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Defining national biogenic methane targets: implications for national food production & climate neutrality objectives

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Abstract

Methane is a short-lived greenhouse gas (GHG) modelled distinctly from long-lived GHGs such as carbon dioxide and nitrous oxide to establish global emission budgets for climate stabilisation. The Paris Agreement requires a 24-47% reduction in global biogenic methane emissions by 2050. Separate treatment of methane in national climate policies will necessitate consideration of how global emission budgets compatible with climate stabilisation can be downscaled to national targets, but implications of different downscaling rules for national food production and climate neutrality objectives are poorly understood. This study addresses that knowledge gap by examining four methods to determine national methane quotas, and two methods of GHG aggregation (GWP_{100} and GWP*) across four countries with contrasting agriculture, forestry and other land use (AFOLU) sectors and socio-economic contexts (Brazil, France, India and Ireland). Implications for production of methane-intensive food (milk, meat, eggs and rice) in 2050 and national AFOLU climate neutrality targets are explored. It is assumed that methane quotas are always filled by food production where sufficient land is available. Global methane budgets for 1.5°C scenarios are downscaled to national quotas based on: grand-parenting (equal *percentage* reductions across countries); equity (equal *per capita* emissions); ability (emission reductions proportionate to GDP); animal protein security (emissions proportionate to animal protein production in 2010). The choice of allocation method changes national methane quotas by a factor of between 1.7 (India) and 6.7 (Ireland). Despite projected reductions in emission-intensities, livestock production would need to decrease across all countries except India to comply with quotas under all but the most optimistic sustainable intensification scenarios. The extent of potential afforestation on land spared from livestock production is decisive in achieving climate neutrality. Brazil and Ireland could maintain some degree of milk and beef export whilst achieving territorial climate neutrality, but scenarios that comply with climate neutrality in India produce only circa 30% of national calorie and protein requirements via rice and livestock. The downscaling of global methane budgets into national policy targets in an equitable and internationally acceptable manner will require simultaneous consideration of the interconnected priorities of food security and (land banks available for) carbon offsetting.

Keywords: net zero GHG; climate stabilisation; CH_4; LULUCF; land sparing; carbon offset

1. Introduction

Most national climate plans are based on aggregation of the principal greenhouse gases (GHG) methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) using the 100-yr average global warming potentials (GWP_{100}) recommended for national inventory reporting (UNFCCC, 2014). Recent modelling has demonstrated that short-lived GHGs such as CH_4 (circa 20 year atmospheric half-life) behave more like flow pollutants, whilst long-lived GHGs such CO_2 and N_2O act more stock pollutants, in terms of their climate-forcing effects (Alleln et al., 2018). This results in overestimations in long-term climate forcing being attributed to current CH_4 emissions under the GWP_{100} metric, and the GWP* aggregation metric (elaborated below) has been proposed to better represent cumulative climate forcing of different emissions through time (Allen et al., 2018; Cain, 2019). Furthermore, unlike fossil-CH_4 emitted from e.g. fossil fuel fracking operations, biogenic CH_4 arising from biological processes does not contribute to increasing atmospheric CO_2 concentrations (and thus climate forcing) upon eventual oxidation in the atmosphere as the carbon was, in most cases, recently assimilated by vegetation from the atmosphere. Thus, global climate modelling indicates that biogenic CH_4 reductions of 24-47%, relative to 2010 are sufficient to achieve climate stabilisation at a global mean surface temperature 1.5 degrees centigrade above pre-industrial times (Rogelj et al., 2018a).

Over half of global CH_4 emissions come from food production (Saunois et al., 2020), specifically livestock rearing and rice cultivation, and there is strong interest in application of separate biogenic CH4 targets, or a GWP* approach, to determine emission pathways for national climate neutrality in national climate plans among countries where livestock contribute substantially to national emissions, such as New Zealand and Ireland (Reisinger and Leahy, 2019). According to the GWP* method (Allen et al., 2018; Cain et al., 2019), the *future* climate forcing effect of emissions depends on the recent *change* in CH_4 emissions (usually over a 20-yr period). This representation is more consistent with climate modelling used to determine pathways towards climate stabilisation at the global scale (Intergovernmental Panel on Climate Change, 2018), and could be used to more accurately determine the contribution of national CH_4 emissions, at given fluxes of CO_2 and N_2O, to climate neutrality. However, it involves the 'grand-parenting' of CH_4 emissions which has pronounced implications for how the global CH_4 budget is apportioned, and that may be challenged in terms of international fairness (Rogelj and Schleussner, 2019). New Zealand's climate neutrality policy is not directly based on GWP*, but aims to reduce biogenic CH_4 emissions by 24-47% between 2017 and 2050 (Ministry for the Environment, 2019). There is no internationally agreed method to establish separate targets for CH_4 in national climate plans. The aim of this paper is to elucidate trade-offs and complementarities among different approaches to establish national biogenic CH_4 targets in terms of international equity, national food security and national climate targets. To do this, implications of different national biogenic CH_4 targets compatible with global climate stabilisation for national CH_4-emitting food production (milk, eggs, meat, rice) and national agriculture and land use GWP balances are explored across four contrasting countries (Brazil, France, India, Ireland).

The 195 signatory countries of the Paris Agreement agreed to "holding the increase in the global average temperature well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" and to achieve a "balance between anthropogenic emissions by sources and removals by sinks of GHG in the second half of this century, on the basis of equity, and in the context of sustainable development" (UNFCC, 2016). The agriculture, forestry and other land use (AFOLU) sector has a critical role to play in achieving the balance between emissions sources and sinks (IPCC, 2019). On the one hand, it accounts for 24% of current global emissions (IPCC, 2014), including difficult-to-abate emissions of CH_4 and N_2O from livestock and soils and rice, alongside ongoing release of terrestrial carbon from conversion of forest areas to agriculture. On the other hand, the AFOLU sector represents a huge potential sink for CO_2 in soils and new perennial biomass (forest) growth, alongside the production of bio-based products that can substitute GHG-intensive products (Aguilar et al., 2018; IPCC, 2019). Climate stabilisation will require substantial reductions in CH_4 and N_2O, alongside net CO_2 sequestration to offset residual CH_4 and N_2O emissions (Rogelj et al., 2014; Tanaka and O'Neill, 2018). This has been translated into ambitious climate policies for the AFOLU sector within e.g. National Determined Contributions (NDCs) from Benin and Ethiopia (Richards et al. 2018), the UK plan for Net Zero GHG emissions (Committee on Climate Change, 2020), and New Zealand's climate policy target to reduce biogenic CH_4 emissions to the lower range of the Paris objectives (Reisinger and Leahy, 2019). The objective of the Paris agreement is to achieve "a balance between anthropogenic emissions by sources and removals by sinks of GHG" at the global level and for all sectors, and effort sharing across national AFOLU sectors remains to be discussed. Various notions of fairness underpin rules applied by different governments to allocate non-CO_2 agricultural emission reduction targets (Richards et al., 2018). Fleurbaey et al. (2014) defined the notion of fairness in relation to five dimensions: responsibility, capability, equality, equal cumulative per capita emissions and staged approaches. Richards et al. (2018) defined reduction targets for non-CO_2 emissions from the agricultural sector based on different allocation rules (Wollenberg et al., 2016) in order to assess the climate ambition of various NDCs. It is clear from previous studies that different approaches result in very different CH_4 targets within national AFOLU sectors. There remains a need to develop an approach, based on internationally acceptable principles, that restricts this range in order to increase the chances of (collective) attainment of climate stabilisation.

Finally, climate plans do not exist in isolation of other policy objectives and societal priorities. There is a challenge to reduce global CH_4 emissions whilst increasing the production of nutritious food by 82-149% by 2050, compared with 2010, in order to deliver food security (Huppmann et al., 2019). Biogenic CH_4 emissions are largely associated with the production of nutritious (high-quality-protein) food (Key and Tallard, 2012). Some might argue that tackling global malnutrition could be threatened by the introduction of quotas on ruminant production (Adesogan et al., 2020), whilst rice, the only CH_4-emitting crop, represents a primary source of energy for 3.5 billion people who depend on it for more than 20% of their daily calories (Maclean et al., 2013). The amount of livestock and rice production compatible with climate neutrality will depend not just on CH_4, but other GHG emissions associated with such production, notably N_2O, and also land requirements which in turn determine how much land is available for emissions offsetting via, in particular, forestry (IPCC, 2019). Therefore, there is an urgent need to understand the implications of different approaches for establishing separate biogenic CH_4 targets for, *inter alia,* food security and AFOLU climate neutrality objectives at national scale.

The primary objective of this study is to provide new insight into linkages between different value judgements, national biogenic CH_4 targets compatible with global climate stabilisation, food security and national climate neutrality objectives. Greater understanding of the implications of different approaches for establishing separate national targets for CH_4 will be crucial in order to advance international coordination on this critical aspect of climate policy.

2. Methodology

2.1. Overview of the method

The objective of this study is to elaborate the impact of different rules for allocating global biogenic CH_4 mitigation required to limit global warming to 1.5 degrees on national level food production and GHG emissions. Different national biogenic CH_4 targets for Brazil, France, India and Ireland compatible with the 1.5 degrees scenario are derived by scaling down global targets (Huppmann et al., 2019) using different allocation rules. The four selected country examples provide a diverse spread of AFOLU and socio-economic contexts. The impact on agricultural production, other AFOLU emissions and land-based carbon sequestration potential are then quantified to elucidate the wider climate and food security implications of how global biogenic CH_4 emissions targets are allocated. The methodology comprises six steps, and a core series of nine equations detailed subsequently (Figure 1):

1. the allocation of national CH_4 quotas according to different rules (equation 0)
2. the influence of different CH_4 quotas on production (equations 1, 2, 3, 4)
3. the influence of different levels of production on land use (equation 5)
4. the influence of different national CH_4 quotas on AFOLU CO_2 emissions (equation 6)
5. the influence of different national CH_4 quotas on AFOLU N_2O emissions (equations 7,8)
6. the influence of all the above on the aggregate GWP balance for national AFOLU sectors, calculated using GWP_{100} and an adapted GWP* approach (Rogelj and Schleussner, 2019) (equation 9)

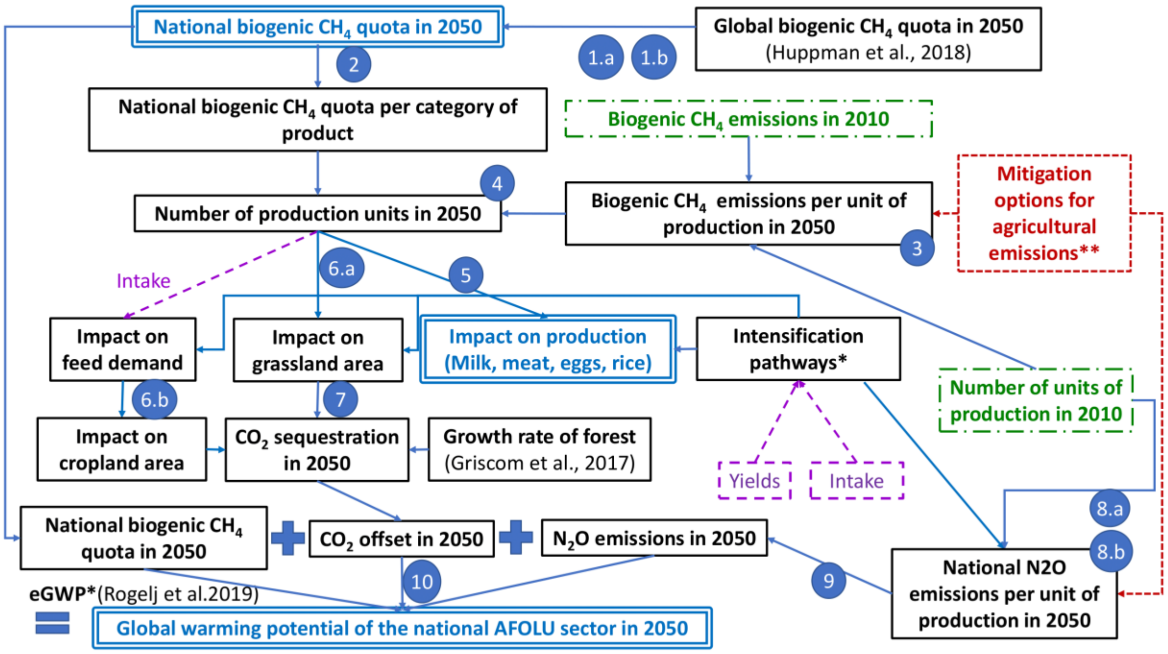


Figure 1: Overview of the methodology used in this study. Data used to compute purple (dashed box) elements are taken from the GLEAM-i data base (FAO, 2018). Data used to compute green elements (long-short dashed box) are taken from FAOSTAT (FAOSTAT, 2015). Data used to compute red elements are taken from national abatement cost curves presented in Eory et al. (2017) (short dashed box). Numbers in the schematic represent the equations presented in the following method. Blue boxes (double line boxes) represent the major outputs from this study.

The methodology is fully elaborated for the case of milk production in Ireland in S1. High-level country specific activity data (FAOSTAT) do not always represent best available data at national level, but do provide comparable data for cross-country comparison. The five most important assumptions behind the methodology are explored with sensitivity analyses and discussion.

2.2. National biogenic CH_4 quotas

Ninety global biogenic CH_4 emission targets were defined using a top-down approach to achieve the objective of climate stabilisation at the global scale (Huppmann et al., 2019), based on all scenarios that reach the 1.5-degree climate target outlined in the IPCC special report on 1.5 degrees (IPCC, 2019). Four different allocation rules are used to calculate national biogenic CH_4 quotas among the four case study countries, taking 2010 as a base year for which all necessary data are available across the four study countries. Calculations and underlying data are elaborated in S1. Two of the rules illustrate important aspects of equity, as previously applied for national allocation of global GHG emissions targets (Gignac and Matthews, 2015; Richards et al., 2018). A reduction in emissions proportional to Gross Domestic Product (GDP) has been chosen to define the *ability* of states to reduce biogenic CH_4 emissions. This is calculated by allocating the absolute reduction in global annual emissions necessary by 2050 according to the share of global GDP represented by each country (Table S1.10). A constant per capita allocation was chosen to define an *equal* allocation among all people on the planet.

The other two rules for allocating biogenic CH_4 quotas represent a simple '*grand-parenting'* approach and a *food security* approach. The grand-parenting approach reflects the simple adoption of global percentage reductions in biogenic CH_4 at the national scale, irrespective of the pre-existing level of emissions for each country. This approach may be politically expedient for high-emitting countries, and aligns with possible application of the GWP* method to derive national GHG emission targets. Finally, a large share of biogenic CH_4 emission arises from food production, in particular livestock production of high-quality protein. Acknowledging the contribution of some higher-emitting countries to world *food security,* a biogenic CH_4 emission quota was derived in proportion to national animal-protein production in 2010. Based on the rules listed above, we deduce national biogenic CH_4 quotas in 2050 ($CH_{4\,2050}^{i}$):

- If the rule (R) is based on an allocation of global biogenic CH_4 emissions as a population-based or protein-based allocation:

$$CH_{4\,2050}^{i} = \mathrm{R} \times \alpha_E^{world} \times CH_4^{world}{}_{2010} \tag{1.a}$$

With $\mathrm{R} = \frac{Pop_i^{2010}}{Pop_w^{2010}}$ or $\mathrm{R} = \frac{Prot_i^{2010}}{Prot_w^{2010}}$, Pop_i^{2010} is the population in 2010 of the country i, Pop_w^{2010} is the global population in 2010, $Prot_i^{2010}$ is the animal-protein production of the country i, $Prot_{world}^{2010}$ is the global animal-protein production, α_E^{world} is the reduction (between 0 and 1) of global biogenic CH_4 emission in 2050 compared to 2010 compatible with 1.5 degrees scenario (See appendix for a presentation of this factor) and $CH_4^{world}{}_{2010}$ is the global biogenic CH_4 emissions in 2010.

- If the rule (R) is based on a reduction in emissions relative to 2010 emissions such as a reduction in emissions that is GDP-based or biogenic CH_4 debt-based:

$$CH_{4\,2050}^{i} = \mathrm{R} \times CH_4^{world}{}_{2010} \times \left(\alpha_E^{world} - 1\right) + CH_{4\,2010}^{i} \tag{1.b}$$

With $R = \frac{GDP_i^{2010}}{GDP_w^{2010}}$ or $R = \frac{Debt_i^{2010}}{Debt_w^{2010}}$, GDP_i^{2010} is the GDP in 2010 of the country i, GDP $_w^{2010}$ is the global GDP in 2010, $Debt_i^{2010}$ is the biogenic CH_4 debt of the country i and $Debt_w^{2010}$ is the global biogenic CH_4 debt in 2010.

2.3. Influence of CH_4 quotas on agricultural production

To calculate the impact of the different national biogenic CH_4 quotas on agricultural production and the GWP balance of national AFOLU sectors, a biophysical approach was adopted to represent linear relationships between the different elements of agricultural production. This approach does not provide spatial resolution on land use changes, and neither does it explore changing profiles of the national biogenic CH_4 quota among the different types of food production (rice, milk, meat and eggs), the cost of these changes, nor their economic feasibility. On the other hand, this method has the advantage of relative simplicity, reproducibility to any country and transparency, providing a new insight into the link between equity rules for biogenic CH_4 allocation and AFOLU-related policy objectives. Transparency is a crucial element for coordination and climate negotiations within the UNFCCC (Rogelj and Schleussner, 2019). Local sensitivity analyses were conducted for major assumptions (detailed later).

Assumption 1: The allocation of the national biogenic CH_4 emission allowance between the different production systems is made in proportion to their shares of 2010 emissions.

Step 1 is allocation of the national biogenic CH_4 quota ($CH_{4\,2050}^{i}$) in country *i,* to the different production systems *j,* responsible for biogenic CH_4 emissions (production of milk, pork, beef, poultry meat, eggs and rice). Each production system maintains an equal share of biogenic CH_4 emissions in 2050 as in 2010:

$$CH_4^{i,j}{}_{2050} = \frac{CH_4^{i,j}{}_{2010}}{CH_{4\,2010}^{i}} \times CH_{4\,2050}^{i} \tag{2}$$

The different CH_4-intensive production systems and associated CH_4 emissions are presented in Table S2.1 for Brazil, France, India and Ireland.

Assumption 2: The production of each good *j* (milk, ruminant meat, monogastric meat, eggs and rice) strongly depends on the emission intensity which is computed in 2050.

Step 2 is the calculation of future CH_4 and N_2O intensities of production, assuming full implementation of national marginal abatement cost curves ('2050 MACC' scenario), in combination with animal productivity gains under sustainable intensification ('2050 SI' scenario). Table 1 displays annual production and emissions per 'production unit' (PU), where ($PU_{2010}^{i',j}$) is defined in this study as the biophysical entity producing product *j* in 2010 in the country *i.* Milk, meat, eggs and rice are produced, respectively, by the following UP: one milking cow, one slaughtered cattle, sheep, swine or poultry animal, one laying poultry animal and one hectare of harvested rice (details in Table S2.2).

Mitigation in the MACC scenario is achieved through, *inter alia*, use of nitrogen-based products (MUP, etc) to consume volatile fatty acids and reduce enteric CH_4, increasing the consumption of concentrates and the use of ionophores for cattle, and improving water management for rice cultivation in India (Sapkota et al., 2019); the use of concentrates, additives, livestock breeding and improved water management for rice cultivation in Brazil (Moraes et al., 2012); increasing liveweight gain, beef maternal traits, dairy breeding, animal health, sexed semen and extended grazing in Ireland

(Lanigan and Donnellan, 2018); the use of fatty acids, additives and improved water management in rice cultivation in France (Pellerin et al., 2017). Production and emission intensities for baseline production efficiency and MACC production efficiency per PU associated with each measure are summarised in Table 1, whilst detailed breakdowns are provided in S2.3. CH_4 and N_2O emission intensities per PU remain relatively stable between 2010 and 2050, with the exception of N_2O emissions from mineral fertilisation, CH_4 emissions from rice and CH_4 emissions from enteric fermentation in India. However, PU productivity increases in most cases, so that the CH_4 and N_2O intensities per unit of final product (e.g. kg milk) decline significantly – e.g. by up to 57% in the case of enteric CH_4 for milk production in India.

There is greater potential for yield increases in developing and transition countries with large yield gaps than industrialised countries *(Pradhan et al., 2015)*. To represent the potential effects of differential animal yield improvement across the four example countries, ’2050 SI’ scenarios were derived from intensification curves based on national herd productivity data from GLEAM *(FAO, 2018)*. Curves represented animal-level production versus feed intake across dairy and beef cattle, sheep, poultry and pigs, separately for tropical and temperate countries (details in Table S2.1). Rice EI is presented in Table 1b, whilst effects of a universal 25% increase in per-hectare yields are explored using sensitivity analyses (Table 3).

Table 1: Production and emission intensities (EI) in 2010 computed based on FAOSTAT data (scenario 'Base'), and in 2050 based on mitigation potentials described in relevant national marginal abatement cost curves (scenario '2050 MACC'), also in combination with animal productivity increases derived from intensification curves (see S2.1) representing sustainable intensification (scenario '2050 SI'). Mitigation potentials are listed in Table S9 in supplementary information.

a. Animal emission intensities

		Production (t/head)			**Enteric CH4 (kg/hd)**			**Manure storage CH4 (kg/hd)**			**Manure storage N2O (kg/hd)**		
Country	**Type of product**	**Base**	**2050 MACC**	**2050 SI**	**Base**	**2050 MACC**	**2050 SI**	**Base**	**2050 MACC**	**2050 SI**	**Base**	**2050 MACC**	**2050 SI**
Brazil	**Cattle. dairy-Beef and Buffalo Meat**	0.23	0.23	0.28	72.00	69.65	56.90	1.00	1.00	1.00	1.81	1.81	1.81
	Cattle. dairy-Milk. Total	1.13	1.13	1.68	72.00	69.65	56.90	1.00	1.00	1.00	1.81	1.81	1.81
	Cattle. non-dairy-Beef and Buffalo Meat	0.23	0.23	0.29	56.00	53.65	74.53	1.00	1.00	1.40	1.52	1.52	2.13
	Chickens. layers-Eggs Primary	0.007	0.007	0.011	NA	NA	NA	0.020	0.020	0.020	0.018	0.018	0.018
	Poultry Birds-Meat. Poultry	0.002	0.002	0.010	NA	NA	NA	0.020	0.020	0.045	0.015	0.015	0.032
	Sheep and Goats-Sheep and Goat Meat	0.015	0.015	0.015	5.000	5.000	5.000	0.157	0.157	0.157	0.292	0.292	0.292
	Swine-Meat. pig	0.09	0.09	0.12	NA	NA	NA	1.00	1.00	1.63	0.59	0.59	905.82
France	**Cattle. dairy-Beef and Buffalo Meat**	0.30	0.30	0.33	117.00	95.50	97.17	22.10	22.09	26.47	3.05	2.65	6.67
	Cattle. dairy-Milk. Total	4.02	4.02	7.42	117.00	95.50	97.17	22.10	22.09	26.47	3.05	2.65	3.18
	Cattle. non-dairy-Beef and Buffalo Meat	0.30	0.30	0.33	57.00	41.50	46.91	6.55	6.55	8.72	1.60	1.41	1.88
	Chickens. layers-Eggs Primary	0.017	0.017	0.017	NA	NA	NA	0.182	0.182	0.182	0.019	0.017	0.017
	Poultry Birds-Meat. Poultry	0.002	0.002	0.010	NA	NA	NA	0.058	0.058	0.097	0.018	0.016	0.026
	Sheep and Goats-Sheep and Goat Meat	0.017	0.017	0.017	7.542	7.542	7.542	0.181	0.180	0.180	0.364	0.305	0.305
	Swine-Meat. pig	0.09	0.09	0.09	NA	NA	NA	6.36	6.35	6.36	0.27	0.23	0.23
India	**Cattle. dairy-Beef and Buffalo Meat**	0.12	0.12	0.32	58.00	34.97	34.41	5.00	4.70	4.70	1.13	1.07	2.19
	Cattle. dairy-Milk. Total	1.02	1.02	1.68	58.00	34.97	34.41	5.00	4.70	4.70	1.13	1.07	1.07
	Cattle. non-dairy-Beef and Buffalo Meat	0.12	0.12	0.42	27.00	10.11	29.80	2.00	1.64	4.97	0.35	0.29	0.86
	Chickens. layers-Eggs Primary	0.011	0.011	0.011	NA	NA	NA	0.020	0.020	0.020	0.018	0.018	0.018
	Poultry Birds-Meat. Poultry	0.001	0.001	0.010	NA	NA	NA	0.020	0.020	0.076	0.015	0.015	0.058

	Sheep and Goats-Sheep and Goat Meat	0.011	0.011	0.011	5.000	4.380	4.380	0.172	0.172	0.172	0.323	0.323	0.323
	Swine-Meat. pig	0.04	0.04	0.07	NA	NA	NA	5.17	5.17	13.89	0.14	0.01	57.09
Ireland	**Cattle. dairy-Beef and Buffalo Meat**	0.33	0.36	0.37	117.00	93.29	93.57	21.00	20.34	20.82	3.05	2.96	8.79
	Cattle. dairy-Milk. Total	4.97	5.72	8.53	117.00	93.29	93.57	21.00	20.34	20.82	3.05	2.96	3.03
	Cattle. non-dairy-Beef and Buffalo Meat	0.33	0.36	0.37	57.00	55.35	57.69	6.00	5.89	6.52	1.60	1.57	1.74
	Chickens. layers-Eggs Primary	0.012	0.012	0.012	NA	NA	NA	0.182	0.180	0.180	0.019	0.019	0.019
	Poultry Birds-Meat. Poultry	0.001	0.001	0.010	NA	NA	NA	0.067	0.065	0.127	0.018	0.018	0.034
	Sheep and Goats-Sheep and Goat Meat	0.020	0.020	0.020	7.993	7.993	7.993	0.190	0.184	0.184	0.356	0.344	0.344
	Swine-Meat. pig	0.08	0.08	0.08	NA	NA	NA	6.30	6.24	6.24	0.27	0.16	0.16

[1] EI of dairy cattle for meat production are changing without yield change because the EI of dairy cattle are mainly driven by milk production

b. Crop emission intensities

	Rice production (t/ha)			**CH_4 from rice (kgCH_4/ha)**			**Fertilisation cropland (kgN_2O/kgN)**		
Country	**Base**	**2050 MACC**	**2050 SI**	**Base**	**2050 MACC**	**2050 SI**	**Base**	**2050 MACC**	**2050 SI**
Brazil	4.127	4.127	4.127	64.96	32.48	32.48	20.82	20.82	20.82
France	5.043	5.043	5.043	504	252	252	20.90	14.79	14.79
India	3.359	3.359	3.359	105.56	24.56	24.56	20.90	10.26	10.26
Ireland	-	-	-	-	-	-	20.90	10.03	10.03

Based on these mitigation potentials ($\Delta CH_4^{\imath',j}$), the reference CH$_4$ intensity of the product *j* in the country *i'* ($CH_4^{i',j}{}_{2010}$), and the CH$_4$ intensity per production unit for good *j* in 2050 in the country *i* ($ch_4^{i,j}{}_{2050}$), are calculated:

$$ch_4^{i,j}{}_{2050} = \frac{CH_4^{i',j}{}_{2010} - \Delta CH_4^{i',j}}{PU_{2010}^{i',j}} \tag{3}$$

The number of production units ($PU_{2050}^{i,j}$) compatible with the biogenic CH$_4$ emission quota ($CH_4^{i,j}{}_{2050}$) and the emission intensity ($CH_4^{i,j}{}_{2050}$) for the good *j* is calculated thus:

$$PU_{2050}^{i,j} = \frac{CH_4^{i,j}{}_{2050}}{ch_4^{i,j}{}_{2050}} \tag{4}$$

The production of the good *j* in the country *i* ($P_{2050}^{i,j}$) is deduced according to relevant national yields:

$$P_{2050}^{i,j} = PU_{2050}^{i,j} \quad \times Y_{2050}^{i,j} \tag{5}$$

2.4. Influence of CH$_4$ quotas on land-use

Assumption 3: The amount of land needed to produce feed, grass and rice is calculated from the current national yields.

Step 3 is the calculation of areas of land needed to produce rice, or grass and feed crops for livestock production under different biogenic CH$_4$ quotas. Five land uses are defined: cropland inside the national border (1) or outside the national border (2) used for feed, grassland (3), cropland used for rice production (4) and for purposes other than feed and rice (e.g. food or bioenergy) (5). For each animal type (cattle, sheep, poultry and swine) and each country, concentrate and grass use ($U_k^{i',j}{}_{2010}$) are calculated based on total intake (computed from equation 10.18b of IPCC methodology (IPCC, 2006) for dairy cattle and from the GLEAM database (FAO, 2018) for other animals), share of each feed type in the ration from the GLEAM database (FAO, 2018) and average national grass yields (Table S2.4). Concentrate areas are calculated from quantities of major crops required based on feed requirements per PU, multiplied by the share of major crops (maize, soybean, barley...) in the ration (see 'Feed' in the food balance sheets of FAOSTAT), and their share domestically produced and average national yields of each crop taken from FAOSTAT (2015) – elaborated for Ireland in Tables S1.3, S1.4 & S1.7. Only the national area of the production factor *k* in the country *i* is included by using the share of the demand for the production factor k in 2010 which is domestically produced ($T_{2010}^{i,k}$) (elaborated in Table S1.1). The national area in 2050 of the production factor *k* needed to produce the good *j* in country *i* ($A_{2050}^{i,j,k}$) is deduced:

$$A_{2050}^{i,j,k} = \frac{PU_{2050}^{i,j} \quad \times U_k^{i,j}{}_{2010} \times T_{2010}^{i,k}}{\overline{Y_{2050}^{\imath',k}}} \tag{6.a}$$

Areas required abroad for imported feed production are computed based on the average global yield for the feed mix computed in 2010 and demand for imported feed. Grass demand is entirely satisfied by national production. The share of imported feed and the average global yield for feed used in the country *i* ($Y^{world,k}_{2050}$) are held constant between 2010 and 2050:

$$A^{i,j,k}_{2050} = \frac{PU^{i,j}_{2050} \quad \times U^{i,j}_{k\ \ 2010} \times (1 - T^{i,k}_{2010})}{\overline{Y^{world,k}_{2050}}} \qquad (6.b)$$

The influence of a blanket 25% increase in yields is explored using sensitivity analyses. Areas dedicated to purposes other than feed (abbreviated to 'food area'), are set constant at their 2010 level (FAOSTAT, 2015). The area of rice cultivation associated with the production quantity linked to the biogenic CH_4 quota is calculated from mean national rice yields (FAOSTAT, 2015).

2.5. Influence of biogenic CH_4 quotas on CO_2 emissions

Assumption 4: Average sequestration rates of 10.3 and 17.8 Mg CO_{2e} ha^{-1} yr^{-1} are realised for temperate and tropical afforestation, respectively, and an average emission of 25.1 Mg CO_{2e} ha^{-1} yr^{-1} for imported deforestation.

Step 4 is the calculation of CO_2 fluxes in national AFOLU sectors in 2050 related to areas required for the production of different 'CH_4-intensive' goods, and areas deforested or spared for afforestation/reforestation, respectively:

$$CO^{i}_{2\,2050} = \sum_{j\epsilon\{prducts\}} \sum_{k\in\{factors\}} \left((A^{i,j,k}_{2050} - A^{i,j,k}_{2010}) \times EF^{w}_{2050} \right) \qquad (7)$$

In the case of afforestation ($A^{i,j,k}_{2050} < A^{i,j,k}_{2010}$) , the mean sequestration factor in 2050 (EF^{w}_{2050}) and the average forest growth rates for temperate and tropical climates are used, considering the share in each of these biomes of planted and natural forests (Griscom et al., 2017) (Table S2.5). Emission factors of deforestation occurring inside the national boundary are computed based on national cumulative emissions from forest to agricultural land conversion and national cumulative areas of deforestation between 1961 and 2010 (FAOSTAT, 2015), divided by a transition period of 20 years as described in the IPCC methodology (Table S2.6). Imported deforestation was assumed to occur at the global agricultural frontier, which was defined as native grassland in Argentina and forest in Brazil, Indonesia, Thailand and Angola according to the five countries showing the greatest expansion in agricultural area over five years (FAOSTAT, 2015). An annualised emission factor of 25.7 tCO_2 ha^{-1} yr^{-1} is deduced (See Table S2.7).

2.6. Influence of CH_4 quotas on N_2O emissions

Step 5 is the computation of N_2O emissions associated with manure management and fertilisation. Emission factors are calculated per PU for manure for each project in each country ($EF^{i,j,manure}_{2050}$), accounting for projected manure management mitigation ($\Delta N_2O^{i',j,manure}$) taken from marginal abatement cost curves (Eory et al., 2018) (Table 1 and Table S2.3):

$$EF^{i,j,manure}_{2050} = \frac{N_2O^{i\ \ ,j,manure}_{\qquad 2010} - \Delta N_2O^{i,j,manure}}{PU^{i,j}_{2010}} \qquad (8.a)$$

Similarly, N_2O emission factors for N fertilisation in 2050 ($EF_{2050}^{i,k,j,fert}$) are computed based on the fertilization mitigation in the country *i* provided by the the marginal abatement cost curve:

$$EF_{2050}^{i,j,k,fert} = \frac{{N_2O^{i,j,k,fert}}_{2010} - \Delta N_2O^{i,j,k,fert}}{F_{2010}^{i,j,k,fert}} \tag{8.b}$$

$F_{2010}^{i,j,k,fert}$ is the amount of N fertilisation used to produce the factor of production *k* (grass, feed, rice area and food area) for the production of the good *j* in the country *i* in 2010, estimated through allocation of national fertiliser application totals (UN FAO Stat, 2020) between cropland and grassland, assuming average cropland fertiliser rates are three times higher than average grassland fertilisation rates (including rough grazing areas with no application). N fertilisation in 2050 is based on the fertiliser rate of the production factor *k* multiplied by the area used to produce this production factor *k* (Table S1.6), where the fertilisation of *k (grass or feed)* in 2050 is proportional to the yield in each land use based on the fertiliser rate in 2010 ($F_{2010}^{i,j,k,fert}$). Overall N_2O emissions associated with the production of the good j in the country I are deduced thus:

$${N_2O^{i,j}}_{2050} = \sum_{s\in\{manure\}} \left(PU_{2050}^{i,j} \times EF_{2050}^{i\prime,j,s}\right) + \sum_{k\in\{factors\}} \left(PF_{2050}^{i,j,k,fert} \times EF_{2050}^{i,j,k,fert}\right) \tag{9}$$

2.7. Global warming balance of the AFOLU sector

Step 6 is the calculation of aggregate GWP balances for national AFOLU sectors though application of: (i) time-averaged GWP_{100} factors of 1, 25 and 296 for CO_2, CH_4 and N_2O, respectively, as per national inventory accounting (Secretariat of the United Nations Framework Convention on Climate Change, 2004), and; (ii) a modified version of GWP* (Rogelj and Schleussner, 2019) to represent the dynamics of short-lived CH_4 emissions and long-lived N_2O and CO_2 emissions through time. GWP is calculated separately for each global context and each national biogenic CH_4 allocation rule, considering the potential emission reductions by 2050. The eGWP* method (Rogelj and Schleussner, 2019) avoids the emission 'grandparenting' assumption implicated in calculation of emission change from a reference baseline in the GWP* method (if the reference level is high, then CH_4 reduction towards the quota will confer a large GWP_{100} 'credit', rewarding countries with high baseline emissions). Thus, reference level CH_4 emissions in each country are re-calculated by allocating global biogenic CH_4 emissions in 2010 according to the same allocation rules used to calculate respective quotas for 2050 (Table S2.8). Note that application of eGWP* in the 'grand-parenting' quota scenario is equivalent to application of the non-modified GWP* method to 2010 baseline emissions. Re-calculated reference CH_4 emissions are summarised in Table S2.9. The eGWP* metric takes the following form (Rogelj and Schleussner, 2019):

$$eGWP^{*}\left({CH_4^i}_{2050}\right) = \frac{{CH_4^i}_{2050} - {CH_4^i}_{ref}}{T} \times GWP_T \times (2050 - 2010)$$

Where ${CH_4^i}_{2050}$ which is the CH_4 target previously defined based on different allocation methods, ${CH_4^i}_{ref}$ is the national reference CH_4 level in 2010, GWP_T is the global warming potential for the period T. In this study, GWP_{100} for a period of $T = 100$ years is applied because it is the UNFCC's official GHG equivalent metric.

Finally, the AFOLU global warming potential of the country i ($GWP^i_{AFOLU_{2050}}$) is expressed as follows by summing the Global warming potential of each gas:

$$GWP^i_{AFOLU_{2050}} = eGWP^* \left(CH^i_{4_{2050}}\right) + GWP_{100} \times \left(N_2O^i{}_{2050}\right) + CO^i_{2_{2050}} \tag{10}$$

2.8. Scenario synthesis

The modelling approach generates data for 136 national scenarios, based on: (i) downscaling of global biogenic CH_4 budgets from all 1.5°C scenarios presented in Huppmann et al. (2018), according to the four separate allocation rules; (ii) the three different food production pathways. The full spread of results is presented and discussed, but in order to distil out pertinent associations, national-level results were divided into quartiles based on the AFOLU GWP balance determined by eGWP*. For each quartile of national scenarios, median values were extracted for key parameters relating to GWP balance and food security, along with metrics representing the prevalence of different food production pathways and allocation rules within that quartile. Food security metrics were expressed as person equivalents for energy and protein supply. Meat production was calculated through multiplication of animal carcass weight by species-specific dressing (bone-free meat) fractions, taken from the Global Livestock Environmental Assessment Model (FAO, 2018). Protein and energy (kcal) contents of all livestock and rice products were taken from (McCance and Widdowson, 2019). Total protein and energy production in each national scenario were then divided by recommended annual intakes (EFSA NDA Panel, 2012) to generate annual person equivalent protein and energy supplies, respectively.

2.9. Sensitivity analysis

Four major assumptions made during the core scenario development are likely to have an important influence on results. Firstly, it is assumed that each production system accounts for the same share of AFOLU emissions as it did in 2010 within each country, with the exception of India where expansion of rice output in 2050 is constrained by available area rather than by CH_4 quota. It is beyond the scope of this paper to analyse the plethora of food system transformations that could arise within countries, which would generate an overwhelming array of results. Instead, national food production CH_4 profiles are fixed in order to generate indicative estimates of future food production. Whilst this is not an accurate prediction of the future, it does provide clear evidence on the sustainability of current systems with implementation of mitigation measures. The application of variable levels of mitigation based on national MACC reports is sensitive to time frame (most MACC assumptions extend to 2030, rather than 2050) and degree of ambition represented in the MACC measures evaluated. Sensitivity analysis is therefore applied on the CH_4 intensity of each PU, by applying CH_4 intensities that are 25% lower than 2010 baseline levels (Table 1). Assumption 3 relates to average national grass and crop yields used for animal feed, which were conservatively held constant at 2010 levels. Sensitivity analysis is applied by considering a universal yield increase of 25% for 2050 yields. These yield changes are associated with a proportional change in synthetic nitrogen fertilisation and associated emissions. The fourth assumption relates to aggregated forest growth rates for temperate and tropical regions, detailed above. Forest growth rates are highly sensitive to the species of tree planted, environmental conditions and management factors. Sensitivity analysis varies forest growth rates ±25% of values in Table S2.5. To test the robustness of results to these assumptions, Kruskal Wallis tests were undertaken on production and AFOLU GWP balance results for each country and each allocation method, to test for a significant effect from each of the aforementioned sensitivity analyses (Table S2.10).

3. Results

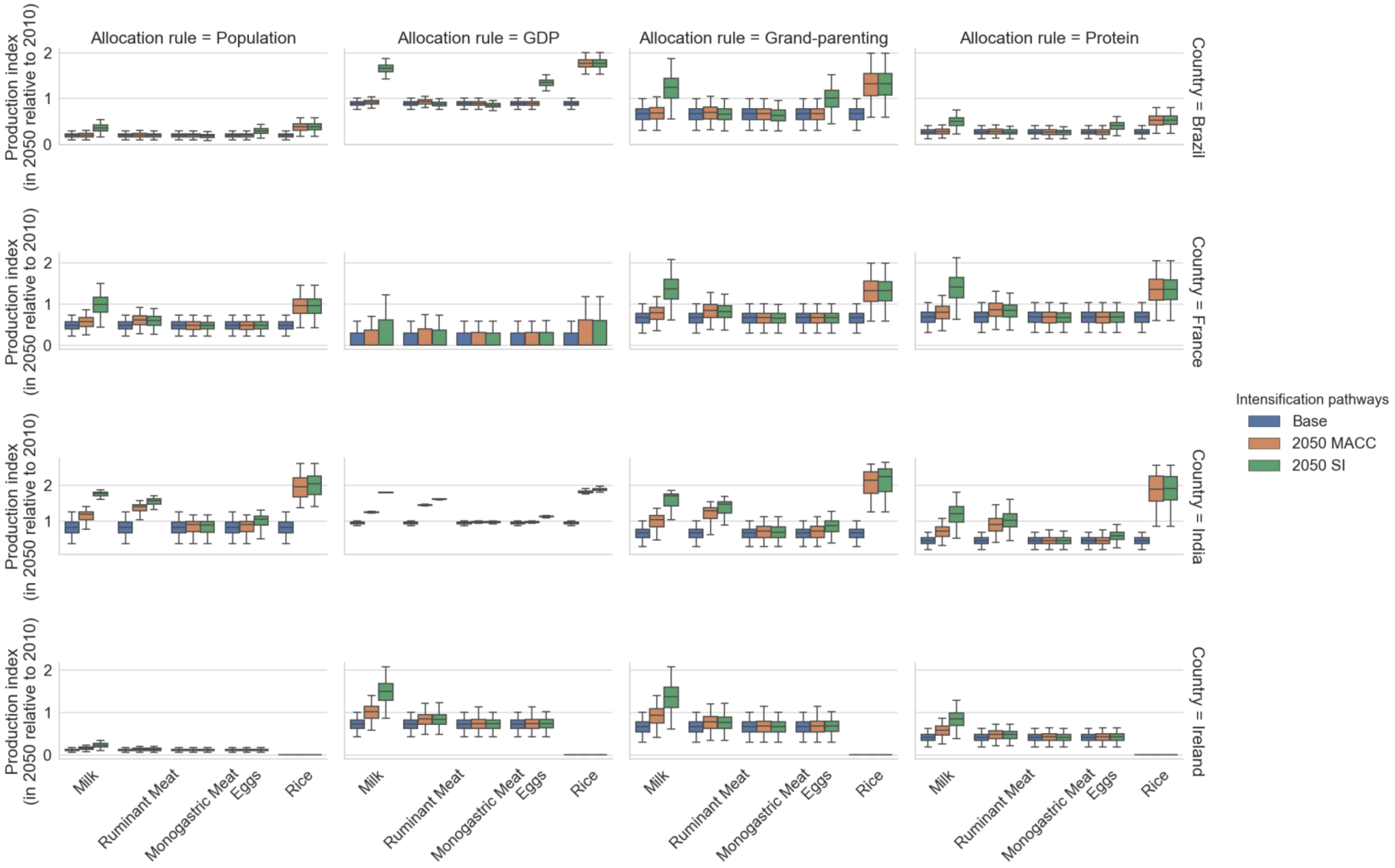
3.1. National biogenic CH_4 quotas and production

To comply with global emission scenarios compatible with climate stabilisation, national biogenic CH_4 emissions would need to be reduced by 11-81% for Brazil, 28-80 % for France, 26-59% for India and 30-79% for Ireland, depending on the allocation rule (Table 2). The choice of allocation rule has a greater influence on national CH_4 quota than the choice of global scenario compatible with 1.5 degree warming, with more than a factor of six in the difference in quota depending on allocation method for Ireland (Table 2). Based on inverse-GDP effort, the smallest *relative* reduction on 2010 emissions (11%) is seen for Brazil, reflecting high baseline emissions per US$ GDP (Table S1.10), whilst the largest required reduction in both absolute and relative terms (80%) is seen for France. In fact, because GDP allocation represents national shares of global emission reduction (rather than remaining budgets), France's CH_4 quota has a zero lower bound for many scenarios with GDP allocation (Fig. 2a) Population-based allocations require reductions of 81% and 79% on 2010 biogenic CH_4 emissions for Brazil and Ireland, respectively, reflecting high emissions from production for export of beef and milk from those countries. However, protein-based allocation requires the smallest reduction (31%) for France, compared to Brazil or Ireland, owing to a high share of protein production from pigs in France and poultry, that are less CH_4-intensive than cattle, compared with the other countries. Finally, of the four studied countries, only India could not expand current production to fill all its 2050 CH_4 quota, owing to a high assumed CH_4 mitigation potential for rice and constraints on the area of land into which future rice production could expand. This resulted in non-used quotas of 0.9 to 4.4 kt CH_4 in 2050 (Table 2).

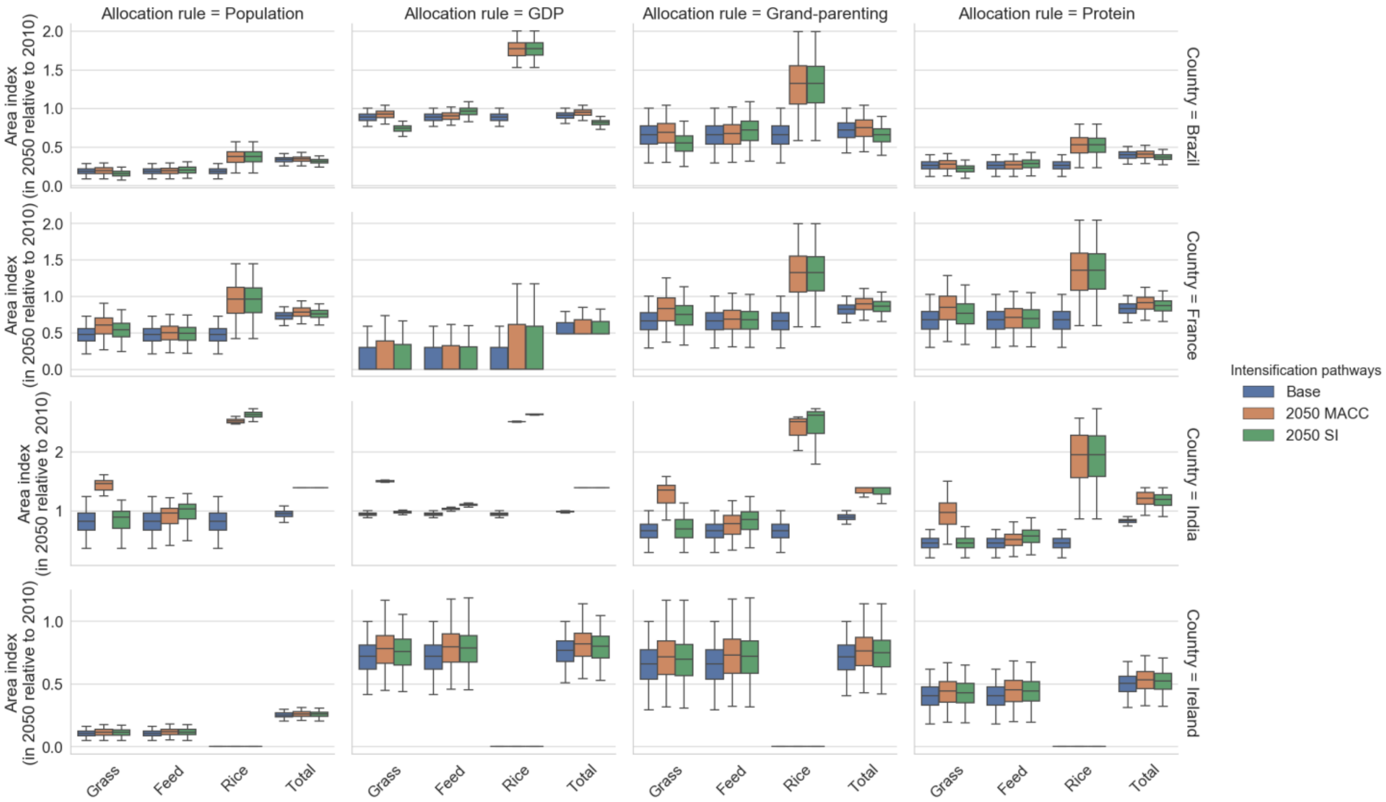
Table 2: National biogenic methane targets for 2050 across Brazil, France, India and Ireland based on four different allocation approaches to share the global biogenic methane budget compatible with climate stabilisation (right), with percentage reductions from national 2010 emissions shown in brackets. Also shown are reference 2010 methane emissions.

	Reference emissions in 2010 (ktCH4)	**Methane 2050 (ktCH4)**				**Non-used biogenic CH4 quota 2050 (ktCH4)**			
		GDP	**Grand-parenting**	**Population**	**Protein**	**GDP**	**Grand-parenting**	**Population**	**Protein**
Brazil	13.5	11.9 (-11%)	9.1 (-33%)	2.6 (-81%)	3.6 (-73%)	NA			
France	1.8	0.4 (-80%)	1.2 (-33%)	0.9 (-28%)	1.2 (-31%)	NA			
India	19.4	13.9 (-28%)	10.3 (-47%)	12.3 (-26%)	8.0 (-59%)	4.4	2.7	3.9	0.9
Ireland	0.6	0.4 (-30%)	0.4 (-35%)	0.06 (-79%)	0.2 (-58%)	NA			

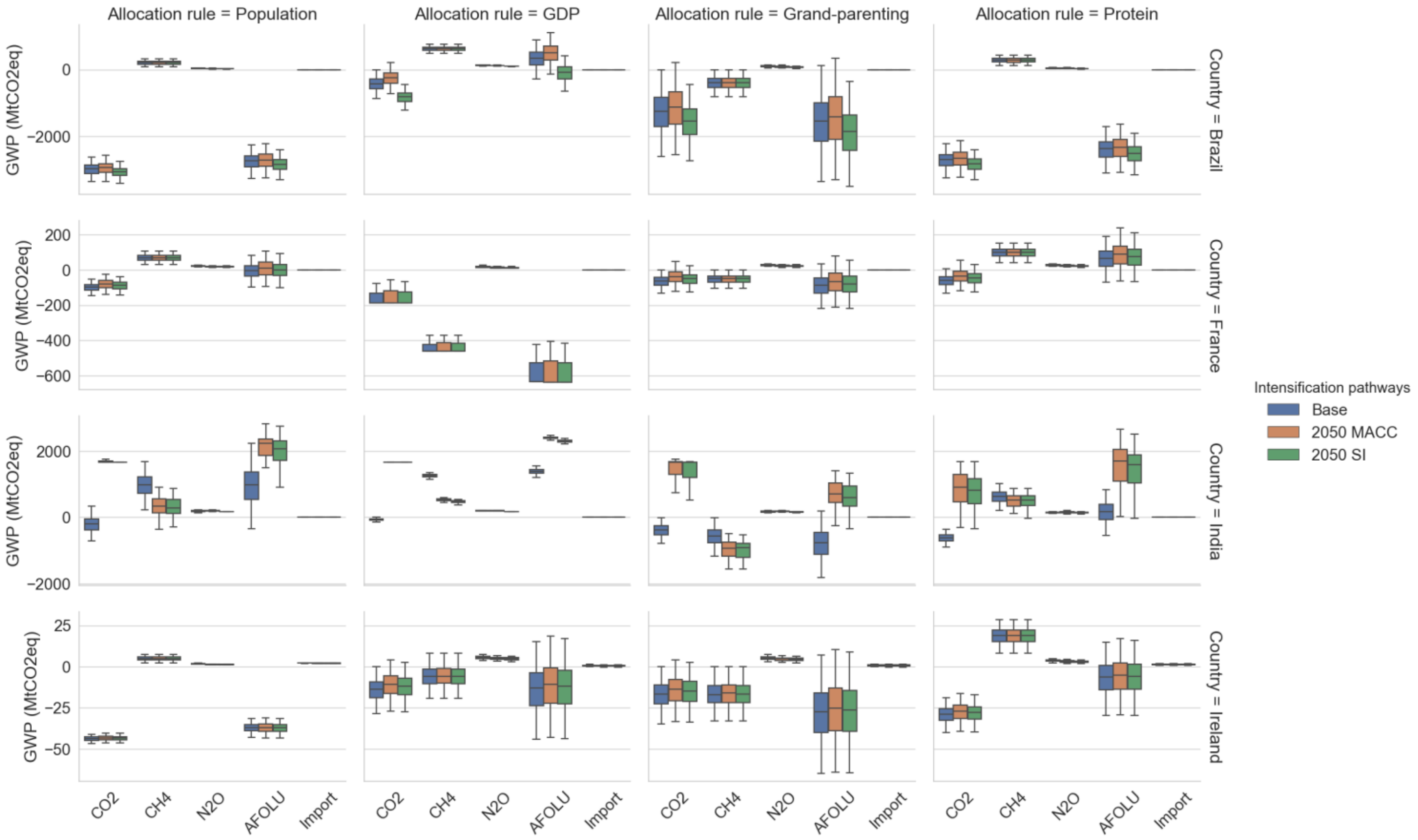
At baseline emission intensities, median animal production decreases in all countries under all allocation rules (Fig. 2a and Table S2.10). With full MACC implementation, median animal production remains below 2010 levels in all countries for all allocation rules except for milk and ruminant meat production in India for GDP-, grand-parenting and population-based allocation. Rice production increases in Brazil, France and India. With full SI, milk production and mono-gastric meat production in 2050 also increases relative to 2010 under GDP and grand-parenting rules for Brazil, grand-parenting and protein rules for France, and under GDP and grand-parenting allocation rules for Ireland (Fig. 2a). Rice production increases dramatically, especially in India, more than doubling for grand-parenting allocation, owing to high mitigation potential (Table 1b).



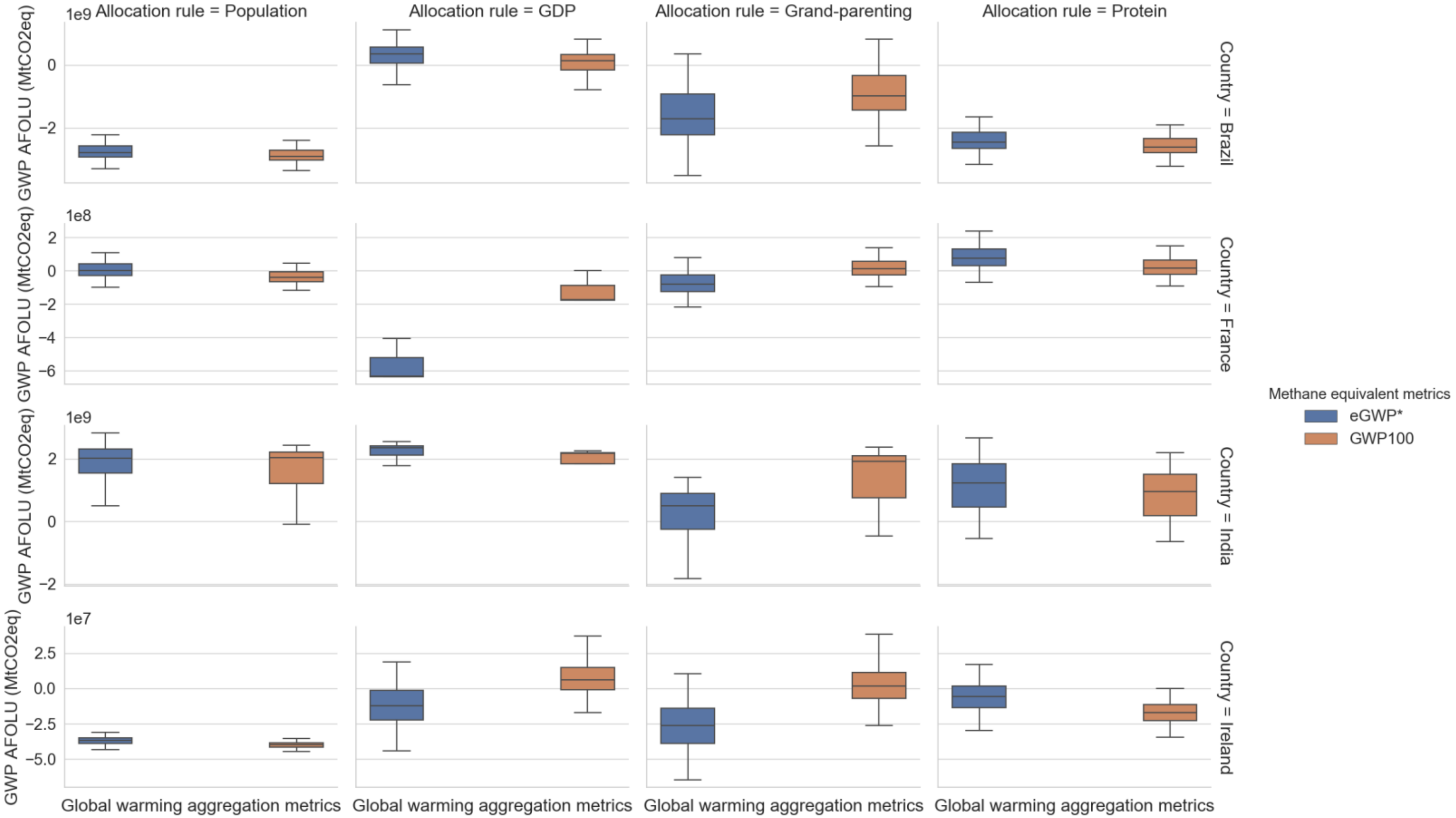
(a) Production changes in 2050 relative to 2010 for different methane allocations, methane targets and products



(b) Area change in 2050 relative to 2010 for different methane allocations, methane targets and productions



(c) Annual fluxes of specific GHG emissions in 2050, expressed as Mt CO_2 eq. (GWP_{100} aggregation)



(d) Agriculture, forestry and other land use (AFOLU) global warming potential balance 2050, based on either eGWP* aggregation (left) or GWP$_{100}$ aggregation (right)

Figure 2: Average (and standard error) production levels of milk, meat, eggs and rice in Brazil, France, India and Ireland for different allocation rule of biogenic CH$_4$ (a), areas required for those levels of production (b), fluxes of individual greenhouse gases for the agriculture, forestry and other land use (AFOLU) sector considering marginal loss or expansion of forest cover (c), and integrated global warming potential (GWP) balance of the AFOLU sector

calculated using different approaches (eGWP and GWP*$_{100}$*). Note that eGWP* with grand-parenting is equivalent to non-modified GWP* using a 2010 baseline.*

3.2. AFOLU emission balance

The AFOLU GHG emission balance reflects the interaction of CH_4-quota-production quantities, GHG emission intensities of production and areas deforested or afforested depending on areas required for production (Fig. 2b). Nitrous oxide (N_2O) emissions decline along with biogenic CH_4 (Fig. S2.1 and Fig. 2c) largely reflecting reduced livestock production (and thus emissions from direct N excretion, manure management and forage and feed fertilisation). The exception is India, where N_2O emissions increase (Fig. S2.1) in line with increased cattle (milk & meat) and rice production within quota and area constraints (Fig. 2a). Total agricultural area utilised in 2050 reduces by 12-158, 2.8-12.5 and 0.9-3.9 Mha for Brazil, France and Ireland, respectively, compared with 2010 (Table S2.11). Total agricultural area required to produce meat, milk and rice up to allowable CH_4 quotas in India in 2050 ranges from 31 Mha less to 70 Mha more than in 2010.

Land use, land use change & forestry (LULUCF) CO_2 fluxes have the strongest influence on overall AFOLU GHG emissions, closely followed by CH_4 (Fig. 2c). Thus, perhaps counter-intuitively, MACC and SI scenarios often exhibit higher net GHG emissions (or lower negative emissions) because lower CH_4-intensties translate to higher levels of 'allowable' production of animal products and rice. Net CO_2 fluxes from AFOLU sectors are negative for Brazil, France and Ireland for median SSP scenario points across all CH_4 allocation methods (Fig. 2c), reflecting land sparing associated with reduced production outputs and/or improved land efficiencies (Fig. 2a-b). Increased cattle and rice production in India result in median annualised national CO_2 emissions from deforestation for most scenario and allocation rule combinations, of up to 1658 Mt CO_2e by 2050 for the 2050 MACC scenario with GDP allocation (Fig. 2c and Table S2.12). Annual GHG emissions from India's AFOLU sector increase substantially across all allocation rules and scenarios in 2050 apart from the baseline production efficiency and grand-parenting combination (Fig. 2c), by up to 1820 Mt CO_2e using the GWP_{100} metric (Table S2.13). Brazil's AFOLU sector becomes a net sink of GHG emissions for all but the GDP-based allocation rule under eGWP* aggregation, generating net annual offsets of circa 2600 and 2900 Mt CO_2e under protein and population-based allocation (and baseline production efficiency), respectively (Fig. 2c and Table S2.13). Ireland's AFOLU sector acts as a net GHG sink under all allocation rules according to eGWP* (Fig. 2c), but under only population- and protein-based allocation using the GWP_{100} aggregation metric (Table S2.13). For France, AFOLU acts as a net sink under GDP- and population-based allocation using the GWP_{100} aggregation metric, and for GDP- and grand-parenting allocation using the eGWP* metric. (Fig. 2c and table S2.13). Imported emissions have a negligible influence on AFOLU balances in the four studied countries.

3.3. Influence of GWP metric

Both choice of allocation method and choice of GWP metric strongly influence calculated GWP balances for national AFOLU sectors (Fig. 2d). Under the standard GWP_{100} metric used for UN FCCC national GHG reporting, Brazil's AFOLU sector achieves a net GWP offset for three out of the four allocation methods, whilst France and Ireland's AFOLU sectors achieve net GWP offsets for two of the four allocation methods, and India's AFOLU sector always has a positive GWP_{100} balance. Applying the eGWP* aggregation metric flips the grand-parenting flux from positive to negative and the population flux from negative to positive for France's AFOLU sector (Fig. 2d and Table S2.13). The eGWP* metric also flips grand-parenting fluxes from positive to negative for India and Ireland, and the GDP flux from positive to negative for Ireland, so that Ireland's AFOLU sector ends up as a net GHG sink across all allocation methods (at baseline production efficiency) with eGWP* (Fig. 2d and Table S2.13).

3.4. Sensitivity analysis

Table 3 displays the results of sensitivity analyses around carbon sequestration rates in afforested areas, mitigation efficacy and feed yields. All sensitivity analyses resulted in significant differences in median values for all allocation methods, except for carbon sequestration variations under population and protein allocation methods in Brazil and population allocation in Ireland, and yield variation under GDP allocation in Brazil (results of Kruskal Wallis comparisons displayed in Table S2.14). Increasing carbon sequestration rates and yields significantly lowers the GWP balance of AFOLU sectors owing to higher efficacy and greater extent of afforestation, respectively. As seen for MACC scenarios, stronger mitigation increases the net GWP balance of national AFOLU sectors under stated modelling assumptions because lower CH_4-emission-intensities translate into higher production levels within quota constraints, and therefore less land available for afforestation offsetting.

Table 3: Median GWP_{100} values for national AFOLU for different allocation rules under base case results and under sensitivity analyses where important factors (carbon offset efficacy per hectare, emission intensity per production unit and grass/crop yield are varied by 25%). Green shading denotes better performance than base (default) results, red shaing worse performance.

		AFOLU balance (with GWP_{100})				
		Base	**Carbon +25%**	**Carbon -25%**	**Emission Intensity -25%**	**Yield +25%**
Brazil	**GDP**	-40	-187	107	408	-646
	Grand-parenting	-922	-1255	-589	-591	-1379
	Population	-2874	-3622	-2126	-2782	-3001
	Protein	-2565	-3247	-1883	-2437	-2744
France	**GDP**	-94	-127	-60	-90	-101
	Grand-parenting	34	26	42	46	5
	Population	-25	-44	-6	-17	-44
	Protein	40	33	47	52	10
India	**GDP**	1464	1459	1468	837	1462
	Grand-parenting	1032	982	1081	299	1025
	Population	1283	1256	1311	629	1277
	Protein	534	447	621	-123	530
Ireland	**GDP**	6	3	10	11	0
	Grand-parenting	2	-2	6	6	-4
	Population	-40	-51	-29	-39	-41
	Protein	-17	-24	-10	-14	-21

3.5. Synthesis

Dividing all national scenarios into quartiles reflective of their climate mitigation potential provides addition insight into associations between climate mitigation efficacy and food security within and across countries, in the context of eGWP* accounting for climate forcing (Table 4). CO_2 offset is strongly inversely associated with GWP quartile rankings – more negative GWP balances are associated with higher CO_2 offsets. Meanwhile, biogenic CH_4 quota is positively associated with rankings. These associations, in particular involving CH_4, break down somewhat for India, reflecting the dynamics of mainly land-constrained (rather than CH_4-constrained) food production in India. Notably, India's third quartile is associated with a large median CH_4 quota but more CO_2 offset than the second quartile, and a high share of 'Base' production efficiency – the lower production efficiency increases CH_4 emission per hectare utilised and means that land requirements for production could be constrained by CH_4 in some scenarios, as for the other countries. Across all countries, median CO_2 offsets vary more markedly than median CH_4 quotas, implying a dominant role of offsetting in determining GWP balances, but also showing that offsetting is typically inversely linked with CH_4 quotas via land requirements for 'allowable' food production.

Production of CH_4-intensive foods increases strongly with quartile ranking. National protein production is just over three (India) to six (Ireland) times higher in the fourth quartile than the first quartile. For most countries, median protein production exceeds national population requirements in the upper quartiles, with the notable exception of India where fourth quartile food production is just below the current population of 1.35 billion people. AFOLU climate neutrality for India lies somewhere between the first and second quartiles (between negative and positive median eGWP* values in Table 4). Only the first quartile is compatible with climate neutrality at the national level for India, supporting less than 30% of national protein requirements. Protein security for France lies between the third and fourth quartiles, neither of which comply with climate neutrality at the national level. Ireland and Brazil can achieve national protein security alongside climate neutrality.

Table 4: Median results for key metrics relevant to GHG mitigation and food security within quartiles of AFOLU global warming potential balance according to the eGWP method, across all scenarios – based on all 1.5°C scenarios from Huppmann et al. (2018) multiplied by all allocation rules and all food production pathways (base case, marginal abatement cost curve (MACC) mitigation and Sustainable Intensification). Food security metrics represent total calories and protein within rice and animal products produced within CH_4 quotas for each scenario, divided by per capita recommended daily intakes.*

Country	Quartile	**GHG mitigation**			**Food security**		**Food production pathway**			**Allocation rule**			
		AFOLU balance (eGWP*)	CO_2 offset	Methane emissions	Person fed in energy	Person fed in protein	Base	MACC Mitigation	Sustainable Intensification	GDP	Grand-parenting	Population	Protein
		$MtCO_2e$	$MtCO_2e$	Mt CH_4	Mio heads	Mio heads	% of scenarios within quartile			% of scenarios within quartile			
Brazil	First	-2917	3077	2.2	22.6	56.1	33	27	40	0	15	63	23
	Second	-2472	2776	3.6	34.3	85.5	31	36	32	0	15	35	51
	Third	-1679	1466	8.9	82.6	204.5	33	34	34	12	59	3	27
	Fourth	233	443	12	126.1	298.4	36	36	29	88	12	0	0
France	First	-631	184	0	0	0	34	34	31	96	4	0	0
	Second	-76.3	75.8	0.9	10.4	39.6	39	31	31	2	67	25	7
	Third	16.9	74.0	0.9	11.8	48.2	35	33	31	3	15	52	30
	Fourth	111	4.5	1.3	18.6	73.5	25	35	40	0	14	23	63
India	First	-316	549	9	361.9	383.6	80	9	11	0	57	7	36
	Second	761	-270	10.4	938	923.1	28	35	37	2	40	29	28
	Third	1444	4.5	17.7	709.7	778.8	41	28	31	48	3	24	25
	Fourth	2352	-1658	9.7	1253.7	1278.5	5	50	45	50	0	39	11
Ireland	First	-39.9	43.6	0.1	0.4	1.5	33	33	34	6	35	59	0
	Second	-31.5	30.5	0.2	1.2	4.4	35	32	33	20	30	41	9
	Third	-13.8	16.2	0.3	2	7.1	35	34	32	43	15	0	41
	Fourth	6.1	8.7	0.3	2.6	9.3	31	35	35	31	19	0	50

4. Discussion

4.1. Fairness of a national methane reduction targets

In light of recent criticism of representation of CH_4 warming through time by the GWP_{100} aggregation metric (Allen et al., 2018; Cain et al., 2019), as used to report national GHG emissions (UNFCCC, 2014) and to define national 'net zero' GHG targets (UK CCC, 2019), this study explored the implications of different approaches to determine separate national targets for biogenic CH_4 – with a particular focus on national food production and 'climate neutrality' objectives for 2050 and beyond. Emitting GHGs to the atmosphere is not a basic need per se. Discussion of fairness in GHG mitigation burden-sharing therefore invokes the question of 'allowances' to nations and to individuals (Arnold, 2011; Caney, 2009). As described in Pottier et al. (2017), *"Posner and Sunstein (2008) argue that distributive justice of GHG allocation should not consider a single good independently of other goods which may also impact people's welfare".* In this study, this principle of distributive justice is elucidated by considering biogenic CH4 emission quotas alongside food production and CO_2 offset potential within the AFOLU sector. For example, large reductions in Ireland's CH_4 emissions may be ethically desirable in terms of international CH_4 quotas, but could lead to a 90% reduction in livestock production that, via export, feeds millions of people living in other countries, and could lead to the unemployment of many Irish farmers. Conversely, a hypothetical Indian government desire to achieve territorial climate neutrality would lead to a decline in rice production which could undermine national food security, whilst 'over-shooting' national biogenic CH4 targets based on principles of equity. There is an urgent need for international and cross-sectoral negotiation on burden sharing for CH4 reduction that considers ethics alongside, *inter alia*, food production and CO_2 offset obligations (which ultimately will need to compensate for ongoing emissions in other sectors) (McMullin et al., 2020). To date, such discussion has been limited but it is hoped that this study can provide valuable insights for future discussions.

4.2. Climate policy implications

A simple approach to evaluate progress towards climate neutrality at a national level that appears to be gaining interest would be to use the recently developed GWP* metric to aggregate national GHG emissions. Indeed, the Government of New Zealand (Ministry for the Environment, 2019) has come close to such an approach by establishing a national biogenic CH_4 reduction target directly in line with the global 24-47% reduction required for climate stabilisation (Rogelj et al., 2018b). However, such an approach involves emission 'grand-parenting' at national level, which could deny developing countries an opportunity to expand livestock production and is thus likely to be challenged internationally on grounds of equity (Rogelj and Schleussner, 2019). Therefore, it is difficult to envisage how separate treatment of biogenic CH_4 in national climate policy can be removed from issues around equitable sharing of global biogenic CH_4 budgets (and mitigation burdens). It would be naïve to expect international agreement on a harmonised approach to determine national CH_4 'quotas' as fixed climate targets in the near future, not least because of the wide range of global budgets from which to allocate these quotas depending on climate stabilisation pathways and modelling choices (Huppmann et al., 2018). Rather, this paper aims to expand the small evidence base available to explore whether and how to represent the short-term climate response to biogenic CH_4 emissions within climate policy. Specifically, modelling results presented here elaborate linkages between value judgements, CH_4 quotas, food security and climate objectives at national level through the lens of four contrasting countries, generating new insight pertinent to climate policy. We do not recommend a specific approach to setting biogenic CH4 targets, but instead argues for the definition of explicit biogenic methane targets in climate plans. To assist in the construction of these targets, we provide open-source modelling tool (https://github.com/prudhomme-nuig/methane) in the hope of stimulating the necessary debate.

Any future implementation of national emission targets for biogenic CH4 is likely to be an iterative process, especially if multiple objectives are to be considered as proposed in this paper. Consistency between national and global emission reduction targets could be achieved through periodic review of targets within NDCs. For example, review every 5 years would enable calibration of targets and burden sharing in light of technological advances in CH4 reduction (Dlugokencky et al., 2011), and in light of developing trade-offs between food production and CH4 reduction reflecting e.g. possible dietary shifts (Groenenberg et al., 2001; Voigt and Ferreira, 2016). Reviews would also make it possible to monitor the ambition of these targets as currently done for NDC (Robiou du Pont and Meinshausen, 2018). Constructive criticism of, and buy-in to, these targets requires transparency of calculation methods (Rogelj and Schleussner, 2019). This paper provides some worked-through examples.

4.3. Climate neutrality and food security

Irrespective of allocation method or GWP aggregation metric, these modelling results highlight that livestock production will need to be significantly reduced in most countries in order to achieve climate stabilisation. This is not just to reduce GHG emissions from livestock production, but to spare the land required for carbon sequestration to offset residual GHG emissions. Land sparing has a decisive influence on achieving climate neutrality targets within the AFOLU sector, and indeed more widely given that the AFOLU sector will need to offset residual emissions from other sectors in order to achieve global climate stabilisation (IPCC, 2019). In fact, afforestation of spared land can have a stronger influence on GWP balance than change in CH_4 emission directly (Fig. 2c). This suggests that the direct contribution of livestock to climate change via CH_4 emissions may be exceeded by their indirect contribution to climate change via the ’carbon opportunity cost’ of the large areas of land required to feed them (Searchinger et al., 2018). Consequently, the only opportunity for animal production to increase from 2010 levels in three of the four countries studied here, within CH_4 quotas, is for animal- and area- based yields to increase considerably via ‘sustainable intensification’ (Lamb et al., 2016). Among the studied countries, animal-protein security appears to be compatible with territorial climate neutrality only for Ireland and Brazil. Indeed, owing to their comparatively low population densities, these countries could continue to be net exporters (albeit at a smaller scale than currently) of milk and beef whilst achieving climate neutrality. Conversely, for India, territorial climate neutrality is not at all compatible with protein nor calorie food security from rice and livestock products, despite the high mitigation potential for rice production. This is a simple function of available agricultural land relative to population size, and highlights that different countries have very different biophysical potentials to achieve climate neutrality whilst maintaining basic food security for indigenous populations. To achieve climate stabilisation, countries with low population densities may need to achieve net negative emissions (net sinks), whilst countries with high population densities may continue to be net emitters, as implied by land use patterns explored in the recent IPCC special report on land use (IPCC, 2019). In other words, territorial climate neutrality may not be an appropriate target for many countries – for some it is too ambitious, for others it is insufficiently ambitious. This emphasises the need for international negotiations on burden sharing for CH4 emission reduction in order to ‘put meat on the bones’ of the Paris Agreement. There may be a role for some form of CH_4 emission trading scheme in the future to efficiently allocate CH_4 emissions (Dlugokencky et al., 2011), though this would face considerable barriers in terms of measurement, reporting and verification of CH_4 emissions (Storm et al., 2012) – which are much more difficult to estimate than CO_2 emissions for which trading schemes currently exist. In the meantime, given how far we are from climate stabilisation, territorial climate neutrality (‘net zero carbon’) targets are important placeholders to drive urgently necessary climate mitigation actions.

4.4. Limitations

The modelling approach applied in this paper involved numerous assumptions suitable to illustrate linkages between value judgements, CH_4 quotas, climate neutrality and food security at national level, but which are not fully realistic. Many factors will influence the mix of national food production, which is not likely to remain fixed through time in relation to share of CH_4 emissions. Nonetheless, the four studied countries represent distinct production mixes that exemplify the influence of biogenic CH_4 quotas on different production systems. Results assume that reductions in CH_4-emission-intensities translate into expansion of production to fill CH_4 quotas, and thus reduce the amount of CO_2 offset achievable in the AFOLU sector. It is well documented that past efficiency gains have been associated with increased consumption in Jevon's Paradox (Alcott, 2005). Moving away from an emissions decoupling mindset and towards an absolute net zero (or more accurately climate stabilisation) mindset as per the Paris Agreement, requires a dual focus on absolute emission reduction and emission offset, whilst avoiding of leakage effects: 'better' is no longer good enough. Wider societal trends, including possible reductions in food waste and diet change in industrialised countries away from animal products, are likely to be integral to climate stabilisation (Committee on Climate Change, 2020; IPCC, 2019). In this context, additional mitigation efforts could reduce overall emissions if production does not automatically expand to fulfil CH_4 quotas, so that results presented here may be pessimistic. On the other hand, we optimistically explore the technical potential for climate stabilisation based on all land spared from agriculture going into forestry. In reality, it is unlikely that all spared land would be planted with trees, and there are limits to the rate of annual planting (Committee on Climate Change, 2020). Furthermore, while the GWP balances achievable by 2050 explored here disregard the long-term dynamics of CO_2 sequestration and possible re-emission associated with forests and downstream wood value chains (Nabuurs et al., 2017). Other negative emission technologies that could utilise spared land, such as crop-based bioenergy with carbon capture and storage, were excluded. The framework presented in this paper used readily available data, including for a base year of 2010. A different base year could be selected, and the base year used for calculation could be updated e.g. every five or ten years to reflect different rates of development across countries. The framework could also be updated for countries where higher resolution data are available – e.g. modified Tier 2 and Tier 3 emission factors for production, and spatial resolution on production and afforestation potential. More recent and higher resolution data for Ireland show that milk production has increased by 36% whilst the GHG intensity per kg of milk has reduced by circa 10% between 2010 and 2018 (Buckley et al., 2019) . The scale of livestock reductions required under most scenarios for Ireland would therefore be considerably greater if 2018 was taken as a baseline instead of 2010. Drained organic soils are a very important source of CO_2 and N_2O emissions that were excluded from these analyses and that could be included in future work.

5. Conclusion

Short-lived GHGs such as CH_4 behave more like flow pollutants than stock pollutants in terms of their climate-warming effects. Recent modelling indicates that climate stabilisation requires biogenic CH_4 reductions of 24-47% globally, and GWP* has been proposed as an alternative GHG aggregation metric that better represents the climate-forcing effects of CH_4 through time compared with the GWP_{100} metric currently used for national GHG reporting. However, application of GWP* to determine national GHG budgets compatible with climate stabilisation implies grand-parenting of emissions, which may be perceived as unfair to countries with low baseline emissions. Separate treatment of biogenic CH_4 in climate policy will therefore necessitate consideration of how global biogenic CH_4 budgets compatible with climate stabilisation can be translated into national climate policy targets.

For the first time, this study explored the effects of alternative approaches to set national biogenic CH_4 targets on food production and ability to achieve net zero GHG emissions (GWP_{100} metric) or climate stabilisation (eGWP* metric) within national AFOLU sectors, using four contrasting countries as examples: Brazil, France, India and Ireland. National biogenic CH_4 budgets were derived by downscaling global budgets defined for 1.5°C scenarios based on allocation rules representing principles of equity (emissions proportionate to population), ability to reduce emissions (mitigation proportionate to GDP) and protein security (emissions proportionate to protein production in 2010), alongside a grand-parenting approach for reference. Choice of allocation method was shown to have a profound effect on the level of 'allowable' ruminant production in milk and beef exporting countries such as Ireland and Brazil. Nonetheless, owing to relatively low population densities, AFOLU sectors in these countries have high potential to achieve climate neutrality if spared land is used for forestry. Meanwhile, countries such as India have constrained land areas to fill their CH_4 quota with CH_4-emitting food production (milk, meat, eggs, rice), and may not be able to achieve climate neutrality targets whilst maintaining food (protein and calorie) security. Results illustrate the need for more detailed coordination of international GHG mitigation efforts in order to achieve climate stabilisation, with a particular focus on how global biogenic CH_4 budgets can be equitably allocated. Such coordination will require consideration of food security and land banks available for offsetting activities.

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