decarbonised economy.

A total of 666, 146 and 38 scenarios were classified as N-Z-Fail, N-Z-AFOLU and N-Z-National, respectively. Kruskal Wallace testing showed significant differences across groups for dairy, beef and lowland sheep populations, areas of total spared land (grassland area that no longer supports livestock) and forested land (land converted to forest), and proportions of forest classed as conifer and land rewetting. Dunn's post-hoc analysis indicated highly significant differences in dairy animal numbers across all three categories (Fig. 2). The mean reduction in the dairy and beef herds, for N-Z-AFOLU and N-Z-National respectively, was 42% (CI[40, 44]) and 52% (CI[50, 54]) for dairy, and 38% (CI[36,41]) and 44% (CI[40,47]) was 42%, 39%. Beef population numbers were significantly different at the 1% level between N-Z-Fail and N-Z-AFOLU, and between N-Z-Fail and N-Z-National, but were only significantly different at the 10% level between N-Z-AFOLU and N-Z-National. Lowland sheep populations were significantly different at the 5% level between N-Z-Fail and N-Z-AFOLU, and N-Z-Fail and N-Z-National. Further, there were significant differences regarding total spared area, additional forest area and wetland area between N-Z-Fail and the successful N-Z groups at the 1% level. Spared area was also significantly different between N-Z-AFOLU and N-Z-National (1% level) as was additional forest area (5% level). Finally, the proportion of drained wetland rewetted was significantly different between N-Z-Fail and N-Z-National (1% level) and between N-Z-AFOLU and N-Z-National (5% level).

Among the most notable observations between the three scenario groups are the differences in animal population numbers (Fig.2), with both carbon neutral groups requiring a significant reduction in both dairy and beef herds. The resulting reductions leave a significant area of "spared land" (Fig. 2). This allows for additional afforestation in the AFOLU and national neutral scenarios. Wetland area (organic grassland area rewetted) is constrained by the total area of organic soil under grass, and as such, the total area classified as wetland is similar between the groups.

Scenario input data were averaged by group to generate mean characteristics (Fig. 2) for each of the scenario groups (N-Z-Fail, N-Z-AFOLU and N-Z-National). These mean characteristics were then used as inputs to derive statistically-representative scenarios representing N-Z-Fail, N-Z-AFOLU and N-Z-National. Across the three categories, and relative to the baseline year, agricultural CH_4 emissions (Fig. 3) related to enteric fermentation and manure management were, on average, reduced by 37% and 38%, respectively. N_2O emissions relating to manure management and other direct and indirect sources were reduced by 37%, 43% and 41%, respectively. Lastly, CO_2 emissions related to fertiliser application were reduced by 48%.

Land use emissions of CH_4 increased by 176, 4 and 70% for cropland, forest and wetlands, respectively, on average (Fig. 3). However, grassland emissions were reduced by 31%. N_2O emissions also increased for cropland, forest and wetlands by 176%, 1%, and 125%, respectively. Grassland N_2O emissions (from burning, mineral soils and conversion of forest land to grassland) were reduced to almost zero. It should be noted that the baseline year (2015) reported few wildfires when compared to the average. As such, the scenarios account for higher levels of wildfire given the use of a multi-annual average, explaining the significant higher emissions of CH_4 and N_2O from croplands in 2050, despite management of these areas remaining constant. Additional details can be found in Duffy et al[7]. The average sequestration related to forests increased by 147%, while grassland emissions were reduced by 87%. Finally, emissions related to wetland were reduced by 3%. Cropland has been held constant (due to the small proportion of area devoted to crop use).

Afforestation inputs were "front-loaded" up to 2050 across scenarios, with no additional land being afforested after this point, resulting in a "carbon-cliff" between 2080 and 2090, and again in c.a. 2115, across each of the three scenario groups when large areas of forest planted up to 2050 are harvested (Fig. 4). However, large increments in HWP C storage arising from harvests during this period avoid forestry becoming a (temporary) net source of emissions at any point. As a consequence of the declining forestry sink through time, out of the 850 scenarios generated, a total of 40 scenarios sustained climate neutrality. The majority of these scenarios were in the N-Z-National category (80%), however, only one of N-Z-National scenarios continued to contribute to national level neutrality beyond 2100. The remaining 20% of scenarios sustaining carbon neutrality were from the N-Z-AFOLU category.

The achievement of climate neutrality incurs a significant trade off in relation to national agricultural output (Fig. 5). The highest milk-producing scenario(s) within the N-Z-AFOLU group achieve(s) over 87% of 2015 production, but simultaneously just 21% of 2015 beef production. Maximum beef production in the N-Z-AFOLU group is just 49% of 2015 production, with milk production equivalent to 58% of the 2015 level in the same scenario(s). Investigation of the maximum milk and beef production in the N-Z-National group shows a maximum value of 66% of 2015 production for milk coupled with 20% of 2015 national beef production. Maximum beef production on the other hand is 41% of 2015 production, coupled with milk production at 43% for the same scenario(s).

N-Z-AFOLU and N-Z-National scenarios are associated with much larger areas of land use change, driven by higher rates of afforestation and relatively smaller shares of spared grassland maintained in "farmable condition". Here, we define farmable condition as the removal of animals from the land, with land maintained under current grassland use (i.e. no land use change arising). The mean proportion of spared area kept in farmable condition was, on average, c.27% and 19% lower for N-Z-AFOLU and N-Z-National scenarios than for the N-Z-Failed scenarios. In comparison with afforestation and being left in farmable condition, the average proportions of grassland areas that are rewetted are comparatively smaller, constrained by drained organic soils representing less than 10% of grassland area in the baseline. However, the rewetting of previously drained organic soils under grassland results in average emissions reductions of 0.5, 5.2 and 5.5 Tg CO_2e for N-Z-Fail, N-Z-AFOLU and N-Z-National, respectively

Discussion

As demonstrated by Duffy et al[7], the GOBLIN model has been developed to quantify long-term (circa 100 year) GHG emission fluxes associated with different AFOLU scenarios representing changes in land use over the next three decades. Only 184 of 850 randomised scenarios analysed here achieved either AFOLU climate neutrality or contributed to national climate neutrality (exceeding AFOLU neutrality) in 2050, defined according to a GWP_{100} emissions balance[16,17]. The key differences between scenarios that achieve net-zero GHG emissions and those that do not, are animal numbers and how the remaining (non-farmed) land area is utilised. Larger reductions in animal numbers spare more land. But it is active utilisation of this spared land for CDR that is critical to achieve net-zero. Scenarios that failed to achieve climate neutrality had higher animal numbers, but also larger shares of spared land kept in "farmable condition" – with 45% of spared area, on average, not being used for active CDR via alternative uses.

Afforestation stands out as the most important driver in achieving the net-zero balance, being the primary scalable and near-term option for CDR[18]. Afforestation removals for N-Z-AFOLU and N-Z-National scenarios are on average 73% and 114% greater, respectively, than those for N-Z-Fail. Removing animals without an ambitious CDR strategy will result in a much higher penalty on national herd numbers and ultimately animal protein production. However, given the cyclical nature of forestry, it is important to account for the HWP flows resulting from forest outputs when calculating emissions balances. These flows off-set the "carbon-cliff" that would otherwise result in a net emission. Recent research by Forster et al[19] highlights that, via supply of wood into an expanding future bioeconomy, commercial afforestation is a highly effective option for long-term climate mitigation – through HWP C storage, the displacement of carbon intensive products, and, potentially, through permanent biogenic CO_2 storage following energy generation in future bioenergy carbon capture and storage (BECCS) systems. The specific tree species (or functional types) which comprise future afforestation efforts is also contentious and debated. Forster et al[19] demonstrate that the fast growing species utilised in commercial forestry support much greater climate mitigation than slow-growing semi-natural species over a 100-year time horizon. However, that does not mean that biodiversity has to be sacrificed. The average proportions of conifer planted in N-Z-AFOLU and N-Z-National scenarios are 52% and 55%, respectively, implying considerable scope for the establishment of more biodiverse native woodlands within net-zero constraints.

Irish grassland soils are large carbon stores, and grassland management has been proposed as a CDR option to offset livestock emissions[20]. Recent research by Madigan et al[21] indicates that most Irish grassland soils are close to saturation, although those authors postulate that one-off full inversion tillage of carbon rich topsoil down to 30 cm depth during grassland re-seeding could result in CDR of c.a. 3.7 to 7.3t CO_2e ha^{-1} $year^{-1}$ for a period of at least 20 years. However, the stability and long-term fate of buried carbon is uncertain. If mitigation potential is validated through further research, full inversion tillage could contribute significantly to medium-term CDR needed to achieve national climate neutrality, given that 26% of grassland in Ireland is deemed suitable for this technique. However, this would not negate the critical importance of afforestation as a proven effective and scalable option for the large amounts of CDR needed to achieve climate neutrality over both medium- and long-term time horizons.

It is also clear that the definition of carbon neutrality matters a great deal. Our definition of national climate neutrality is country-context specific, as opposed to broader global (temperature-based) definitions[22], is predicated on successful (90-95%) decarbonisation of non-AFOLU sectors in Ireland by 2050, such that only 5-10% of non—AFOLU emissions in 2019 will need to be offset long-term. Though a significant number of scenarios did achieve net-zero GHG emissions (i.e. a GWP_{100} emissions balance) by 2050 at AFOLU level and beyond, few scenarios were able to maintain this balance through to the end of this century. In the race to net-zero GHG emissions by 2050, it is important to factor in the sustainability of the emissions balance, in particular the longevity of carbon sinks. This will require not just high levels of ambition across stakeholder groups, but coherent inter-sectoral policy making informed by horizon-scanning[15]. In terms of the food production trade-off, this is much higher when spared area is not actively utilised for CDR, so that stakeholders with an interest in maintaining high levels of livestock production in Ireland should be highly motivated to promote active CDR activities (especially afforestation) across farms, rather than seeing such activities as being in competition with food production.

Though GOBLIN represents a significant step forward in terms of holistic modelling of future land use scenarios compatible with national climate neutrality targets[7], future research and development is expected to realise significant emissions abatement for livestock production[23]. For example, the utilisation of 3-nitrooxypropano could substantially reduce methane emissions from enteric fermentation[24], while the use of protected urea fertilisers and enhanced biological N fixation via clover in grasslands could significantly reduce N_2O emissions[25,26]. Further, the incorporation of beneficial land management practices, such as inversion tillage of grassland soils[21], while not a "game changer", will give a more nuanced indication of the scale of land use change necessary in the Irish AFOLU sector. Scenarios that develop additional circularity within the AFOLU sector should also be explored. For example, the use of biochar in agriculture has been extensively studied in recent years[27], with potential uses as a soil amendment, manure additive, and feed additive for livestock. The use of forest and agriculture residues as feedstock for biochar has the potential to reduce fertiliser application, soil leaching, and GHG emissions, while promoting healthier soils and livestock[27,28]. As GOBLIN is developed to include additional country contexts, the abatement potential of practices more suited to areas with a greater focus on crop, as opposed to livestock, production will be necessary. Practices such as zero, or min, tillage, and agro-forestry have potentially wide application[29].

Though GOBLIN, in its current form, can assist policymakers, researchers and other stakeholders in developing holistic, contextualised visions of national agricultural production and land uses compatible with net-zero GHG emissions in relatively vivid detail, there is still scope for improvement. The current model outputs the production potential of randomised input parameters, which is important in terms of illustrating land use potential in an unbiased manner. However, it would also be useful to generate scenarios where livestock inputs are more tightly controlled and the trade-offs between various livestock systems (dairy and beef) can be explored in more detail. Further, co-dependencies between the two systems, in particular the degree to which the beef sector depends on surplus calves from the dairy sector, requires additional modelling. Additional limitations regarding the current iteration have been explored in detail by Duffy et al[7].

This paper has shown that large reductions in animal numbers combined with ambitious afforestation are necessary to achieve net-zero GHG emissions by 2050, but there are several important messages for policymakers. Active management of land spared from livestock production for CDR is crucial, and achieving net-zero GHG emissions will require careful reallocation on spared land (i.e. an integrated national land use plan[8]). The second key message is that, without careful planning to maintain emission sinks beyond 2050, the achievement of net-zero GHG emissions may be fleeting. To sustain an emissions balance beyond 2050, future pathways will require greater ambition in terms of land use change as well as careful planning in terms of HWP utilisation (i.e. parallel development of appropriate bio-based industries and bioenergy infrastructure linked with carbon capture capability). It is also important to note that whilst the Paris Agreement adopts the pragmatic approach of grounding climate action on territorial climate neutrality targets, there are risks of "carbon leakage" if production is simply displaced to countries that do not achieve territorial climate neutrality[30]. Ambitious abatement of CH_4 and N_2O emissions from livestock systems, coupled with intensification of production on the most appropriate soils to spare land elsewhere for CDR, could moderate or even avoid the declines in milk and beef production needed to achieve climate neutrality, mitigating this displacement risk. Alternatively, increasing demand for CDR could drive up land and thus livestock product prices, moderating demand for meat and milk in line with sustainable food system limits[31]. Further work is needed to define plausible upper bounds for abatement and productivity factors, and how AFOLU management for climate neutrality could create price signals affecting food supply and demand. Given the spate of 2050 targets that have been announced by countries and companies alike, the generation of randomised, biophysically resolved combinations of land sector activities is an important step towards improved clarity and context for currently vague climate neutrality plans, helping to explore expected environmental, economic outcomes in relation to adequacy and fairness[6].

Methods

GOBLIN Model

Detailed methodology describing and demonstrating the utilisation of the GOBLIN model can be found in the methodology paper by Duffy et al[7]. GOBLIN represents the main AFOLU sources and sinks (Supplementary Fig. 1) reported in national inventory reporting[9] *inter alia,* CO_2 fluxes to and from (organic) soils and forestry, CH_4 emissions from enteric fermentation, manure management and wetlands, and direct and indirect losses of nitrogen (N) from animal housing, manure management and fertiliser application, in the form of N_2O, ammonia (NH_3) and dissolved forms (e.g. nitrate, NO_3). Further, GOBLIN's complex Tier 3 forestry model represents fluxes, sensitive to compound estimates of species composition, stand age profiles, and harvest rates across hundreds of land parcels.

GOBLIN incorporates 7 modules (Supplementary Fig. 1), which compute the input parameters, national livestock herd, required grassland and fertilisation rates, spared area, and emissions and removals related to the various land use applications. The final, GOBLIN module, summarises the outputs and generates the final outputs. The GOBLIN tool calculates land requirements for the national herd based on Tier 2 IPCC[32,33] approach, allowing for the calculation of both productivity and population.

Harvested Wood Products

The first iteration of the GOBLIN model[7] was extended to account for nationally produced harvested wood product (HWP) in a new module. This additional GOBLIN module follows guidance from IPCC[34] related to three main HWP categories: sawn-wood (planks, beams, joists, boards, rafters, scant- lings, laths, boxboards and various types of lumber), wood-based panels (veneer sheets, plywood, particle board and fibreboard) and paper and paperboard (graphic papers, sanitary and household papers, packaging material and other paperboard). Instantaneous oxidation is assumed for fractions of harvested wood used for energy purposes. Wood flows for Ireland are based on data reported by Knaggs and Nagle[35], following a 7% post-harvest loss. The proportion of recovered harvest destined for sawn-wood production is 64%, while proportion destined for wood-based panels is 31%. The remaining 5% is destined for stake production. An average milling loss of 51% is applied to sawn-wood, with 35% of losses recovered and utilised in wood-based panel production. A 4% milling loss is applied to panel production. Additional detail regarding the modelling of carbon release from various HWP categories can be found in Duffy et al [18].

Scenario Randomisation

A Latin hypercube model[10] is employed to randomly vary the key input parameters between specified ceiling and floor values. Definitions and ranges related to key input parameters utilised in generate scenarios are conveyed in Table 1. Livestock population values listed in Table 1 relate to mature animals, additional cohorts are derived from these. Further detail on GOBLIN input parameters, including cohort coefficients, can be found in the methodological description paper[7]. Of particular note, Ireland's agricultural sector has adapted to exploit high rates of grass growth, and grass represents at least 90% of dry matter intake across cattle and sheep[36]. To explore potential productivity improvements at the animal and land use level, average animal outputs and grass utilisation rate (i.e. the fraction of grass dry matter productivity consumed by livestock) were randomly increased to within proven bounds for these grassland systems (Table 1). While GOBLIN is capable of identifying fertiliser-N-driven grass yield effects, there remains considerable uncertainty about future N response curves given the drive to reduce fertiliser inputs[8]. Therefore, whilst increasing fertiliser-N inputs could drive higher productivity, we conservatively held this constant for the purposes of this modelling.

Data Availability

Authors can confirm that all relevant data are included in the paper and/ or its supplementary information files

Code Availability

The exact version of the model used to produce the results used in this paper is archived on Zenodo[37] and freely available for download.

Acknowledgements

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Author Contribution

Duffy, C conducted design, development, analysis, testing and validation and manuscript preparation.

Prudhomme, R conducted design, development, analysis and validation.

Duffy, B conducted design and development.

Gibbons, J conducted validation, review and editing.

O'Donoghue, C conducted validation, review and editing.

Iannetta, P. P. M validation, reviewing, editing.

Ryan, M conducted validation, review and editing.

Style, D conducted design, development, analysis, review and editing.

Competing Interests

The authors declare that they have no conflict of interest.

Tables

Table 1. Definitions of key model inputs and scenario value boundary ranges.

Parameter category	Definition	Baseline (2015) values		Scenario value range	
				Min	Max
Livestock population	Milking cow/suckler-cow numbers	Milking cow	1,268,000	507,200	12,68,000
		Suckler cow	1,065,000	426,000	1,065,000

	Sheep numbers	Lowland ewe	1,960,000	784,000	1,960,000
		Upland ewe	490,000	196,000	490,000
Productivity	Milk output head^{-1}	Milk output	13.8 kg day^{-1} year $^{-1}$	13.8 kg day^{-1} year $^{-1}$	15.9 kg day^{-1} year $^{-1}$
	Beef output head^{-1}	Heifer weight (1 year)	275 kg head^{-1}	275 kg head^{-1}	322 kg head^{-1}
		Heifer weight (2 year)	430 kg head^{-1}	430 kg head^{-1}	504 kg head^{-1}
Grassland area	Area of grassland required to support national herd	4.07 M ha		Deduced	
Cropland area	Area under crop	361.6 k ha		Static	
Drained wetland area	Area of organic soil drained grazing utilisation	287 k ha		20%	100%
Wetland area	Area of wetland utilised for grazing	1226 k ha		0%	20%
Grassland utilisation	The proportion of grass production consumed by livestock via grazing and feeding on conserved grasses (silage and hay).	57%		57%	73%
Afforested area	The proportion of spared grassland area on mineral soils that will be utilised for forest.	NA		20 – 80% of spared mineral soil area	
Proportion broadleaf	Proportion of forest area that is under broadleaf (vs conifer).	20% (existing forest)		30% – 70% (new forest)	
Proportion conifer	Proportion of forest area that is under conifer (vs broadleaf).	80% (existing forest)		30% – 70% (new forest)	
Proportion conifer harvested	Proportion of conifer area that is harvested.	90% (existing forest)		50 – 90% (new forest)	
Proportion of conifer thinned	The proportion of harvested conifer area that is thinned.	50% (existing forest)		50% (new forest)	

Figure Legends/Captions

Figure 1. Key emissions sources and sinks critical to the determination of "climate neutrality". Ireland's AFOLU sector is accounted for in GOBLIN (white), alongside linked upstream- and downstream- sources and sinks to be included in subsequent life cycle assessment (LCA) modelling to determine wider climate mitigation efficacy. Figure is adapted from Duffy et al[7].

Figure 2. **Key input and output parameter variation and post-hoc analysis.** Individual panels contain animal population inputs (a), total spared, forest and wetland area outputs (b), and proportional input parameters related to livestock productivity, forestry, rewetting and grassland utilisation (c). The mid line in whisker plots represents the median value, whilst the shaded boxes represent InterQuartile Range (IQR) and whiskers extend to 1.5 times the IQR. Alongside, significant differences between specific groups from a Dunn's post-hoc analysis (d). *** denotes statistically significant at 1%, ** denotes statistically significant at 5% and * denotes statistically significant at 10%. The standard deviation is represented by black arrows.

Figure 3. Percentage changes in emissions between 2015 (baseline) and 2050 for statistically representative scenarios. Scenarios N-Z-Fail, N-Z-AFOLU and N-Z-National based on mean input characteristics (Fig. 2) for agricultural sources of CH_4, N_2O, and CO_2 – enteric fermentation, manure management, direct and indirect N_2O from soil N inputs (a). Alongside percentage changes in CH_4, N_2O and CO_2 fluxes from cropland, forest, grassland, and wetland land uses (b).

Figure 4. CO_2 removals from biomass growth and net carbon storage increment in harvested wood products (HWP). Displayed from 1990 through to 2120 (a), and net CO_2e emissions and removals to 2050 (b). Removals for the 2015 baseline year are indicated

Figure 5. Scenarios displaying maximum and minimum levels of milk and beef production within N-Z-AFOLU (a) and N-Z-National (b) categories. Values represent proportions of 2015 values, including the proportion of 2015 grassland area diverted to other land uses (grassland remaining grassland, restored wetlands, total afforested area, and area kept in "farmable condition")

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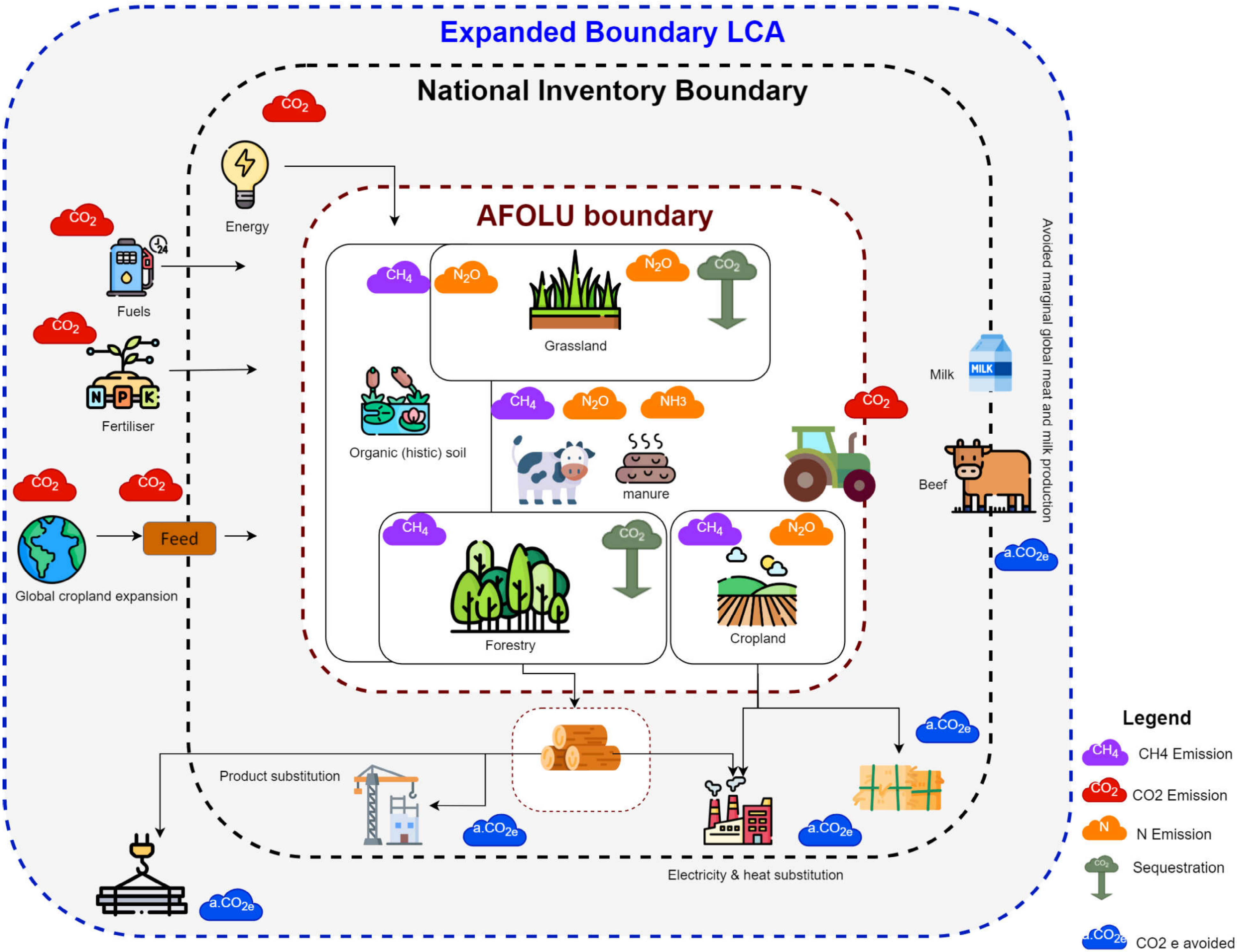
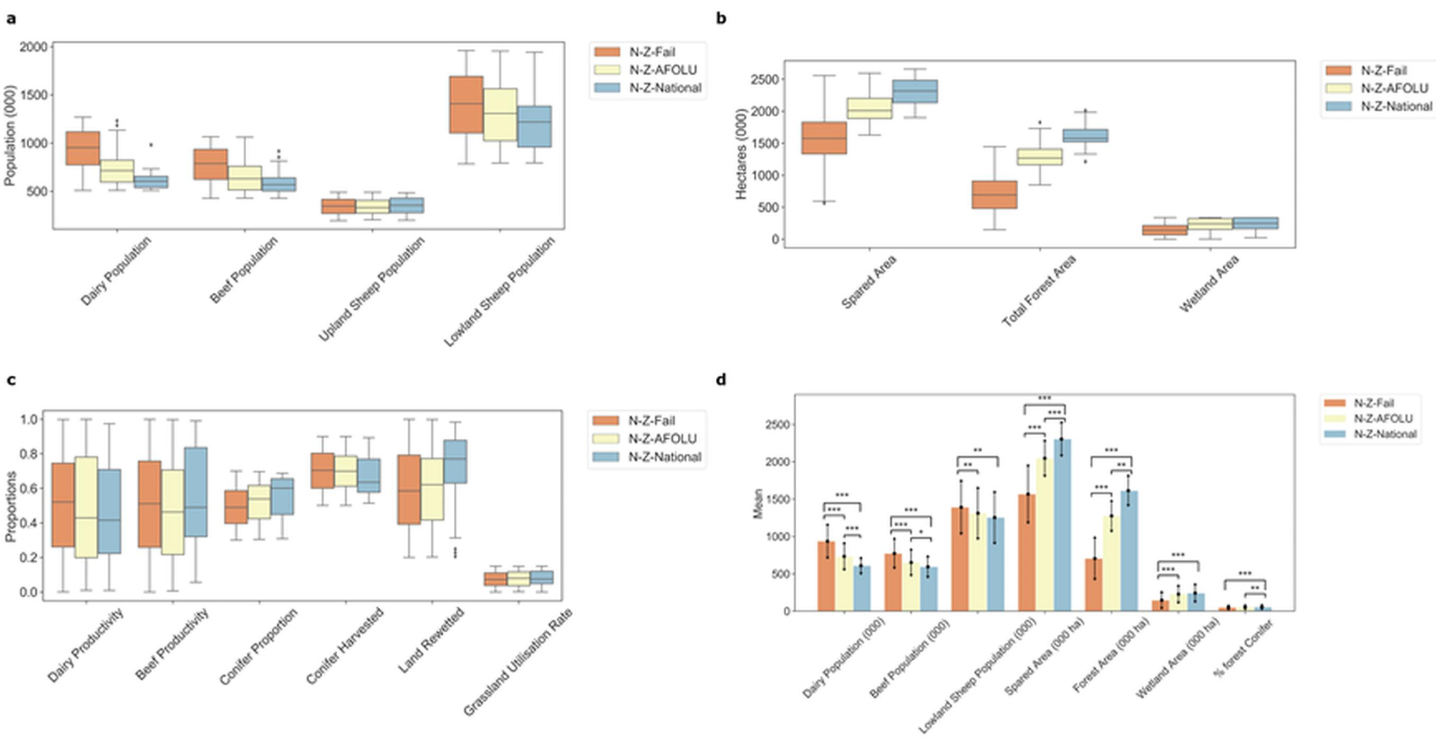
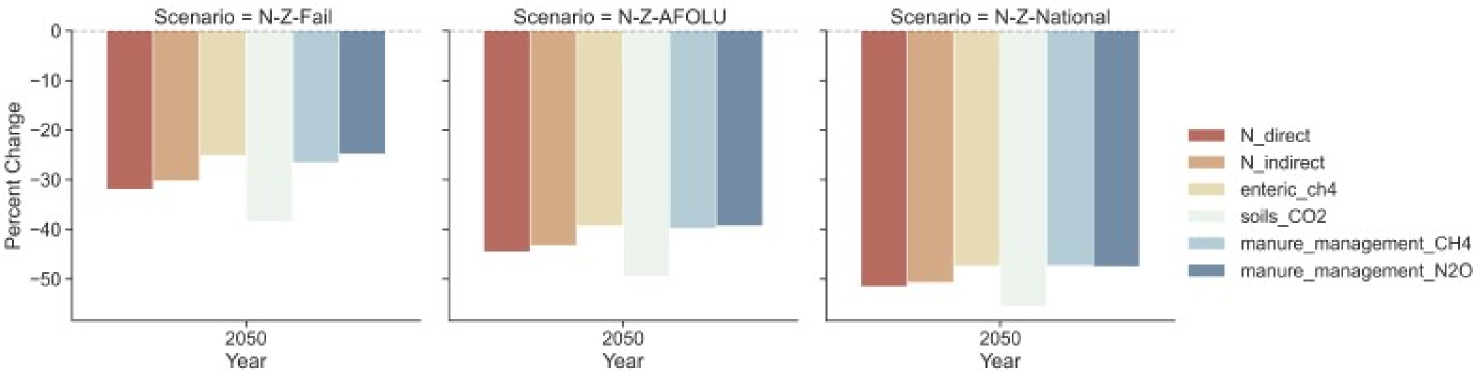


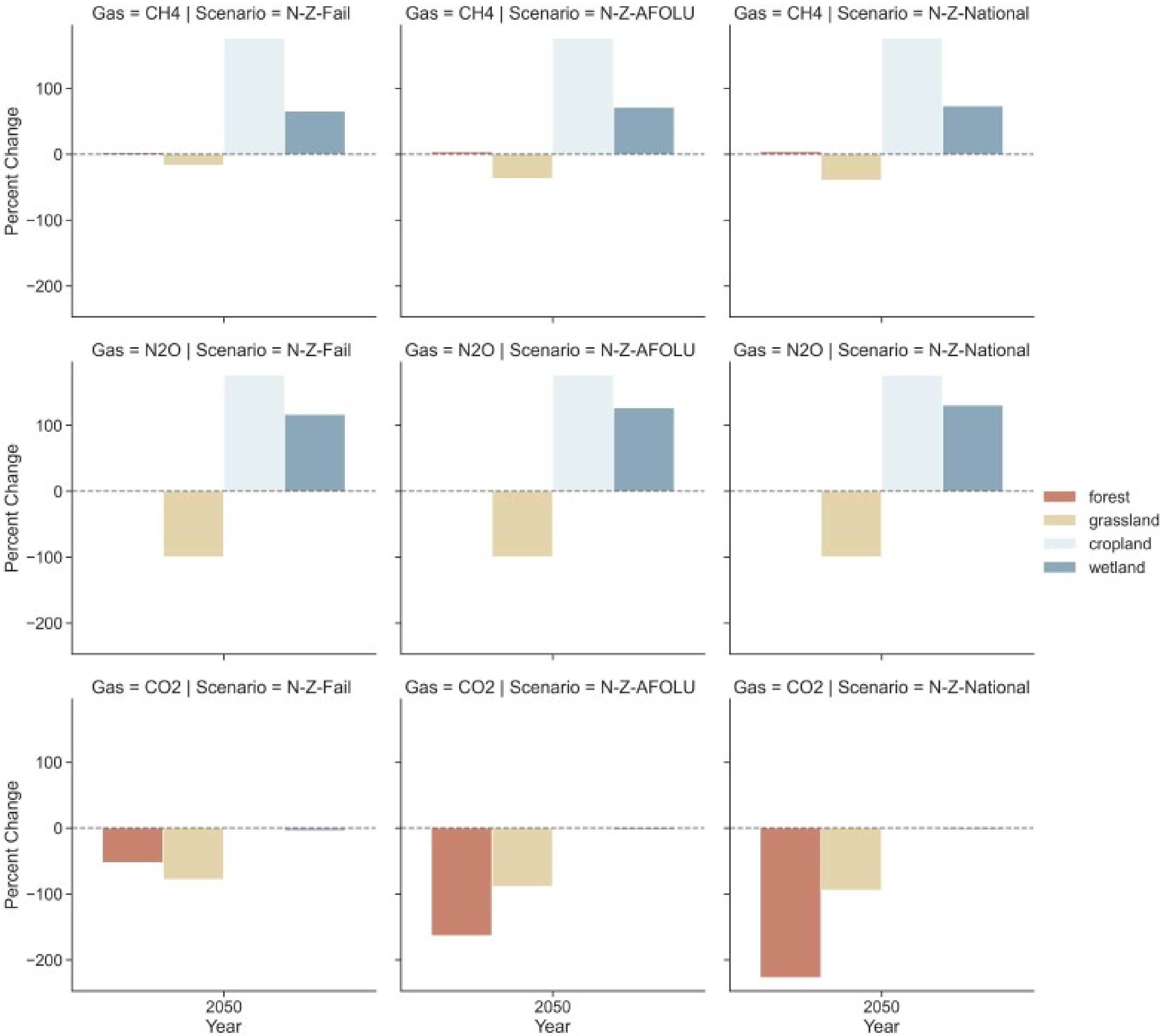
Expanded Boundary LCA
National Inventory Boundary
AFOLU boundary
Energy
Fuels
Fertiliser
Feed
Global cropland expansion
Organic (histic) soil
Grassland
manure
Forestry
Cropland
Milk
Beef
Avoided marginal global meat and milk production
Product substitution
Electricity & heat substitution
Legend
CH4 Emission
CO2 Emission
N Emission
Sequestration
CO2 e avoided



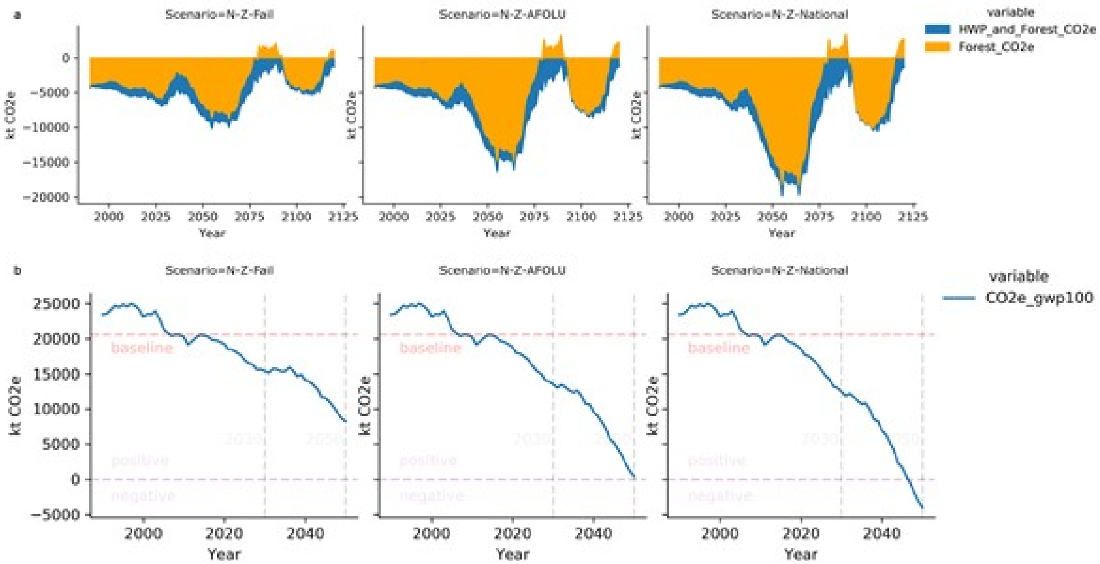
a
Population (000)
Dairy Population
Beef Population
Upland Sheep Population
Lowland Sheep Population
N-Z-Fail
N-Z-AFOLU
N-Z-National
b
Hectares (000)
Spared Area
Total Forest Area
Wetland Area
c
Proportions
Dairy Productivity
Beef Productivity
Conifer Proportion
Conifer Harvested
Land Rewetted
Grassland Utilisation Rate
d
Mean
Dairy Population (000)
Beef Population (000)
Lowland Sheep Population (000)
Spared Area (000 ha)
Forest Area (000 ha)
Wetland Area (000 ha)
% forest Conifer



Scenario = N-Z-Fail
Scenario = N-Z-AFOLU
Scenario = N-Z-National
Percent Change
0
−10
−20
−30
−40
−50
2050
Year
N_direct
N_indirect
enteric_ch4
soils_CO2
manure_management_CH4
manure_management_N2O



Gas = CH4 | Scenario = N-Z-Fail
Gas = CH4 | Scenario = N-Z-AFOLU
Gas = CH4 | Scenario = N-Z-National
Gas = N2O | Scenario = N-Z-Fail
Gas = N2O | Scenario = N-Z-AFOLU
Gas = N2O | Scenario = N-Z-National
Gas = CO2 | Scenario = N-Z-Fail
Gas = CO2 | Scenario = N-Z-AFOLU
Gas = CO2 | Scenario = N-Z-National
Percent Change
100
0
−100
−200
2050
Year
forest
grassland
cropland
wetland



a
Scenario=N-Z-Fail
Scenario=N-Z-AFOLU
Scenario=N-Z-National
variable
HWP_and_Forest_CO2e
Forest_CO2e
kt CO2e
Year
b
Scenario=N-Z-Fail
Scenario=N-Z-AFOLU
Scenario=N-Z-National
variable
CO2e_gwp100
baseline
positive
negative
2030
2050
kt CO2e
Year


a
Total Grassland Area
Milk Output
Beef Output
Farmable Condition
Forest Area
Wetland Area
AFOLU Beef min
AFOLU Beef max
AFOLU Milk min
AFOLU Milk max
0.0
0.2
0.4
0.6
0.8
b
Total Grassland Area
Milk Output
Beef Output
Farmable Condition
Forest Area
Wetland Area
National Beef min
National Beef max
National Milk min
National Milk max
0.0
0.1
0.2
0.3
0.4
0.5
0.6