communications earth & environment

Article

https://doi.org/10.1038/s43247-024-01275-0

Defining national net zero goals is critical for food and land use policy

George Bishop [1,9] ✉, Colm Duffy[2,9], Rémi Prudhomme[3], Annette Cowie [4,5], Cathal O'Donoghue[6], Michelle Cain[7], Gary J. Lanigan[8] & David Styles[1]

The identification of agriculture and land use configurations that achieve net zero (NZ) greenhouse gas emissions is critical to inform appropriate land use and food policy, yet national NZ targets lack consistent definitions. Here, 3000 randomised scenarios projecting future agricultural production and compatible land use combinations in Ireland were screened using ten NZ definitions. When aggregating carbon dioxide, methane, and nitrous oxide emissions using various methods, 1–85% of scenarios met NZ criteria. Despite considerable variation, common actions emerged across definitions, including high rates of afforestation, organic soil re-wetting, and cattle destocking. Ambitious technical abatement of agricultural emissions moderated, but could not substitute, these actions. With abatement, 95th percentile milk output varied from 11–91% of 2021 output, but was associated with reductions of up to 98% in suckler-beef production, and a 47–387% increase in forest cover. Achieving NZ will thus require transformation of Ireland's land sector. Lagging land use change effects require urgent action, but sustaining a just transition will require visioning of future NZ land use combinations supporting a sustainable and resilient food system, alongside an expanding circular bioeconomy. We provide new insight into the sensitivity of such visioning to NZ definitions, pointing to an urgent need for international consensus on the accounting of methane emissions in NZ targets.

151 countries, encompassing 92% of the world economy, have pledged "net zero" (NZ) targets[1], but the terminology used to define these goals is often inconsistent, including terms such as "net zero", "climate neutral", "carbon neutral", and "greenhouse gas (GHG) neutral", often to denote what the IPCC calls GHG neutrality[2]. To limit warming to 1.5 °C, the IPCC[2] identifies that it is necessary to achieve NZ carbon dioxide (CO_2) by around 2050 and to reach NZ GHG by around 2070. Most national targets aim for NZ GHG rather than NZ CO_2, but definitions of scope and implementation are often unclear[3], and deviate from the 100-year global warming potential (GWP_{100}) aggregation of GHGs applied in current national reporting to the UN Framework Convention on Climate Change[4]. The land sector has a critical role to play in meeting NZ targets, especially in providing CO_2 removal, which will be required to reach the temperature goal of well-below 2 °C[2,5]. Deployment of land-based CO_2 removal will compete with current land uses, especially agricultural land dominated by livestock grazing[6]. However, shifting land use has considerable implications for society and the environment[7], including potential consequences for global food security and the risk of GHG "leakage" if food production (especially livestock-based) is displaced from countries where it is comparatively efficient[8].

Livestock methane (CH_4) emissions contribute greatly to global GHG emissions. Adopting alternative GHG accounting methods to GWP_{100} that reflect the short-lived nature of CH_4, including the outcome that a gradual decline in CH_4 emissions will be sufficient to halt global warming[9–11], could result in different land use mixes compatible with national NZ. For example, the use of the GWP* metric may place less emphasis on reducing CH_4 emissions[12,13]. Similarly, introducing separate CH_4 targets for livestock may reduce demand for CO_2 removals (to offset CH_4 emissions on a GWP_{100} basis) elsewhere in the agriculture, forestry, and other land use (AFOLU) sector, whilst aligning with IPCC global emission trajectories for temperature stabilisation that reflect the distinct warming effect of CH_4[2,10,14]. However, despite scientific robustness at global level, downscaling these approaches to national scale has strong implications for perceived fairness in

[1]School of Biological & Chemical Sciences and Ryan Institute, University of Galway, Galway, Ireland. [2]Ecological Sciences, The James Hutton Institute, Dundee, NSW, UK. [3]CIRED, CIRAD, Montpellier, France. [4]NSW Department of Primary Industries, Armidale, NSW, Australia. [5]School of Environmental and Rural Science, University of New England, Armidale, NSW, Australia. [6]University of Galway, Galway, Ireland. [7]Cranfield Environment Centre, Cranfield University, Cranfield, UK. [8]Environment, Soils and Land Use, Teagasc, Johnstown Castle, Co, Wexford, Ireland. [9]These authors contributed equally: George Bishop, Colm Duffy. ✉e-mail: George.Bishop@universityofgalway.ie

global CH_4 emission burden-sharing among nations. NZ definitions with "grand-parenting" allocation principles, i.e., using historic emissions levels as a baseline, or definitions that require the same percentage CH_4 reductions across all countries, may be perceived as unfair to countries with low baseline CH_4 emissions, or countries with high CH_4 emissions but that provide global food security through exports[14–17]. Such trade-offs make it challenging to conclude on the "best" method for addressing CH_4 emissions, and may contribute to the lack of consensus to date on how to define national NZ targets.

Ireland is a significant global exporter of milk and beef products[18,19], with the Irish AFOLU sector contributing over 40% of the country's total GHG emissions[20]. As milk production continues to increase at a faster pace than the decline in suckler beef production[18], and net forest increments decline owing to a continually low rate of afforestation[21], national AFOLU emissions have been rising despite a national target to achieve NZ (defined in legislation as "climate neutrality") by 2050[22]. Using a unique series of detailed AFOLU GHG flux scenarios for Ireland, this study explores the land use combinations necessary to achieve NZ under various definitions and examines the potential effects on national milk and beef production, with and without additional ambitious GHG abatement measures. This research thus provides novel insight into the implications of, and sensitivity to, different definitions of NZ for national AFOLU sectors involving significant livestock production.

Results

Net zero definition implications for Ireland's AFOLU sector

GOBLIN[6,23], a national biophysical AFOLU model, was run to generate 3000 randomised scenarios of Irish agricultural activities (including varying production efficiencies) and land use combinations within biophysical constraints for the year 2050, calculating associated annual GHG emissions out to 2100 (Fig. 1a). Maximum animal numbers were constrained at 2021 levels, and land spared from livestock production allocated to widely accepted carbon-neutral or carbon-positive uses, specifically wetland restoration, afforestation, or 'ungrazed' grassland[6,23,24] (Fig. S3, Table S1), in order to focus data points around NZ boundaries. An ambitious assumption of 30% reduction in agricultural CH_4 and N_2O emissions (representing optimistic but plausible technical abatement efficacy by 2050) was applied post hoc to the original 3000 scenarios, to generate a parallel suite of 3000 abated scenarios. Ten different NZ definitions were applied to filter each scenario (Fig. 1b), as described in the Methods Section. These definitions included achieving by 2050: NZ CO_2 (only) emissions, NZ GHG emissions based on GWP_{100}, no net warming based on GWP*, or separate (non-zero) CH_4 targets[14] alongside a GWP_{100} balance for N_2O and CO_2 fluxes. Variations of these definitions relating to international fairness and longer-term (LT) time horizons (up to 2100) were also explored. For each definition, scenarios were classified into whether they were *successful* in reaching NZ with and without abatement measures (S-NZ-A and S-NZ) or *failed* to reach NZ with and without abatement measures (F-NZ-A and F-NZ).

The definitions which saw most scenarios reach NZ were (Table 1): carbon neutrality, with 2969 of the 3000 scenarios attaining NZ; GWP*, with 2464 and 2547 of non-abated and abated scenarios accomplishing NZ; CH_4 Target Grand-parenting, where 1744 and 2560 of non-abated and abated scenarios reached NZ; and eGWP* Protein, where 1816 and 2511 of non-abated and abated scenarios reached NZ. Conversely, the lowest counts of NZ were for CH_4 Target Population (35 and 92 of the 3000 non-abated and abated scenarios achieved NZ), GWP_{100} LT (551 and 805 of non-abated and abated scenarios attained NZ), and eGWP* Population (770 and 1172 of non-abated and abated scenarios accomplished NZ).

Large differences in new forest areas, new wetland areas (rewetted organic soils), milk outputs, and suckler beef outputs for each NZ definition were observed between the scenarios which succeeded in reaching NZ (S-NZ and S-NZ-A) and the scenarios which failed to reach NZ (F-NZ and F-NZ-A) (Fig. 2). Overall, the scenarios that achieved NZ had considerably larger areas of new forestry and wetlands, but lower quantities of milk and beef output (Fig. 2). The median new forest areas for S-NZ were 1096–2267 kha across the ten definitions, whereas the median ranges for new forest area of F-NZ were between 313–1078 kha. The minimum new forestry area required to achieve S-NZ and S-NZ-A was lowest for the carbon neutrality definition, requiring a median average increase of 142% from 2021 forest cover, and highest for the CH_4 Target Population and GWP_{100} LT definitions, requiring median increases of 294% and 255%, respectively, from 2021 forest cover in the non-abated scenarios (Fig. 2). Median new wetland

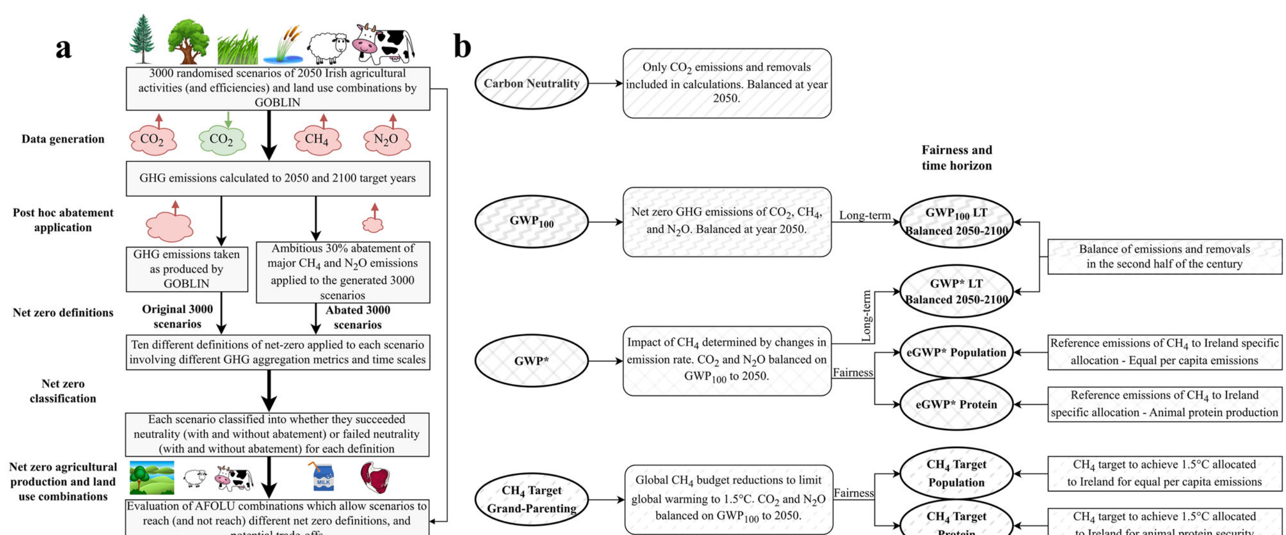

Fig. 1 | Assessment of future agricultural production and land use in Ireland with various NZ definitions. a Workflow indicating generation, abatement modification, NZ filtering, and subsequent post hoc analysis of 3000 scenarios of future agricultural production and land use combinations in Ireland. **b** Summary of NZ definitions applied in this study, with ovals representing definitions. These definitions encompass CO_2 only emissions (carbon neutrality), the balance of GHGs over 100 years (GWP_{100}), warming potential (GWP*), and a national CH_4 emission target based on equal percentage reduction across countries to achieve temperature stabilisation (CH_4 Target Grand-parenting). Definitions on the right are derivatives of four fundamentally different definitions on the left. LT: Long-term, indicating warming or flux balance out to 2100 (as opposed to balance achieved in the year 2050 only). Fairness was explored within GWP* and CH_4 Target definitions by differing Ireland's future NZ CH_4 emission targets and reference emissions levels based on allocation of global CH_4 emissions compatible with temperature stabilisation equally per capita, globally, or by national protein production[14]. Further details can be found in the Methods Section.

areas (i.e., rewetted organic soils and peat bogs) equated to 209–339 kha and 39–207 kha for S-NZ and F-NZ scenarios, respectively, and 209–339 kha and 38–204 kha for S-NZ-A and F-NZ-A, respectively. Maximum possible rewetting (339 kha) corresponded to an inferred increase of 28%, but was also observed as the median average for GWP_{100} LT and eGWP* Population definitions for non-abated scenarios (S-NZ), and GWP_{100} LT and CH_4 Target Population for abated scenarios (S-NZ-A) (Fig. 2). Milk and beef outputs in aggregate declined substantially relative to 2021 levels across all successful NZ scenarios, even with ambitious abatement. Although there was a decline in beef production in the majority of the S-NZ and S-NZ-A scenarios, maximum-beef outputs in S-NZ and S-NZ-A scenarios were close to 2021 levels for most definitions except CH_4 Target Population, which only achieved a maximum total beef output of 22% and 38% of 2021 beef output for S-NZ and S-NZ-A (Fig. 2). However, maximum-milk output S-NZ and S-NZ-A scenarios involved significant reductions in milk output vis-à-vis 2021 for most definitions, especially in CH_4 Target Population and Protein, eGWP* Population, and GWP_{100} LT definitions. Ambitious abatement measures allowed for scenarios to achieve NZ (S-NZ-A) with smaller areas of new forestry, and greater milk and beef outputs than S-NZ, but required similarly large areas of organic soil rewetting. Further statistics and data can be found in the Supplementary Data.

Table 1 | Percentage of the 3000 scenarios which achieved NZ according to each of the definitions explored

Net zero definitions	Percentage of Scenarios	
	S-NZ	S-NZ-A
GWP_{100}	37	50
GWP*	82	85
CH_4 Target Grand-parenting	58	85
CH_4 Target Population	1	3
CH_4 Target Protein	29	50
eGWP* Population	26	39
eGWP* Protein	61	84
Carbon Neutrality	99	99
GWP_{100} LT balanced 2050-2100	18	27
GWP* LT balanced 2050-2100	56	63

S-NZ and S-NZ-A scenarios which were successful in reaching NZ without and with ambitious agricultural abatement, respectively. LT long-term.

Even with the ambitious abatement assumption, it was not possible for any of the S-NZ-A scenarios to simultaneously achieve 2021 population levels for both adult suckler beef and dairy cow numbers for any definition except "carbon neutrality" across the 3000 scenarios (Fig. 3a). Few scenarios under few definitions were able to support 2021 dairy cow populations whilst complying with NZ; the scenarios that did so also involved a reduction of at least two thirds in suckler cow numbers, relative to 2021 as seen by the blank failure areas in the top right of each panel in Fig. 3 – except for the carbon neutrality definition panel where the full spectrum of scenario populations fall within the NZ frontier (Fig. 3a). To achieve NZ with abatement under CH_4 Target Population and Protein, eGWP* Population, and GWP_{100} LT definitions, significant reductions in dairy cow populations were observed. Without optimistic abatement measures, only carbon neutrality and GWP* definitions allowed for 2021 levels of dairy cow populations to be maintained, though with large reductions in suckler-cow numbers for GWP*, leading to lower suckler-beef production (Fig. S1).

Milk output among S-NZ-A scenarios followed the dairy cow population patterns in Fig. 3a. Higher milk output was generally associated with smaller areas of new forest among S-NZ-A scenarios (Fig. 3b), reflecting smaller areas of land spared from cattle at higher milk outputs. However, the spread of new forest area narrowed in an upwards trend towards the highest milk yields for most definitions (especially GWP_{100}), reflecting minimum new forest areas needed to offset emissions from milk production (Fig. 3b).

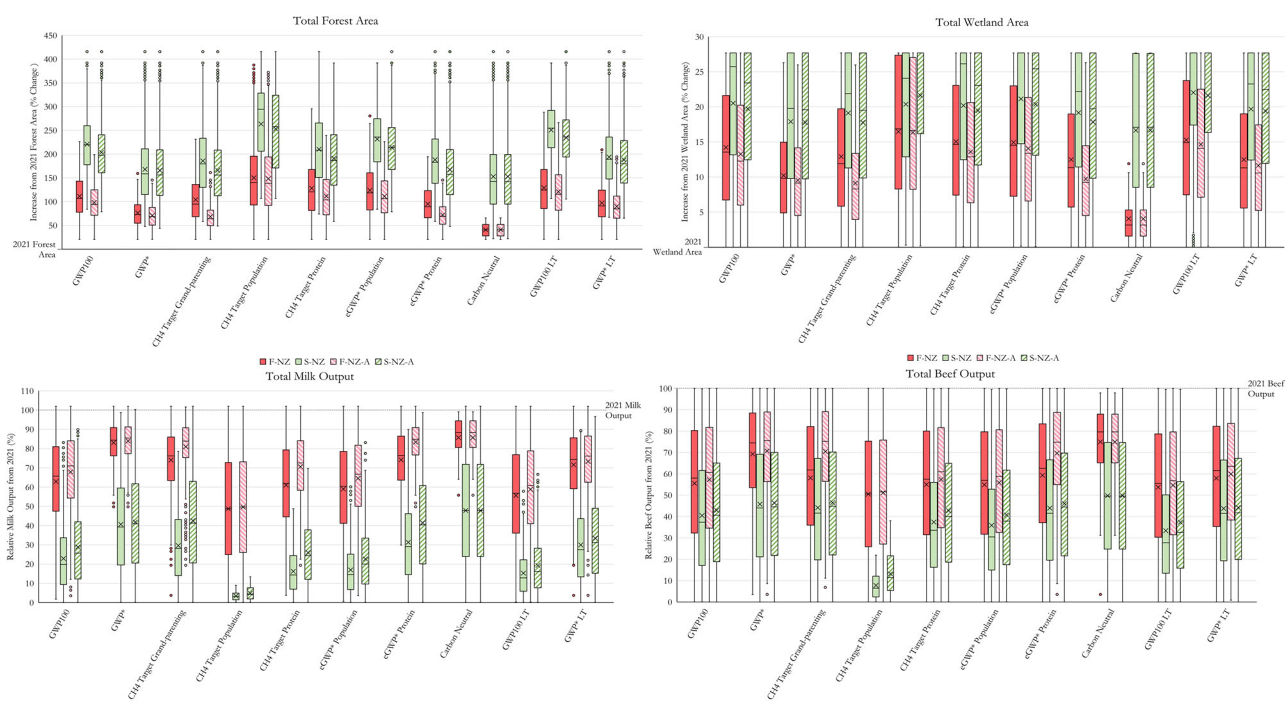

Fig. 2 | Total forest and wetland area, and total milk output and suckler beef liveweight output variation generated by the 3000 scenarios that fit within the different definitions of NZ as percentage changes from 2021 values. Plots display local minimum, Q1 (25th percentile), median, Q3 (75th percentile), local maximum, and outliers. Outliers are considered when they lie 1.5 times the length of the interquartile range from either end of the box. X within bars: mean value, F-NZ Failed to reach NZ, S-NZ succeeded in reaching NZ, F-NZ-A Abated scenarios which failed to reach NZ, S-NZ-A Abated scenarios which were successful in reaching NZ, Raw data can be found in the supplementary materials.

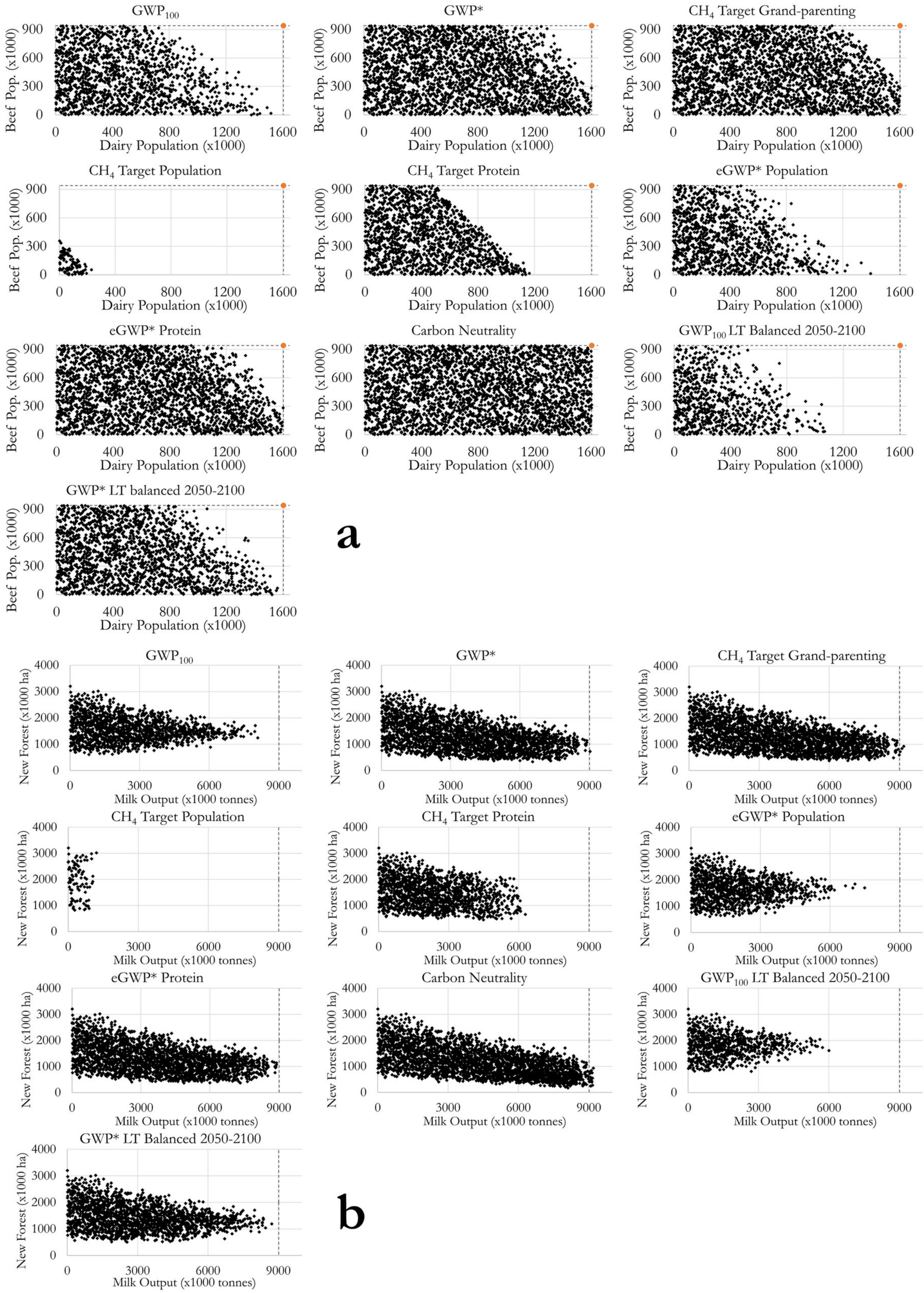

Fig. 3 | Relationships of various parameters under different definitions of NZ. **a** The relationship between adult dairy cow and suckler beef cow populations across the 3000 abated scenarios which successfully achieved NZ (S-NZ-A) for each different definition. **b** The relationship between milk output and new forest planted for the 3000 abated scenarios which successfully achieved NZ (S-NZ-A) for each different definition of NZ. The dashed lines and orange points represent the animal numbers or milk output for the year 2021. (x1000): *x* and *y* axis values are multiplied by 1000, LT long-term. Non-abated relationships can be found in Fig. S1, S2.

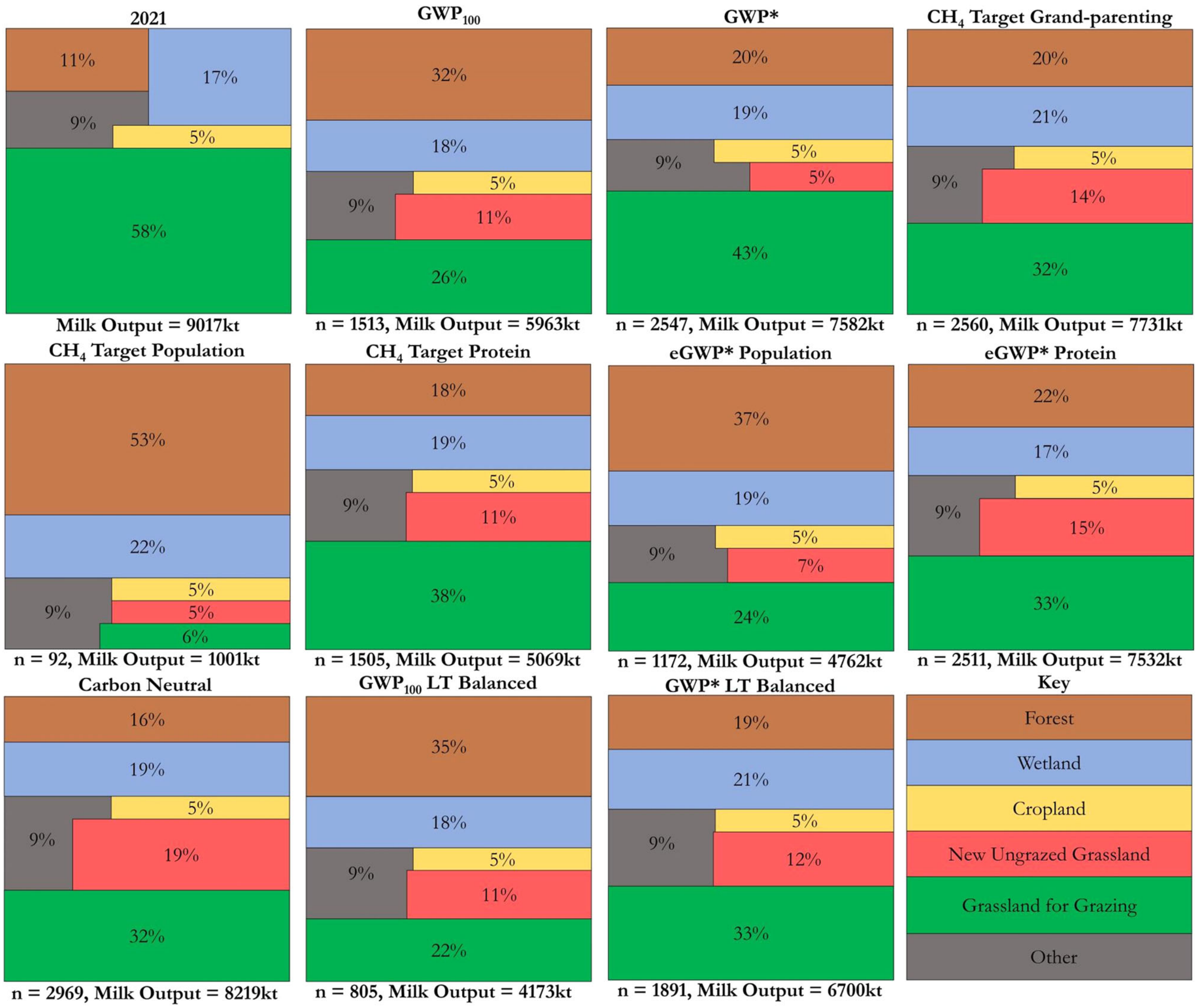

Fig. 4 | National land cover configurations for the 95th percentile scenario of (maximum) milk output from the range of abated scenarios that successfully achieved NZ (S-NZ-A), from the 3000 tested scenarios, according to each definition of NZ. Also shown is land cover for Ireland as of 2021. Below each configuration is the 95th percentile milk output. Boxes represent total land use in Ireland. n: number of scenarios which achieve NZ for that definition.

Maintaining high milk production under different net zero definitions

Given that milk production is far more profitable for farmers than beef or sheep production[25], generating almost €7 billion of dairy exports from Ireland in 2022[26], we analysed the closest scenario to the 95th percentile of maximum milk output among the successful abated (S-NZ-A) scenarios for each definition of NZ. For each definition, 2050 (and beyond) land use in Ireland looks very different from 2021 land use (Fig. 4). To preserve Ireland's profitable dairy sector, large changes in the national landscape are required, including a 26–90% reduction in grassland for grazing all animals, from 58% of national land cover in 2021 to 6–43% land coverage in 2050, alongside a 47–387% increase in forest land, from 11% land area in 2021 to 16–53% cover in 2050. Land and emissions constraints associated with maintaining high milk output also requires large (up to 98%) reductions in suckler beef live weight output, and up to 97% reductions in sheep populations (Fig. 5).

Technical abatement to aid net zero transition

We explored the sensitivity of NZ compliance to varying levels of agricultural emissions through technical abatement measures applied at source (see Abatement Section in Methods), considering a spectrum of technical abatement from 0–100% across the ten definitions (Fig. 6). 0% and 30% abatement levels corresponded with the S-NZ and S-NZ-A scenarios, respectively. At higher levels of abatement, the share of scenarios achieving NZ increased. For instance, increasing technical abatement from 20–80% abatement increased the share of scenarios complying with the GWP$_{100}$ definition from 45–85%. For the CH$_4$ Target Population definition, compliance rose dramatically from just 18% success at 70% abatement to 88% success at 90% abatement. Due to this differential effect across scenarios, the relative rankings of NZ definitions in terms of successful scenarios varied with abatement level. For example, at 20% abatement, GWP$_{100}$ had 119 more successful NZ scenarios than CH$_4$ Target Protein, but by 40% abatement, CH$_4$ Target Protein had 231 more scenarios achieving NZ than GWP$_{100}$. Notably, at 100% technical abatement, the two LT definitions only achieved 91% and 93% success rates, for GWP$_{100}$ LT and GWP* LT, respectively – reflecting the challenge of maintaining a long-term balance in CO_2 fluxes across soils and biomass, even before agricultural emissions are accounted for[6].

It is crucial to underscore the highly speculative nature of these abatement levels, which are extended to the impossible level of 100% simply to illustrate the theoretical bounds of technical abatement measures. Our default abatement assumption of 30% is already considered ambitious[27,28].

		Percentage Change from 2021						
		Milk Output	Beef Output	Total Forest Area	Total Wetland Area	Lowland Sheep Population	Upland Sheep Population	Total Grassland for Grazing
GWP_{100}	S-NZ	-45%	-75%	222%	28%	-82%	-13%	-62%
	S-NZ-A	-34%	-94%	189%	1%	-41%	-52%	-55%
GWP*	S-NZ	-18%	-85%	164%	15%	-80%	-35%	-42%
	S-NZ-A	-16%	-22%	80%	7%	-25%	-4%	-26%
CH_4 Target Grand-parenting	S-NZ	-37%	-34%	103%	16%	-46%	-7%	-48%
	S-NZ-A	-14%	-72%	84%	19%	-85%	-36%	-46%
CH_4 Target Population	S-NZ	-92%	-19%	261%	28%	-79%	-64%	-74%
	S-NZ-A	-89%	-95%	387%	28%	-77%	-42%	-90%
CH_4 Target Protein	S-NZ	-63%	-7%	195%	28%	-97%	-72%	-60%
	S-NZ-A	-44%	-8%	66%	8%	-17%	-57%	-34%
eGWP* Population	S-NZ	-59%	-46%	157%	28%	-21%	-37%	-54%
	S-NZ-A	-47%	-92%	239%	8%	-44%	-3%	-59%
eGWP* Protein	S-NZ	-33%	-95%	118%	9%	-42%	-87%	-57%
	S-NZ-A	-16%	-76%	97%	0%	-35%	-54%	-44%
Carbon Neutral	S-NZ	-9%	-79%	47%	9%	-87%	-68%	-44%
	S-NZ-A	-9%	-79%	47%	9%	-87%	-68%	-44%
GWP_{100} LT Balanced 2050-2100	S-NZ	-61%	-32%	138%	0%	-9%	-37%	-51%
	S-NZ-A	-54%	-98%	223%	2%	-20%	-56%	-62%
GWP* LT balanced 2050-2100	S-NZ	-34%	-69%	182%	10%	-46%	-37%	-53%
	S-NZ-A	-26%	-59%	76%	23%	-10%	-86%	-42%

Fig. 5 | Changes associated with scenarios that give the 95th percentile (maximum) level of milk output for each definition of NZ, expressed as percentage changes from 2021 values for key land uses, sheep populations, and production of milk and suckler-beef liveweight (NB: excludes dairy-beef outputs). Colours represent scale of transformation, with the intensity of red associated with levels of reduction, intensity of blue with levels of increase, and white with low levels of change from 2021 values. S-NZ scenarios which succeeded in achieving NZ, S-NZ-A abated scenarios which succeeded in achieving NZ.

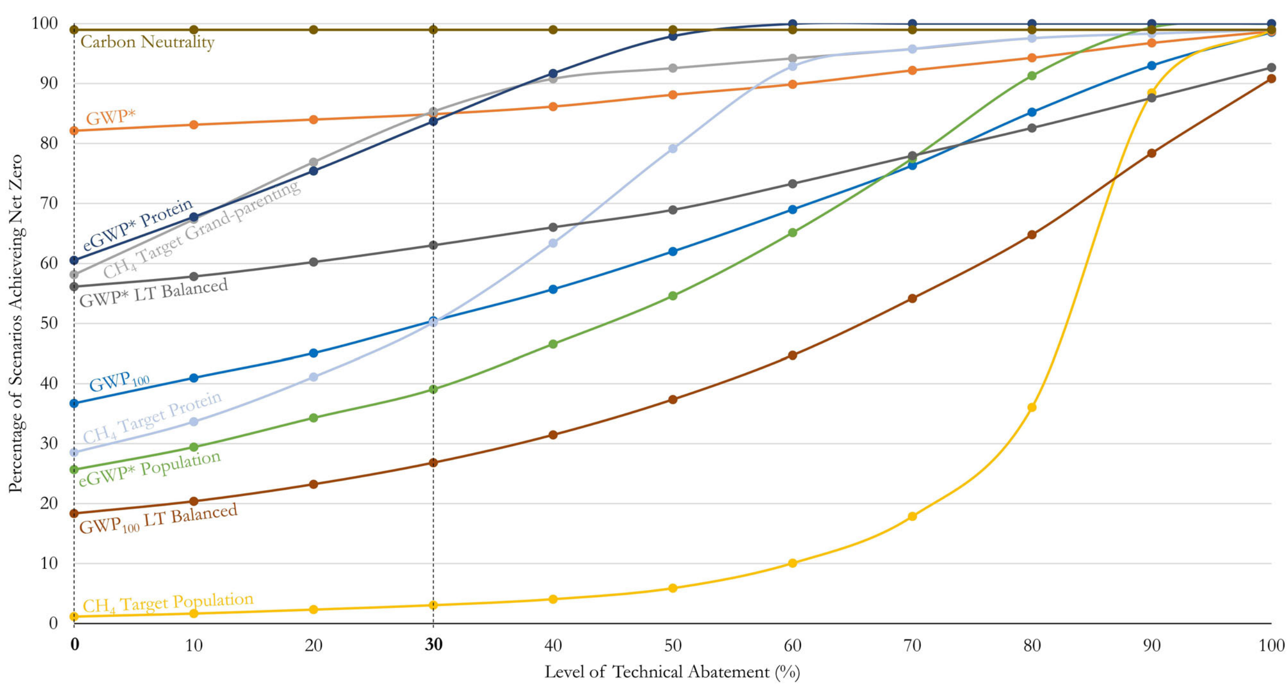

Fig. 6 | Impact of theoretical level of technical abatement on NZ success across different NZ definitions. Each line represents a distinct NZ definition. The vertical dashed lines represent the two default assumptions made within the study, these being scenarios achieving NZ with 0 abatement measures (S-NZ) and scenarios achieving NZ with 30% technical abatement (S-NZ-A). Level of technical abatement relates to reduction in agriculture emissions, assumed uniform for enteric and manure CH_4, and manure, direct, and indirect N_2O emissions.

Discussion

Identifying possible NZ AFOLU configurations is an important step in informing appropriate climate action. It can help stakeholders to visualise the scale of the challenge and to prioritise effective and strategic (future-proof) actions regarding sustainable food production and land use policy. Simply put, if policy makers do not know what national NZ commitments could look like in practice, they cannot effectively plan and implement policy to achieve those commitments. Randomised scenario modelling supports foresight analysis that does not prescribe a "solution" configuration, but rather informs stakeholders about the real constraints involved, and depicts boundaries around a NZ "space" that the AFOLU sector can occupy. Accordingly, this study has shown that future agricultural activities and land uses will need to change dramatically to achieve NZ, but the combination and level of changes will be strongly influenced by the specific NZ definition applied. The wide range of future visions associated with different NZ definitions could impede stakeholder action, leading to debates over appropriate measures and the necessity of action, reluctance to develop strong policies, and apathy towards adopting mitigation practices. More effort is needed to build international consensus on clear definitions for national NZ goals. However, there are important commonalities in inferred NZ AFOLU configurations across the wide range of definitions studied here, pointing to a clear set of actions consistent with reaching territorial NZ that could be prioritised in the absence of a clear definition and end goal. Dramatic expansion of forest cover and re-wetting of organic soils have been highlighted in previous studies[24], and even the most moderate changes observed to achieve different NZ definitions here will require rapid ramping up of action beyond existing policy targets[22]. Our study further demonstrates that, even with optimistic abatement measures to reduce agricultural GHG emission intensities, substantial reductions in the cattle herd are required to reach NZ by 2050 for all definitions excluding carbon (only) neutrality (Figs. 2, 3). The quantification of these requisite actions necessary to achieve a NZ AFOLU sector in Ireland, and their sensitivity to a range of NZ definitions, constitute the main novel findings of this study. For instance, considering the average NZ forest area observed for each definition implies that Ireland will require 2.4–3.9 times more forest area by 2050 (relative to 2021). Although these values appear extreme, it is worth noting that Ireland has the third lowest forest cover area in EU-27[29], standing at 11%[29,30], far below the EU average of 39%[29].

These results highlight the inescapable need for difficult decisions to be made on whether to prioritise milk or beef output (or reduce both similarly) if Ireland is to achieve its policy goal of NZ by 2050. Although some mitigation measures have low costs and can be applied without adverse production effects, most mitigation actions involve trade-offs that should be fully considered before they are implemented, including impacts on livelihoods, food security, biodiversity, and export income[31]. Reducing output could also risk international GHG "leakage" by displacing milk and/or beef production to regions with less efficient (higher GHG intensity) production systems[8], as Ireland currently exports 90% of milk and beef output internationally[32,33], and has amongst the lowest GHG intensity beef and milk production, globally[34]. That said, while the Paris Agreement presents NZ GHG as a global target for the second half of the century[5], it has led to countries (and companies) adopting NZ targets on a territorial basis[3], shifting discussion away from comparative efficiency of (milk and beef) production towards simultaneous zero-sum equations for emissions and land carbon uptake at national level. Such an approach is more in line with principles of absolute sustainability thresholds[35], and with transformative changes needed to achieve food system sustainability – including diet shifts, waste reduction, and closing yield gaps in developing countries, as well as efficiency improvements[36,37]. In general, such an approach is also consistent with a shift in land use towards biomass production to support expansion of biomaterial and bioenergy value chains, and/or delivery of ecosystem services, as part of the transition towards a circular bioeconomy[38]. It has been shown that cascading use of wood from commercial forestry could support stronger and longer climate mitigation from afforestation than is considered in the national inventory accounting approach applied in this study[39]. There remains a need to better understand the potential economic value of these alternative uses, that could compensate farmers for foregone livestock production and stimulate a broader bioeconomy within a NZ future.

GWP_{100} is the internationally accepted metric to measure progress towards Paris Agreement commitments in Nationally Determined Contributions[4], and so a GWP_{100} "net zero GHG" balance remains the default definition for national governments to work towards. However, alternative methods have been proposed to better represent global emissions profiles required to achieve temperature goals[5,10,14,16,40]. We explored ten definitions of NZ previously proposed in the scientific and policy literature. This list is not exhaustive, but does include distinctive features relating to, *inter alia*: alignment with long-term temperature stabilisation emissions profiles at global scale, international fairness, and flexibility across gases. No definition is ideal across all aspects, and trade-offs are involved in selecting one method over another. For example, GWP_{100} definitions are potentially better aligned with international fairness than GWP* definitions[16], but the 2050 GWP_{100} definition is less well aligned with long-term temperature stabilisation. GWP_{100} and GWP* definitions enable flexibility across gases, whilst separate methane targets do not (though could be adapted to do so with a hybrid approach where variations from the CH_4 target are compensated by a warming-equivalent balance for CO_2 and N_2O[41]). The population-based CH_4 target and eGWP* definitions score well for international fairness and alignment with long-term temperature stabilisation, but the former would involve reducing milk and beef production more than three quarters for Ireland, even assuming ambitious emissions abatement via technical measures. Thus, distinguishing CH_4 from CO_2 and N_2O based on its characteristics as a potent SLCP is a double-edged sword for countries such as Ireland with high CH_4 emissions (owing to large ruminant, rice, or fossil fuel sectors) and could lead to increases in CH_4 emissions globally in the short term if less efficient production fills the gap[8]. Calculating NZ solely based on CO_2 (carbon neutrality) overlooks major climate forcing emissions for countries such as Ireland with large agricultural emission sources, thereby disregarding important actors directly contributing to, and capable of mitigating, climate impact. Consequently, although it is necessary to achieve global carbon neutrality by 2050[2], such a narrow metric is inadequate to design appropriate pathways towards achieving NZ within national AFOLU sectors. Definitions based on cumulative emissions between 2050 and 2100 are better aligned with long-term temperature stabilisation, but also depend on much less certain future activity-flux relationships (emission factors and CO_2 removal opportunities) beyond 2050, and may be a step too far (ahead) for policy makers operating in the context of short voting cycles.

In summary, new evidence presented here highlights the striking diversity of AFOLU configurations that could successfully achieve NZ, depending on the definition applied. This is not necessarily a barrier to near-term action as several common activities emerged across NZ scenarios regardless of the different definitions, including high rates of afforestation, extensive re-wetting of organic soils, and modest cattle destocking. Achieving a high degree of technical abatement for agricultural CH_4 and N_2O emissions can moderate the required rates of the aforementioned activities but cannot avoid the need for substantial land use change and shifts in production. As nations work towards their NZ goals, governments will face difficult policy decisions as the zero-sum nature of land and GHG balances needed to achieve these goals become clearer, and consequences for agricultural activities, land use change, and livelihoods/rural communities emerge. Results for Ireland are stark, owing to the outsize contribution of AFOLU within the national emission profile, providing a powerful illustrative case study. Achieving NZ urgently requires evidence-based, yet sensitive, engagement with all stakeholders to drive the transformative action required. Greater clarity on the end-goal is crucial to ensure timely and progressive implementation of actions, particularly those associated with a significant delay in GHG-flux response (e.g., afforestation); and also ensure that bioeconomy opportunities are identified to support a just transition. This in turn requires national policy leadership to clearly define NZ, preferably based on international consensus, which remains lacking. Progress can still be made without an agreed definition given the commonalities we found across all NZ definitions, but the chances of a just transition based on consistent strategic policy making, and stakeholder buy-in around an end-point vision, will diminish with each passing year.

Methods

GOBLIN model

Detailed methodology describing the "GOBLIN" (General Overview for a Back-casting approach of Livestock INtensification) model can be found in

Duffy et al.[23] and (for harvested wood product accounting update) Duffy et al.[6]. To summarise, GOBLIN is a national biophysical AFOLU model which runs randomised scenarios of agricultural activities and land use combinations within biophysical constraints to calculate annual GHG emissions along trajectories to selected future target years, here 2050 and 2100. GOBLIN consists of eight modules (Figure S3), the first of which randomises key input parameters: national dairy and beef cattle and sheep numbers, animal level productivity, fertiliser application rates and distribution rules for grassland spared from livestock production. Deduced parameters include milk and beef production, areas of spared grassland, and new areas of rewetted organic soils, and broadleaf and commercial forestry. From these parameters, AFOLU GHG emissions and removals are calculated using IPCC Tier 1 and Tier 2 methodologies[23,42,43], consistent with Ireland's UNFCCC reporting[20]. Cropland emissions are included, but the area is assumed to be constant over time.

Scenarios

3000 randomised scenarios were generated using a Latin hypercube sampling method[44] by randomly varying input parameters utilised in GOBLIN between set minimum and maximum values for each individual scenario (Table S1). This sampling approach ensures a comprehensive exploration of the future parameter space. Table S1 in the supplementary material provides a detailed overview of the key inputs into the GOBLIN model, presenting the value ranges of key variables from which each of the 3000 scenarios is randomly derived. Total animal numbers were set between one and values reported for 2021[45], with grassland utilisation rate calibrated at between 67% and 80% of grass produced being consumed by livestock (variable across scenarios) based on calculated grass uptake and total grassland area utilised by the updated national herd and flock numbers[23]. Further details on GOBLIN input parameters, including background data information, can also be found in Duffy et al.[23] and Duffy et al.[6]. It is important to note that the target year for AFOLU configurations is 2050; no further changes to annual agricultural production or land use are considered after 2050. Emissions beyond 2050 thus represent this new "equilibrium" land use, incorporating forestry (re)growth and harvest cycles in pre-existing forests and "new" forests planted up until 2050. Although animal numbers in Ireland are increasing[18], early runs of the model[6] indicate current animal numbers are already exceeding the emissions levels necessary to achieve NZ across definitions. As such, animal numbers were capped at their recent levels to avoid returning excessive scenarios which failed to reach NZ, of less relevance to conclusions. It is important to note that by setting minimum animal populations at 1, and applying a randomized input algorithm, we are not pre-determining a future for Ireland – on the contrary, we are attempting to remove value judgments as far as possible in order to objectively explore what alternative futures could look like in terms of GHG emissions. However, to maximise data resolution around likely bounds of NZ under different definitions from the 3000 scenarios, parameter ranges forced static or reduced animal numbers, static or increased grass use efficiency, and allocation of land spared from livestock production to carbon-neutral or carbon-positive uses, such as organic soil rewetting and afforestation – reflecting insight from recent model runs[6]. The aim of this paper was not to make economic or feasibility assessments, but rather to explore the various AFOLU configurations that align with different definitions of NZ through randomised scenario simulations.

Net zero definitions

The following methods elaborate on the definitions pertaining to NZ for the year 2050.

GWP_{100}. GWP_{100} is the most widely used climate metric. At COP24 it was decided to use GWP_{100} for reporting national emissions to the Paris Agreement[4]. GWP_{100} (Eq. 1) is defined as the ratio of the (100-year) time-integrated radiative forcing (RF) from the instantaneous release of 1 kg of a trace substance i relative to that of 1 kg of a reference gas (typically CO_2)[46]:

$$GWP_i(H) = \frac{\int_0^H RF_i(t)\,dt}{\int_0^H RF_{CO_2}(t)\,dt} = \frac{AGWP_i(H)}{AGWP_{CO_2}(H)} \tag{1}$$

where H is the time horizon over which the calculation is considered (here 100 years); RF_i is the radiative forcing due to a pulse emission of gas i; (t) is the time-dependent decay in abundance of a pulse emission; and the corresponding quantities for the reference gas (typically CO_2) are in the denominator. In other words, GWP is the ratio of Absolute GWP (AGWP) for i over AGWP for the reference gas CO_2[46]. The GWP_{100} in this study used AR5 emission metric values for CO_2, CH_4, and N_2O emissions, with cumulative forcing over 100 years equalling 1, 28, and 265, relatively[47]. GWP_{100} was used to calculate GHG neutrality[2], where to be classified as NZ (S-NZ) the net sum of GHG emissions had to balance with an equivalent amount of removals or be net-negative in the year 2050 (only – the trajectory after 2050 was not considered).

GWP*. GWP* defines equivalence based on the warming impact of a change in SLCP emissions to the warming impact of CO_2 emissions, termed the CO_2-warming-equivalent (CO_2-we)[40,48,49]. GWP* is sensitive to the rate of change of SLCPs, with small absolute increases in emissions leading to a large warming impact and a larger value for CO_2-we emissions than would be for GWP_{100} based CO_2-e emissions. Conversely, any decline in SLCP emissions larger than about 0.3% per year leads to negative CO_2-we emissions. CO_2-warming-equivalent emissions of CH_4 within this study were calculated from the latest GWP* equation (Eq. 2)[40]:

$$E^*(t) = 4.53 \times E_{100}(t) - 4.25 \times E_{100}(t-20) \tag{2}$$

where E^* (t) is the CO_2-we emissions at time t; E_{100} (t) is the SLCP emission rate at t, calculated as CO_2e using GWP_{100}; and E_{100} (t-20) is the rate of SLCP emissions 20 years before t, calculated as CO_2e using GWP_{100}.

The CO_2 and N_2O emissions (E) within this definition were calculated based on GWP_{100} methodology as a CO_2e emission (ECO_2e) quantity by multiplying by the appropriate GWP conversion factor for the specified time-horizon (H), here 100 years (Eq. 3):

$$E_{CO_2-e} = E \times GWP_H. \tag{3}$$

As noted in Allen et al.[9], halting global warming requires NZ emissions of LLCFs such as CO_2 and N_2O, and declining (but not necessarily zero) net emissions of SLCFs such as CH_4. Following the GWP* principles, if we have a scenario which maintains NZ CO_2-we emissions for the year 2050 (S-NZ) then we have a scenario which should not drive temperatures upwards.

Methane targets. Prudhomme et al.[14] developed a series of national biogenic CH_4 quotas compatible with limiting global warming to 1.5 °C. International fairness was explored where global CH_4 budgets for 1.5 °C scenarios were allocated to national quotas based on: grand-parenting (equal percentage reductions across countries) (Eq. 4); population (equality, or equal per capita emissions) (Eq. 5); and animal protein security (emissions proportionate to animal protein production in 2010) (Eq. 6). According to the three allocation methods above, CH_4 quotas for Ireland for 2050 were calculated in Prudhomme et al.[14]:

$$CH^i_{4_{2050}} = \frac{CH^i_{4_{2010}}}{CH^{world}_{4_{2010}}} \times CH^{world}_{4_{2010}} \times \left(\alpha_E^{world} - 1\right) \tag{4}$$

$$CH^i_{4_{2050}} = \frac{Pop^i_{2010}}{Pop^{world}_{2010}} \times \alpha_E^{world} \times CH^{world}_{4_{2010}} \tag{5}$$

$$CH^{i}_{4_{2050}} = \frac{Prot^{i}_{2010}}{Prot^{world}_{2010}} \times \alpha^{world}_{E} \times CH^{world}_{4_{2010}} \quad (6)$$

where the national biogenic CH_4 quotas in 2050 ($CH^{i}_{4_{2050}}$) are dependent on specific allocation rules for a specific country, *i*, here Ireland. $CH_{4_{2010}}$ is the national (*i*) or global (*world*) biogenic CH_4 in 2010. Pop is the 2010 population of the country or globally, and Prot is the global or national animal-protein production. α^{world}_{E} refers to the reduction (between 0 and 1) of global biogenic CH_4 emissions in 2050 compared to 2010 compatible with 1.5 °C scenarios (see Prudhomme et al.[14] for further details). Deduced CH_4 targets for Ireland for 2050 were 358, 60, and 229 kt of CH_4 for Grand-parenting, Population, and Protein approaches, respectively. Here, scenarios that complied with the CH_4 target and achieved at least NZ (or net negative) CO_2 plus N_2O using GWP_{100} by 2050 were assigned S-NZ.

eGWP*. Rogelj and Schleussner[16] argue that when applied at national level, the CH_4 emission grand-parenting implied via the reference emission level used in the GWP* calculation introduces a preferential treatment of countries that have large contemporary CH_4 emissions. The eGWP* method is an attempt to introduce international fairness into the GWP* method by adjusting the national reference emission level for CH_4 to a "fair share" of global emissions, rather than the contemporary emission level[16]. Here, we adapt eGWP* to incorporate the latest GWP* equation combined with reference level CH_4 emissions derived from allocation rules introduced above for Ireland[14,40]. In its broken-down form for any SLCP, GWP* is given in Eq. 7[40]:

$$E^{*}(t) = \left[gA \times E_H(t) - gB \times E_H(t - \Delta T)\right] \times GWP_H \quad (7)$$

where g denotes a scaling factor of 1.13; A is a coefficient calculated as 75/$\Delta T + 0.25$, where *t* is the GWP* time interval, the 75 is a rate-based component (0.75*100) (where 0.75 is the weighting given to the impacts of changing the rate of SLCP emissions[49]), 0.25 is the stock component (the weighting given to the impacts of the current emissions rate[49]); and B is the coefficient 75/ΔT. Equation 7 is identical to Eq. 2.

When the reference emissions level of CH_4 is modified as per the eGWP* methodology, the output can be written as Eq. 8:

$$eE^{*}(t) = \left[gA \times E_H(t) - gB \times E_{Ref\,H}(t - \Delta T)\right] \times GWP_H \quad (8)$$

where the eGWP* CH_4 reference values $E_{Ref\,H}$ in this study were extracted from Prudhomme et al.[14]. The calculations, performed in Prudhomme et al.[14] for population and protein CH_4 reference values and displayed in Eqs. 9, 10, respectively, result in reference values of 89.12 and 340.10 kt CH_4 for equal-per-capita, and equal-per-protein in 2010, respectively.

$$CH^{i}_{4_{ref}} = \frac{Pop^{i}_{2010}}{Pop^{world}_{2010}} \times CH^{world}_{4_{2010}} \quad (9)$$

$$CH^{i}_{4_{ref}} = \frac{Prot^{i}_{2010}}{Prot^{world}_{2010}} \times CH^{world}_{4_{2010}} \quad (10)$$

It should be noted that although reference emissions are usually a value 20 years before the first term in the equation for CH_4 (as per GWP*), reference values here were from the year 2010, based on availability of consistent data needed for international allocation calculations in the underlying study by Prudhomme et al.[14], therefore introducing a larger ΔT of 40 years, between 2010 and 2050. Successful NZ scenarios achieve <0 kg CO_2^{-} we at the year 2050.

Carbon neutrality. The term "carbon neutrality" is often interchangeably characterised as an alternative to NZ (or GHG neutrality[50]). However, the IPCC[50] defines "carbon neutrality" as the "condition in which anthropogenic CO_2 emissions associated with a subject are balanced by anthropogenic CO_2 removals". As such, only the CO_2 emissions and sequestered CO_2 were calculated within this definition. Successfully achieving NZ (S-NZ) was assigned to scenarios where the net sum of CO_2 emissions balances with (or were less than) an equivalent amount of removals in 2050.

Long-term net zero. The parties to the Paris Agreement have agreed to pursue mitigation measures to achieve a balance of anthropogenic GHG emissions by sources and removals by sinks in the second half of the 21st century[5]. To explore this definition of LT NZ, two further interpretations of NZ were analysed for both GWP_{100} and GWP*, termed "GWP_{100} LT" and "GWP* LT", to assess which scenarios sustained NZ across the period 2051-2100, that is, balanced their cumulative GHG emissions during 2051–2100 whilst maintaining constant land use after 2050 (but with extended forest sequestration accounted for[6,23]), using the same methodology as described above, again assigning the scenarios to S-NZ or F-NZ.

Abatement

It is possible for NZ targets to be met not just through specific configurations of agricultural production and land use, but through the reduction of agricultural emissions at source following the implementation of abatement measures. Effective abatement measures for CH_4 and N_2O that can reduce emissions with minimal, neutral, or positive effect on productivity can include the displacement of mineral N fertiliser by biologically-fixed N (using grass clover or multi-species pastures) or mobilisation of soil N via pH manipulation, applying protected urea fertilisers, improving animal genetics, anti-methanogenic feed additives, low-emission storage and spreading techniques for manures, acidification of manures, and use of methane and nitrification inhibitors[27,51,52]. Within this study, abated scenarios assume an ambitious 30% reduction in agriculture emissions uniformly applied to enteric and manure CH_4, as well as manure, direct, and indirect N_2O emissions. This reduction represents the realistic upper end of cumulative abatement potentials possible with identified technologies[27,28]. Employing these abated scenarios reflects a conservative approach in drawing final conclusions with respect to the magnitude of impacts from efforts to meet NZ, and thus is our default assumption. Each of the 3000 abated scenarios was classified into whether they succeeded (S-NZ-A) or failed (F-NZ-A) to meet NZ with abatement, according to each NZ definition.

Although we refer to our abatement assumption as ambitious, some studies demonstrate significantly greater efficacy for certain technical abatement measures, far exceeding the 30% benchmark. For instance, red seaweed has exhibited an exceptional ability to reduce enteric CH_4 emissions, with some early upper-end studies reporting over 80% CH_4 mitigation[53,54]. However, these results may be overly optimistic for achieving a 2050 deadline for a national herd average, with several challenges still to be addressed on feasibility, long-term efficacy, and effects on animal production and health[55]. Nevertheless, a sensitivity analysis was undertaken on the level of technical abatement on the ability of scenarios to achieve NZ, ranging from 0% to 100%.

Limitations

While the GOBLIN model endeavours to simulate real-world consequences, it is important to acknowledge certain limitations inherent to its design, in addition to those outlined in the Methods Section. The model ran randomised scenarios within predefined parameter boundaries (Table S1); however, it is essential to note that the scope of land use changes was restricted exclusively to positive transformations on spared grassland. Specifically, spared grassland resulting from decreased animal numbers or increased productivity was constrained to either rewetting when on organic soil, afforestation on mineral soil, or preservation as ungrazed grassland. Notably, the model deliberately excluded any possibility of negative land use changes emanating from spared grassland. This design choice aligns with realistic pathways towards NZ based on identified necessary actions[2,36], limiting the number of scenarios that would fail to reach NZ, but still constitutes a noteworthy limitation.

Additionally, the linear interpolation of scenario values from the baseline year to 2050 may marginally impact definitions influenced by trends, particularly the GWP* definitions. Further, the uncertainty inherent in long-term projections beyond 2050 is underscored by GOBLIN's assumption of equilibrium AFOLU configurations and static flux factors from 2050 onwards (excluding forest growth-harvest cycles, which are modelled out to 2100). Consequently, many long-term effects, both positive and negative, arising from individual scenarios might be overlooked. There remains a need to consider interaction between land-based CO_2 sinks and downstream bioeconomy innovations, especially cascading use of wood culminating in bioenergy with carbon capture and storage that could dramatically extend the longevity of critical carbon sinks. Further GOBLIN model limitations can be found at Duffy et al.[6,23].

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. The 3000 abated scenario results, parameters, emissions, and calculations can be found in Supplementary Data 1. The 3000 non-abated scenario results, parameters, emissions, and calculations can be found in Supplementary Data 2.

Code availability

Information and links to the GOBLIN model can be found at Duffy et al.[23] and https://fusion-research.eu/goblin-package-documentation.html#goblin-package-documentation. Key GOBLIN model inputs used within the study can be found in the Supplementary Information.

Received: 13 July 2023; Accepted: 16 February 2024;
Published online: 28 February 2024

References

1. Lang, J. et al. Net zero tracker. *Energy & Climate Intelligence Unit (ECIU), Data-Driven EnviroLab (DDL), NewClimate Institute, Oxford Net Zero*. https://www.zerotracker.net (2023).
2. IPCC. Climate Change 2022: Mitigation of Climate Change. *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (2022).
3. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Net-zero emissions targets are vague: three ways to fix. *Nature* **591**, 365–368 (2021).
4. UNFCCC. *Report of the conference of the parties serving as the meeting of the parties to the Paris agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018*. *Addendum 2. Part two: Action taken by the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement.* (FCCC/PA/CMA/2018/3/Add.2 2019).
5. UNFCCC. *Adoption of the Paris agreement. Report No. FCCC/CP/2015/L.9/Rev.1*. (2015).
6. Duffy, C. et al. Randomized national land management strategies for net-zero emissions. *Nature Sustainability 2022* 1–8 https://doi.org/10.1038/s41893-022-00946-0 (2022).
7. Harrison, M. T. et al. Carbon myopia: The urgent need for integrated social, economic and environmental action in the livestock sector. *Glob Chang Biol* **27**, 5726–5761 (2021).
8. Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253 (2018).
9. Allen, M. R. et al. Net zero: science, origins, and implications. https://doi.org/10.1146/annurev-environ-112320-10505047, 849–887 (2022).
10. Tanaka, K. & O'Neill, B. C. The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets. *Nat. Clim. Change* **8**, 319–324 (2018).
11. IPCC. Summary for Policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://doi.org/10.1017/9781009157940.001 (2018).
12. Lynch, J., Cain, M., Frame, D. & Pierrehumbert, R. Agriculture's contribution to climate change and role in mitigation is distinct from predominantly fossil CO2-emitting sectors. *Front Sustain Food Syst.* **4**, 300 (2021).
13. Allen, M. R. et al. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Clim. Atmos. Sci.* **1**, 1–8 (2018).
14. Prudhomme, R., O'Donoghue, C., Ryan, M. & Styles, D. Defining national biogenic methane targets: Implications for national food production & climate neutrality objectives. *J. Environ. Manage* **295**, 113058 (2021).
15. Kartha, S. et al. Cascading biases against poorer countries. *Nat. Clim. Chang.* https://doi.org/10.1038/s41558-018-0152-7 (2018).
16. Rogelj, J. & Schleussner, C. F. Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. *Environ. Res. Lett.* **14**, 114039 (2019).
17. Richards, M. B., Wollenberg, E. & van Vuuren, D. National contributions to climate change mitigation from agriculture: allocating a global target. *Climate Policy* **18**, 1271–1285 (2018).
18. Kelly, P., Shalloo, L., Wallace, M. & Dillon, P. The Irish dairy industry – Recent history and strategy, current state and future challenges. *Int. J. Dairy Technol.* **73**, 309–323 (2020).
19. Hennessy, T., Doran, J., Bogue, J. & Repar, L. *The economic and societal importance of the Irish suckler beef sector*. https://www.ifa.ie/wp-content/uploads/2020/08/2018-The-Economic-and-Societal-Importance-of-the-Irish-Suckler-Beef-Sector-Aug-2018.pdf (2018).
20. Duffy, P. et al. *Ireland's National Inventory Report 2021*. www.epa.ie (2021).
21. Ryan, M., O'Donoghue, C., Hynes, S. & Jin, Y. Understanding planting preferences – A case-study of the afforestation choices of farmers in Ireland. *Land Use Policy* **115**, 105982 (2022).
22. DECC. Climate Action Plan 2021. *Securing Our Future*. https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/ (2021).
23. Duffy, C. et al. GOBLIN version 1.0: a land balance model to identify national agriculture and land use pathways to climate neutrality via backcasting. *Geosci. Model Dev.* **15**, 2239–2264 (2022).
24. IPCC. Summary for Policymakers. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/syr/ (2023) https://doi.org/10.59327/IPCC/AR6-9789291691647.
25. Teagasc. *National Farm Survey 2022*. (2023).
26. DAFM. *Trade Factsheet Full Year 2022*. (2023).
27. Lanigan, G. J. et al. *An analysis of abatement potential of Greenhouse Gas emissions in Irish agriculture 2021-2030*. Teagasc, Oak Park, Carlow, Ireland (2018).
28. Rees, R. M. et al. How far can greenhouse gas mitigation take us towards net zero emissions in agriculture? *Nutrient Management in Farmed Landscapes.* 1–8 (2020).
29. Eurostat. *39% of the EU is covered with forests - Products Eurostat News - Eurostat*. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20210321-1 (2021).
30. DAFM. *Forest Statistics Ireland 2020*. https://www.teagasc.ie/media/website/crops/forestry/advice/Forest-Statistics-Ireland-2020.pdf (2020).
31. Cohen, B., Cowie, A., Babiker, M., Leip, A. & Smith, P. Co-benefits and trade-offs of climate change mitigation actions and the sustainable development goals. *Sustain Prod. Consum.* **26**, 805–813 (2021).

32. Shortall, O. Cows eat grass, don't they? Contrasting sociotechnical imaginaries of the role of grazing in the UK and Irish dairy sectors. *J. Rural Stud.* **72**, 45–57 (2019).
33. O'Donovan, M., Hennessy, D. & Creighton, P. Ruminant grassland production systems in Ireland. *J. Agric. Food Res.* **59**, 225–232 (2021).
34. O'Mara, F. et al. Sustainability of ruminant livestock production in Ireland. *Animal Front.* **11**, 32 (2021).
35. Steffen, W. et al. Planetary boundaries: Guiding human development on a changing planet. *Science (1979)* **347**, 1259855–1259855 (2015).
36. Searchinger, T., Waite, R., Hanson, C. & Ranganathan, J. *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. (2019).
37. Springmann, M. et al. Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
38. European Commission. *Bioeconomy: the European way to use our natural resources. Action plan 2018*. https://data.europa.eu/doi/10.2777/79401 (2018) https://doi.org/10.2777/79401.
39. Forster, E. J., Healey, J. R., Dymond, C. & Styles, D. Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nat. Commun.* **12**, 1–12 (2021).
40. Smith, M. A., Cain, M. & Allen, M. R. Further improvement of warming-equivalent emissions calculation. *NPJ Clim. Atmos Sci.* **4**, 29 (2021).
41. Allen, M. et al. Ensuring that offsets and other internationally transferred mitigation outcomes contribute effectively to limiting global warming. *Environ. Res. Lett.* **16**, 074009 (2021).
42. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (2019).
43. IPCC. *IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (2006).
44. McKay, M. D., Beckman, R. J. & Conover, W. J. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* **42**, 55–61 (2000).
45. CSO. *AAA09 - Number of Livestock in June*. https://data.cso.ie/ (2022).
46. IPCC. Climate Change 2001: The Scientific Basis. *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. (2001).
47. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. http://www.ipcc.ch. (2014).
48. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *NPJ Clim. Atmos Sci.* **2**, 29 (2019).
49. Lynch, J., Cain, M., Pierrehumbert, R., Allen, M. & Demonstrating, G. W. P. a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.* **15**, 044023 (2020).
50. IPCC. *Annex I IPCC AR6 WGIII - Glossary*. (2022).
51. O'Brien, D. et al. An evaluation of the effect of greenhouse gas accounting methods on a marginal abatement cost curve for Irish agricultural greenhouse gas emissions. *Environ. Sci. Policy* **39**, 107–118 (2014).
52. Reisinger, A. et al. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Philos. Trans. Royal Soc. A* **379**, 20200452 (2021).
53. Roque, B. M. et al. Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. *PLoS One* **16**, e0247820 (2021).
54. Kinley, R. D. et al. Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. *J. Clean Prod.* **259**, 120836 (2020).
55. Hristov, A. N., Melgar, A., Wasson, D. & Arndt, C. Symposium review: effective nutritional strategies to mitigate enteric methane in dairy cattle. *J. Dairy Sci.* **105**, 8543–8557 (2022).

Acknowledgements
This research was supported by EPA Research 2030, funded by Ireland's Environment Protection Agency under grant number EPA-CCRP-MS.57, and by Ireland's Department of Environment, Climate and Communications under FORESIGHT land use modelling services contract.

Author contributions
G.B.: Conceptualisation, Analysis, Methodology, Manuscript preparation. C.D.: Methodology, Software, Validation, Review and editing. R.P.: Validation, Review and editing. A.C.: Validation, Review and editing. C.O.D.: Validation, Review and editing. M.C.: Validation, Review and editing. G.J.L.: Validation, Review and editing. D.S.: Conceptualisation, Analysis, Validation, Review and editing.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains Supplementary Material available at https://doi.org/10.1038/s43247-024-01275-0.

Correspondence and requests for materials should be addressed to George Bishop.

Peer review information *Communications Earth & Environment* thanks Martino Malerba and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: I-Yun Hsieh and Martina Grecequet. A peer review file is available