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

Supplementary information

S1. Elaboration of the methodology for an example product and country

The impact of the allocation of a national methane quota on overall emissions and production is described in the method section of the core of the paper. To illustrate this methodology and make it as transparent as possible, we provide here a full list of all equations referred to in the body of the paper accompanied by a worked example for a methane-intensive product (milk).

Table S1.1: Summary of variables and equations used in the modelling framework to compute the impacts on emissions and "allowable" production levels associated with different national biogenic methane quotas. An example is provided for the influence of an average methane quota for Ireland, based on a "protein allocation", on Irish milk production with deployment of full mitigation options by 2050.

Number of the equation[1]	Theoretical	Milk in Ireland
0	$CH_{4\,2050}^{i} = R \times CH_{4\ 2050}^{w}$	$CH_{4\,2050}^{i} = 0.0025 \times 87097 \ = 217.7\ GgCH_4$
	$CH_{4\,2050}^{i}$: National biogenic methane quota of the country i in 2050 R: Allocation rule used to share the burden of the global biogenic methane reduction (In this example, we used the "per capita" allocation method: $R = \frac{Prot_{Ireland}^{2010}}{Prot_{w}^{2010}} = 0.25\%$) $CH_{4\ 2050}^{w}$: Mean global biogenic methane target in 2050 compatible with 1.5 degree ($CH_{4\ 2050}^{w} = 87097\ GgCH_4$)	
1	$CH_{4\ 2050}^{i,j} = \frac{CH_{4\ 2010}^{i,j}}{CH_{4\,2010}^{i}} \times CH_{4\,2050}^{i}$	$CH_{4\ \ 2050}^{Ireland,Milk} = \frac{148}{550} \times 217.7$ = 58 GgCH$_4$
	$CH_{4\ 2050}^{i,j}$: Methane emissions for the type of product j in the country i in 2050 $CH_{4\ 2010}^{i,j}$: Methane emissions for the type of product j in the country i in 2010 ($CH_{4\ \ 2010}^{Ireland,Milk}$= 148 Gg CH$_4$) $CH_{4\,2010}^{i}$: Overall methane emissions in the country i in 2010 ($CH_{4\ \ 2010}^{Ireland}$: 550 Gg CH$_4$) $CH_{4\,2050}^{i}$: Overall methane quota in the country i in 2050 ($CH_{4\ \ 2050}^{Ireland}$: 217.7 Gg CH$_4$)	

<table>
<tr><td rowspan="2">2</td><td>$$ch_{4\ 2010}^{i,j} = \frac{CH_{4\ 2010}^{i,j} - \Delta CH_4^{i,j}}{PU_{2010}^{i,j}}$$</td><td>$$ch_{4\ 2050}^{Ireland,Milk} = \frac{(148-10)\times 10^3}{1.1\times 10^6} = 0.11\ Mg\ \mathrm{CH4.Head}^{-1}$$</td></tr>
<tr><td colspan="2">$ch_{4\ 2050}^{i,j}$: Methane intensity of the production unit for the product j in the country i in 2050
$CH_{4\ 2010}^{i,j}$: Methane emissions for the type of product j in the country i in 2010 ($CH_{4\ 2010}^{Ireland,Milk}$: 285 $GgCH_4$)
$\Delta CH_4^{i,j}$: Methane emission reduction[3] for the type of product j in the country i in 2010 ($\Delta CH_4^{Ireland,Milk}$: 10 $GgCH_4$)
$UP_{2010}^{i,j}$: Number of production unit for the product j in the country i in 2010 ($UP_{2010}^{Ireland,Milk}$: 1.1×10^6 Heads)</td></tr>
<tr><td rowspan="2">3</td><td>$$PU_{2050}^{i,j} = \frac{CH_{4\ 2050}^{i,j}}{ch_{4\ 2050}^{i,j}}$$</td><td>$$PU_{2050}^{Ireland,Milk} = \frac{113\times 10^9}{0.11\times 10^6} = 1.0\ \times 10^6\ \text{Heads}$$</td></tr>
<tr><td colspan="2">$UP_{2050}^{i,j}$: Number of units of production for the product j in the country i in 2050
$CH_{4\ 2050}^{i,j}$: Methane emissions for the type of product j in the country i in 2050 ($CH_{4\ 2050}^{Ireland,Milk}$: 113 $GgCH_4$)
$ch_{4\ 2050}^{i,j}$: Methane intensity of the production unit j in the country i in 2050 ($ch_{4\ 2050}^{Ireland,Milk}$: 0.11 $Mg\mathrm{CH4.Head}^{-1}$)</td></tr>
<tr><td rowspan="2">4</td><td>$$P_{2050}^{i,j} = PU_{2050}^{i,j} \times Y_{2050}^{i,j}$$</td><td>$$P_{2050}^{Ireland,Milk} = 4.97\times\ 1.0\ \times 10^6 = 5.0\times 10^6\ \text{Mg}$$</td></tr>
<tr><td colspan="2">$P_{2050}^{i,j}$: Production of the product j in the country i in 2050
$UP_{2050}^{i,j}$: Number of production unit for the product j in the country i in 2050 ($UP_{2050}^{Ireland,Milk}$: 1.0 $\times 10^6$ Heads)
$Y_{2050}^{i,j}$: Yield of the product j per production unit for in the country i in 2050 ($Y_{2050}^{Ireland,Milk}$: 4.97 Mg/Year)</td></tr>
<tr><td rowspan="2">5</td><td>$$A_{2050}^{i,j,k} = \frac{PU_{2050}^{i,j} \times U_{k\ 2010}^{i,j} \times T_{2010}^{i,k}}{\overline{Y_{2050}^{i,k}}}$$</td><td>$$A_{2050}^{Ireland,Milk,grass} = \frac{1.0\ \times 10^6\ \times 2301\times 1}{3.8\times 10^3} = 0.6\ \times 10^6\text{ha}$$
$$A_{2050}^{Ireland,Milk,concentrate} = \frac{1.0\times 10^4\times 278\times 0.61}{6.5\times 10^3} = 0.03\ \times 10^6\text{ha}$$</td></tr>
<tr><td colspan="2">$A_{2050}^{i,j,k}$: Area used by the production factor k to produce the product j in the country i in 2050
$PU_{2050}^{i,j}$: Number of production unit for the product j in the country i in 2050 ($UP_{2050}^{Ireland,Milk}$: 1.0 $\times 10^6$ Heads)
$U_k^{i,j}$: Utilisation by production factor k for the production of product j in country i in 2010 ($U_{grass}^{Ireland,Milk}$: 2301 kg DM/Head/yr and $U_{concentrate}^{Ireland,Milk}$: 278 kg DM/Head/yr (MacLeod et al. 2013))</td></tr>
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	$\underline{T_{2010}^{i,k}}$: Share of the production factor k which is domestically produced in the country i in 2010 ($\underline{T_{2010}^{Ireland,grass}} = 1$ and $T_{2010}^{Ireland,Feed} = 0.61$) $\underline{Y_{2050}^{i,k}}$[5]: Average yield of the production factor k per production unit for in the country i in 2050 ($\underline{Y_{2050}^{Ireland,concentrate}}$: 6.3 tDM/ha and $\underline{Y_{2050}^{Ireland,grass}}$: 3.8 tDM/ha)	
6	$CO_2^{i,j}{}_{2050}^{offset} = \sum_{k \in \{factors\}} -\left((A_{2050}^{i,j,k} - A_{2010}^{i,j,k}) \times (1 - s_{2010}^{imp,k}) \times EF_{2050}^{CZ,i}\right)$	$CO_2^{Ireland,Milk}{}_{2050}^{offset} = -(2.5 - 0.6) \times 10^6 \times 2.8 \times \frac{44}{12} - (0.2 - 0.04) \times 10^6 \times 2.8 \times \frac{44}{12} = -27$ $TgCO_2$
	$CO_2^{i,j}{}_{2050}^{offset}$: CO_2 sequestration associated with the change of production of the product j in the country i in 2050 $A_{2050}^{i,j,k}$: Area used by the input k to produce the product j in the country i in 2050 ($A_{2050}^{Ireland,Milk,grass}$:0.6× 10^6 ha and $A_{2050}^{Ireland,Milk,concentrate}$:0.04× 10^6 ha) $A_{2010}^{i,j,k}$: Area used by the input k to produce the product j in the country i in 2010 ($A_{2050}^{Ireland,Milk,grass}$:2.5× 10^6 ha and $A_{2050}^{Ireland,Milk,concentrate}$:0.2× 10^6 ha) $s_{2010}^{imp,k}$: Share of net importation in the production if the feed k in the country i ($s_{2010}^{imp,concentrate}$ =0.46, details of this number are provided in Table S6) $EF_{2050}^{CZ,i}$: Forest Growth Rate (if $A_{2050}^{i,j,k} < A_{2010}^{i,j,k}$) of the climate zone CZ of the country j (2.8 MgC). Deforestation rate (if $A_{2050}^{i,j,k} < A_{2010}^{i,j,k}$) of the country i $factors$: Production factors used to produce the product j in the country I (grass and concentrate)	
7	$EF_{2050}^{i,j,s} = \frac{N_2O^{i,J,s}{}_{2010} - \Delta N_2O^{i,J,s}}{PU_{2010}^{i,J}}$	$EF_{2050}^{Ireland,Cattle,manure} = \frac{3331-285}{6.6} = 0.461\ MgN2O/1000$ Heads $EF_{2050}^{Ireland,Cattle,fert} = \frac{6530 - 1663}{313649} = 0.016\ MgN2O/MgN$
	$EF_{2050}^{i,j,s}$: Emission factor of nitrous oxide associated with the production unit used to produce the product j in the country i in 2050 for the emission source *s* $N_2O^{i,J,s}{}_{2010}$: Nitrous oxide emissions associated with the source s from the production unit J in the country i in 2010 ($N_2O^{Ireland,Cattle,manure}{}_{2010} = 3331\ MgN_2O$, $N_2O^{Ireland,Cattle,fert}{}_{2010} = 6530 MgN_2O$) $\Delta N_2O^{i,J,s}$: Reduction of nitrous oxide emissions associated with the source s from the production unit J in the country i in 2050 compared to 2010 ($\Delta N_2O^{Ireland,Cattle,manure} = 285\ MgN_2O$, $\Delta N_2O^{Ireland,Cattle,fert} = 1663\ MgN_2O$) $PU_{2010}^{i,J}$: Production unit J (Cattle) in the country i in 2010 ($UP_{2010}^{Ireland,Cattle} = 6.6$ Mheads, $UP_{2010}^{Ireland,Nfert} = 313649$ tN)	

8	$$N_2O^{i,j}{}_{2050} = \sum_{s\in\{sources\}} \left(PU^{i,j}_{2050} \times EF^{i,J,s}_{2050}\right) + \sum_{k\in\{factors\}} \left(PF^{i,k,fert}_{2050} \times EF^{i,fert}_{2050}\right)$$	$N_2O^{Ireland,Milk}{}_{2050} = PU^{Ireland,Milk}_{2050} \times EF^{Ireland,Cattle,manure}_{2050} + PF^{Ireland,grass,fert}_{2050} \times EF^{Ireland,fert}_{2050} + PF^{Ireland,concentrate,fert}_{2050} \times EF^{Ireland,fert}_{2050} = 1.0 \times 10^6 \times 0.461 \times 10^{-3} + 0 \times 0.016 + 0.016 \times 62.7 \times 10^3 = 1.5 \times 10^3\ MgN_2O$
	$N_2O^{i,j}{}_{2050}$: Agricultural nitrous oxide emissions to produce the good j in the country i in 2050 $PU^{i,J}_{2050}$: Production unit used to produce the product j in the country i in 2050 ($PU^{Ireland,Milk}_{2050}$=1.0 $\times 10^6\ Heads$) $PF^{i,k,fert}_{2050}$:Amount of N mineral fertilizer used for the production of the production factor k in the country ($PF^{Ireland,concentrate,fert}_{2050} = \frac{0.04}{0.2} \times 313649 = 62729$ MgN) $EF^{i,J,s}_{2050}$: Emission factor of nitrous oxide associated with the type of product J (Cattle, Swine, Poultry, N use) in the country i in 2050 for the emission source s (Manure, fertilization) ($EF^{Ireland,Cattle,fert}_{2050} = 0.016\ MgN2O/MgN$, $EF^{Ireland,Cattle,manure}_{2050}$=0.461 $MgN2O$/1000 Heads)	
9	$GWP^{i}_{AFOLU\,2050} = GWP^*_R\left(CH^i_{4\,2050}\right) + GWP_{100} \times \left(N_2O^i{}_{2050}\right) + CO^i_{2\,2050} + GWP_{100} \times N_2O^{i\ Other}_{\ 2050}$	For the purpose of the example, the global warming potential is computed at the scale of the milk product despite this include N_2O emissions from the cattle used to produce meat: $GWP^{Ireland,Milk}_{AFOLU\ 2050} = GWP^*_{Pop}(218) + 298 \times 1.5 - 27000 = -1635 + 625.8 - 25600$ = -26678 Gg $CO_{2,e}$
	$GWP^{i}_{AFOLU\,2050}$: Global warming potential associated with the AFOLU sector in the country i in 2050 (in the example, it is only computed for milk) $GWP^*_R\ \left(CH^{i,j}_4{}_{2050}\right)$: Global warming potential equivalent to offset the methane quota ($CH^i_{4\,2050} = 218GgCH_4$) in the country I with a capita rule based GWP* (Details of the computation in Table S5) $N_2O^i{}_{2050}$: Nitrous oxide emissions in 2050 (in the example, associated with the production of the cattle: $N_2O^{Ireland,Cattle}{}_{2050} = 1.5\times 10^3\ MgN_2O$) $CO^{i,j}_2{}_{2050}$: CO_2 sequestration associated with the change of production of the product j in the country i in 2050 ($CO_2^{Ireland,Milk}{}^{offset}_{2050} = -27$ $TgCO_2$) $N_2O^{i\ Other}_{\ 2050}$: Nitrous oxide emissions in the country I from fertilization of crops for other uses than	

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$$GWP^{i}_{Trade\,2050} = GWP_{100} \times N_2O^{i,Trade}{}_{2050} + CO_2^{i,Trade}{}_{2050}$$
$$= GWP_{100} \times \sum_{k\in\{factors\}} \left(PF^{Trade,k,fert}_{2050} \times EF^{Trade,fert}_{2050}\right) + \sum_{j\in\{product\}}\sum_{k\in\{factors\}} -\left(\left(A^{i,j,k}_{2050} - A^{i,j,k}_{2010}\right) \times s^{imp,k}_{2010} \times EF^{w}_{2050}\right)$$

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$PF^{i,k,fert}_{2050}$:Amount of N mineral fertilizer used for the production of the production factor k in the country ($PF^{Ireland,concentrate,fert}_{2050} = \frac{0.04}{0.2} \times 313649 = 62729$ MgN)
$EF^{i,J,s}_{2050}$: Emission factor of nitrous oxide associated with the type of product J (Cattle, Swine, Poultry, N use) in the country i in 2050 for the emission source s (Manure, fertilization) ($EF^{Ireland,Cattle,fert}_{2050} = 0.016\ MgN2O/MgN$, $EF^{Ireland,Cattle,manure}_{2050}$=0.461 $MgN2O$/1000 Heads)
$CO_2^{i,Trade}{}_{2050}$: CO_2 sequestration associated with the change of production of the product j in the country i in 2050
$A^{i,j,k}_{2050}$: Area used by the input k to produce the product j in the country i in 2050 ($A^{Ireland,Milk,grass}_{2050}$:0.6$\times 10^6$ ha and $A^{Ireland,Milk,concentrate}_{2050}$:0.04$\times 10^6$ ha)
$A^{i,j,k}_{2010}$: Area used by the input k to produce the product j in the country i in 2010 ($A^{Ireland,Milk,grass}_{2050}$:2.5$\times 10^6$ ha and $A^{Ireland,Milk,concentrate}_{2050}$:0.2$\times 10^6$ ha)
$EF^{CZ,i}_{2050}$: Forest Growth Rate (if $A^{i,j,k}_{2050} < A^{i,j,k}_{2010}$) of the climate zone CZ of the country j (2.8 MgC). Deforestation rate (if $A^{i,j,k}_{2050} < A^{i,j,k}_{2010}$) of the country i
$factors$: Production factors used to produce the product j in the country I (grass and concentrate)

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[1] The summary of the modelling framework with the equation sequence number is detailed in Figure 2.

[2] The emission reduction of methane and nitrous oxide from agricultural sources in each country and for each product j in 2050 is taken from national MAC curves (Lanigan and Donnellan 2018, Moraes et al. 2012, Pellerin et al. 2017, Sapkota et al. 2019). These emissions reductionsare described in Table S3

[3] The number of units of production refers to not only milking cows but also all the calves, the heifers and the dry cows of the dairy system. This number is computed here as the share of milking cows among the meat and milk producing cows, multiplied by the total number of cattle. An extensive description of the computation of these units of production in 2010 is provided in Table S2.

[4] The average yield of the concentrate for the country i in 2050 is computed in Table S4

Table S1.2: Computation of the emission reduction with the example of the milk production in 2050 In Ireland

	Mitigation measures*	Emission reduction in cattle production	Share of the emission reduction in the dairy sector	Emission reduction in the dairy sector by mitigation measure	Total emission reduction in the dairy sector
$\Delta CH_4^{i',j} = \sum_{m \in M} \Delta CH_4^{i',j,m}$ M is the set of mitigation measures for the product j in the country j'	Improved live weight gain (tCH_4)	2178.57	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}}=0.17$	871	6455 tCH_4
	Beef maternal replacement (tCH_4)	903.57	0	0	
	Dairy economic breeding index (tCH_4)	1265	1	1265	
	Extended grazing (tCH_4)	3429	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}}=0.17$	1372	
	Animal health (tCH_4)	5250	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}}=0.17$	2100	
	Sex seemed (tCH_4)	867.85	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}}=0.17$	347	
	Fatty Acids (tCH_4)	1250	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}} = 0.17$	500	
$\Delta N_2O_{Fert}^{i',j} = \sum_{m \in M} \Delta N_2O_{Fert}^{i',j,m}$ M is the set of mitigation measures for the product j in the country j'	Clover cover (tN_2O)	231	$\frac{A_{2010}^{Ireland,Milk,Grass}}{A_{2010}^{Ireland,Meat,Grass}+A_{2010}^{Ireland,Milk,Grass}}=\frac{1.6}{4.1}=0.39$	92	1055 tN_2O
	Fertiliser type (tN_2O)	1748	$\frac{A_{2010}^{Ireland,Milk,Grass}}{A_{2010}^{Ireland,Meat,Grass}+A_{2010}^{Ireland,Milk,Grass}}=0.39$	699	
	Mineral soil drainage (tN_2O)	661	$\frac{A_{2010}^{Ireland,Milk,Grass}}{A_{2010}^{Ireland,Meat,Grass}+A_{2010}^{Ireland,Milk,Grass}}=0.39$	264	
$\Delta N_2O_{Manure}^{i',j}$	Slurry amendments	41	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat}+N_{2010}^{Ireland,J,Milk}} = 0.4$	16.4	173 tN_2O

$= \sum_{m \in M} \Delta N_2O_{Manure}^{i',j,m}$ M is the set of mitigation measures for the product j in the country j'	Low-emission slurry spreading	393	$\frac{N_{2010}^{Ireland,J,Milk}}{N_{2010}^{Ireland,J,Meat} + N_{2010}^{Ireland,J,Milk}} = 0.4$	157	

* From Lanigan et al. (2018)

Table S1.3: Computation of the average yield of concentrate ($Y_{2010}^{i,concentrate}$) with the example of Ireland in 2010

Average yield of concentrate	List of crops	Share in the feed ration	National yield (tFM/ha)	Dry matter to fresh matter	National yield (tDM/ha)	Imported share	Average yield (tDM/ha)
$\overline{Y_{2010}^{i,concentrate}} = \sum_{m \in C} Y_{2010}^{i,c} \times s_{2010}^{i,c}$ C is the set of crops consumed by livestock in the country i in 2010 $s_{2010}^{i,c}$: Share of the crop c consumed in the ration of livestock in the country i $Y_{2010}^{i,c}$: Yield of the crop c consumed in the ration of livestock in the country i	Wheat	27,50%	8.6	0.88	7.568		5.53
	Barley	52,60%	7	0.88	6.16		
	Maize	12,40%	0	0.88	0		
	Cereals Other	0,40%	0	0.88	0		
	Sugar Cane	0,10%	0	0.27	0		
	Soyabeans	0,60%	0	0.89	0		
	Vegetables Other	1,20%	0	0.1	0		
	Oats	2,90%	7.5	0.88	6.6		
	Potatoes	0,10%	34.4	0.21	7.33		
	Oilcrops Other	2,00%	0	1	0		
	Rice (Milled Equivalent)	0,10%	0	0.87	0		
	Peas	0,00%	4.7	0.9	4.23		
	Beans	0,20%	5.7	0.9	5.13		

Table S1.4: Computation of the average yield of grass ($Y_{2010}^{i,grass}$) with the example of Ireland in 2010

Theoretical	Variables	Milk in Ireland
$\overline{Y_{2010}^{i,grass}} = \frac{\sum_r d_{grass}^{r,i,2010} \times N_{2010}^{i,r}}{A_{grass}^{2010}}$	$A_{grass}^{i,2010}$: Area of grass in 2010 in the country i $d_{grass}^{r,i,2010}$: Grass consumption per head of ruminant of type r in the country I in 2010 ($d_{2010}^{Ireland,Cattle,dairy} = 5363\ kg\ DM/head, d_{2010}^{Ireland,Cattle,non-\ dairy} = 2008\ kg\ DM/head\ , d_{2010}^{Ireland,Sheep\ and\ Goats} = 197 kg\ DM/head$) $N_{2010}^{i,r}$: Number of ruminants of type r in the country I in 2010 ($N_{2010}^{Ireland,Cattle,dairy} = 1070800\ heads, N_{2010}^{Ireland,Cattle,non-\ dairy} = 5535800\ heads, N_{2010}^{Ireland,Sheep\ and\ Goats} = 4755900\ heads$)	$\overline{Y_{2010}^{i,grass}} = \frac{5363 * 1070800 + 2008 * 5535800 + 197 * 4755900}{4.1 * 10^6} = 4.3\ t\ DM/ha$

Table S1.5: Computation of the methane equivalent of a CO_2 offset with the example of Ireland in 2010

GWP* formula	Rule	Parameters	Example applied to the milk production in Ireland with a 'protein' allocation
$GWP_R^*(CH_{4_{2050}}^i) = \frac{(CH_{4_{2050}}^i - R \times CH_{4\ 2010}^w)}{T} \times GWP_T \times (2050 - 2010)$	Capita based rule	$R = \frac{Prot_i^{2010}}{Prot_w^{2010}}$ $T = 100$ $GWP_T = 34$	$GWP_{AFOLU\ \ 2050}^{Ireland} = \frac{(218 - 0.0025 \times 135301)}{100} \times 34 \times (2050 - 2010) = -1635\ GgCO_{2,eq}$

Table S1.6: Computation of fertilization of the production factor (grass or concentrate) with the example of Ireland in 2010

Product		Fertilization of the production factor k	Variables values for Ireland in 2010	Numerical example
Milk	Grass	$PF_{2050}^{i,j,k,fert} = N_{2010}^{i,k,fert} \times \frac{Y_{2050}^{i,k}}{Y_{2010}^{i,k}} \times A_{2050}^{i,j,k}$ $N_{2010}^{i,fert}$: Fertilization rate of the production factor k in the country i in 2010 $Y_{2050}^{i,k}$: Yield of the production factor k in the country i in 2010 $Y_{2010}^{i,k}$: Yield of production factor k in the country i in 2010 $A_{2050}^{i,j,k}$: Area of the production factor k in the country i in 2010	$N_{2010}^{Ireland,grass,fert}$: 0 $Y_{2050}^{Ireland,grass}$: 3.8 tDM/ha $Y_{2010}^{Ireland,grass}$: 3.8 tDM/ha $A_{2050}^{Ireland,Milk,grass}$:1.5 Mha	$PF_{2050}^{Ireland,Milk,concentrate,fert} =$ 0 ktN
	Concent rate		$N_{2010}^{Ireland,concentrate,fert}$: $\frac{N_{2010}^{Ireland,fert}}{A_{2010}^{Ireland,cropland}} = \frac{0.3}{1.01} =$ 0.3 tN/ha $Y_{2050}^{Ireland,concenrate}$:6.3 tDM/ha $Y_{2010}^{Ireland,concenrate}$:6.3 tDM/ha $A_{2050}^{Ireland,Milk,concentrate}$:0.1 Mha	$PF_{2050}^{Ireland,Milk,concentrate,fert} =$ 30 ktN

Table S1.7: Computation of the share of imported production factor (grass or concentrate) with the example of Ireland in 2010

Product	Share of imported production factor k		Variables values for Ireland in 2010	Numerical example
Milk	Grass	$s^{imp,k}_{2010} = \sum_k N^{i,k,fert}_{2010} \times \frac{Y^{i,k}_{2050}}{Y^{i,k}_{2010}} \times A^{i,j,k}_{2050}$ $s^{imp,k}_{2010}$: Share of net importation in th : Yield of the production factor k in the country i in 2010 $Y^{i,k}_{2010}$: Yield of production factor k in the country i in 2010 $A^{i,j,k}_{2050}$: Area of the production factor k in the country i in 2010	$N^{Ireland,grass,fert}_{2010}$: 0 $Y^{Ireland,grass}_{2050}$: 3.8 tDM/ha $Y^{Ireland,grass}_{2010}$: 3.8 tDM/ha $A^{Ireland,Milk,grass}_{2050}$:1.5 Mha	$PF^{Ireland,Milk,concentrate,fert}_{2050} =$ 0 ktN
	Concent rate		$N^{Ireland,concentrate,fert}_{2010} : \frac{N^{Ireland,fert}_{2010}}{A^{Ireland,cropland}_{2010}} = \frac{0.3}{1.01} = 0.3$ tN/ha $Y^{Ireland,concenrate}_{2050}$:6.3 tDM/ha $Y^{Ireland,concenrate}_{2010}$:6.3 tDM/ha $A^{Ireland,Milk,concentrate}_{2050}$:0.1 Mha	$PF^{Ireland,Milk,concentrate,fert}_{2050} =$ 30 ktN

Table S1.8: Computation of the share of imported production factor (grass or concentrate) with the example of Ireland in 2010

Mitigation Technology	Brazil			France			India			Ireland		
	Item*	Mitigation potential	Unit	Item*	Mitigation potential	Unit	Item*	Mitigation potential	Unit	Item*	Mitigation potential	Unit
Concentrate increase	Cattle	196428	$tCO_{2,e}$	Cattle	-	-	Cattle	15	%**	Cattle	-	-
Inhibitor use	Cattle	-	-	Cattle	10	%**	Cattle	22	%**	Cattle	-	-
Additives	Cattle	125000	$tCO_{2,e}$	Cattle	14	%**	Cattle	11	%**	Cattle	-	-
Breeding	Cattle	171428	$tCO_{2,e}$	Cattle	-	-	Cattle	-	-	Dairy cattle	1265	$tCO_{2,e}$
Breeding	-	-	-	-	-	-	-	-	-	Beef cattle	903+2178	$tCO_{2,e}$
Extended grazing	-	-	-		-	-	-	-	-	Cattle	3429	$tCO_{2,e}$
Animal health	-	-	-	-	-	-	-	-	-	Cattle	5250	$tCO_{2,e}$
Sex seemed	-	-	-	-	-	-	-	-	-	Cattle	868	$tCO_{2,e}$
Water management for rice	Rice	-50	%**	Rice	-50	%**	Rice	0.098	$tCO_{2,e}$/ha	Rice	-	-
	(Moraes et al. 2012a)			(Pellerin et al. 2017)			(Sapkota et al. 2019)			(Lanigan and Donnellan 2018)		

* Item indicates the type of animal or crop on which the attenuation technology applies

** % indicates the reduction of emission factor

Table S1.9: National mitigation potential of N_2O of different mitigation technologies of biogenic methane emission taken from the literature for Ireland

Emission sources	Brazil			France			India			Ireland		
	Mitigation Technology	Mitigation potential	Unit	Mitigation Technology	Mitigation potential	Unit	Mitigation Technology	Mitigation potential	Unit	Mitigation Technology	Mitigation potential	Unit
Fertilization	-	-	-	All	4277805	tN_2O	Adoption of precision nutrient management technologies	-587242	tN2O	Clover cover	231	tN_2O
										Fertiliser type	1748	tN_2O
										Mineral soil drainage	661	tN_2O
Manure management	All	16778	tN2O	Biogas	17339982	tN2O	Biogas	0.50023	tN2O / ha	Slurry amendments	41	tN_2O
				Pigs N diet	484500	tN2O	Improved manure management	0.03063	tN2O /head	Low-emission slurry spreading	393	tN_2O
										Pigs N diet	168	tN_2O
	(Moraes et al. 2012a)			(Pellerin et al. 2017)			(Sapkota et al. 2019)			(Lanigan and Donnellan 2018)		

Table S1.10: National and global indicators used in allocation rule of national methane quota

	Country value				World value			
	GDP (US$2005)	CH_4 emissions in 2010 (tCH_4)	Population (cap)	Protein	GDP (US$2005)	CH_4 emissions in 2010 (tCH_4)	Population (cap)	Protein
Brazil	2.20E+12	1.35E+04	2.00E+08	1.31E+04	6.6E+13	1.35E+05	6.9E+09	3.32E+05
France	2.60E+12	1.76E+03	6.50E+07	4.42E+03				
India	1.70E+12	1.94E+04	1.20E+09	3.25E+04				
Ireland	2.20E+11	5.51E+02	4.56E+06	8.34E+02				

S2. Specific methodological aspects

S2.1. Intensification pathways

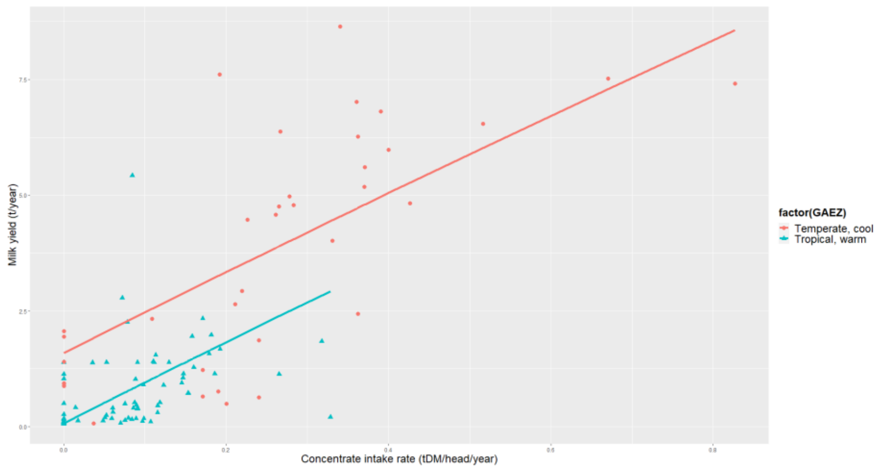
Intensification pathways define yields associated with emission intensities (per head for animals and per ha for rice) and input use rates (intake for animals and N for rice). The ‘current’ pathway corresponds to 2010 yields and the ‘improved’ pathway corresponds to a higher yield. For rice, intensification is already represented in the MAC curves and is not included in the ‘improved’ pathway.

To define the yield and emission intensity of each product from each animal, we use an intensification curve that relates different yields with different intake levels. These relationships are established from Gleam's outputs at the country level (MacLeod et al. 2013). The description of these relationships is provided in the table S2.1. We also calculate enteric fermentation emissions by fitting a relationship between the intensity of enteric fermentation emissions and intakes for dairy and non-dairy cattle (Table S2.1 and Fig. S2.1). The main drivers for manure-related emissions are manure management and spreading systems. For simplicity, the increase in manure emissions intensity in the improved pathway is proportional to the increase in yield.

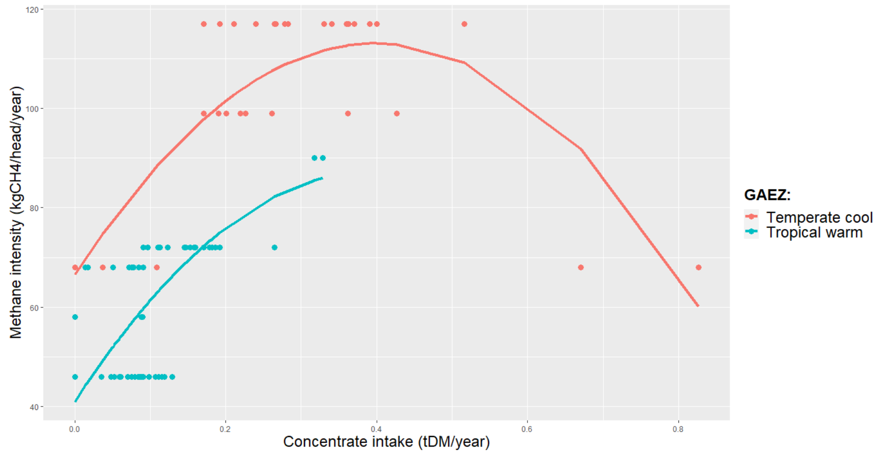
Table S2.1. Intensification relation for each animal and each product based on FAOSTAT (2015) data.

Animal	Product	Relation between yield and intake	Relation between emission intensity if enteric fermentation and intake	Units	R-squared
Dairy cattle	Milk	$\text{Milk yield} = -0.45 + 7.98 \times \text{Grain Intake} - 6.31 \times \text{Grain Intake}^2 - 0.9 \times 1^{Tropical}$	$EF^{Dairy} = 87.5 + 115.2 \times \text{Grain Intake} - 117.1 \times \text{Grain Intake}^2 - 25.6 \times 1^{Tropical*}$	Milk yield: t/ head/yr Intake: tDM/ head/yr Grain intake: tDM/ head/yr EF: tCH4/head/yr Meat yield:tLW/head/yr Carcass yield: tCW/head/yr	$R^2_{Yield} = 0.46$ $R^2_{EF} = 0.84$
	Meat	Meat yield= Meat yield_{2010}			
Non-dairy cattle	Meat	$\text{Meat yield} = 51.3 + 16.0 \times \text{Grain Intake} - 50.2 \times 1^{Tropical*}$	$EF^{Non-Dairy} = -1..9 + 25.0 \times \text{Grain Intake}$		$R^2_{Yield} = 0.7$ $R^2_{EF} = 0.96$
Poultry	Meat	$\text{Carcass yield} = 0.0005 + 0.20 \times \text{Grain Intake}$	-		$R^2_{Yield} = 0.5$
Chicken layers	Eggs	$\text{Eggs yield} = 0.003 + 0.42 \times \text{Grain Intake}$	-		$R^2_{Yield} = 0.76$
	Meat	Carcass yield = Carcass yield_{2010}	-		-
Pigs	Meat	$\text{Carcass yield} = 0.01 + 2.3 \times \text{Grain Intake}$	-		$R^2_{Yield} = 0.53$

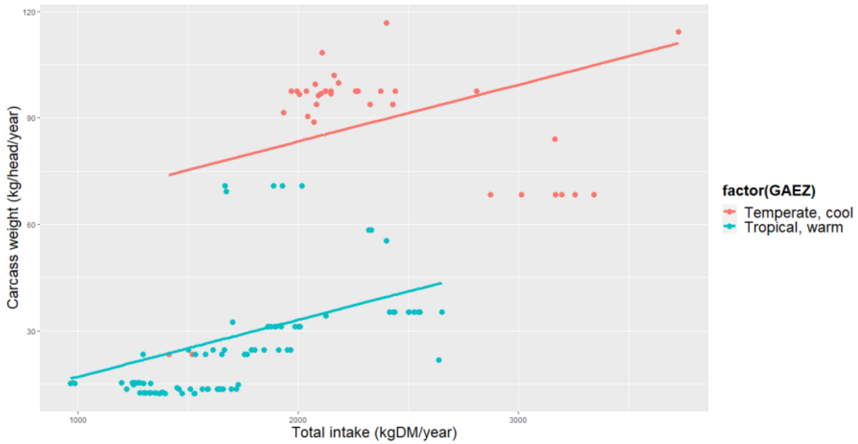
$*1^{Tropical}$: 1 if the country belong to the tropical GAEZ, 0 otherwise

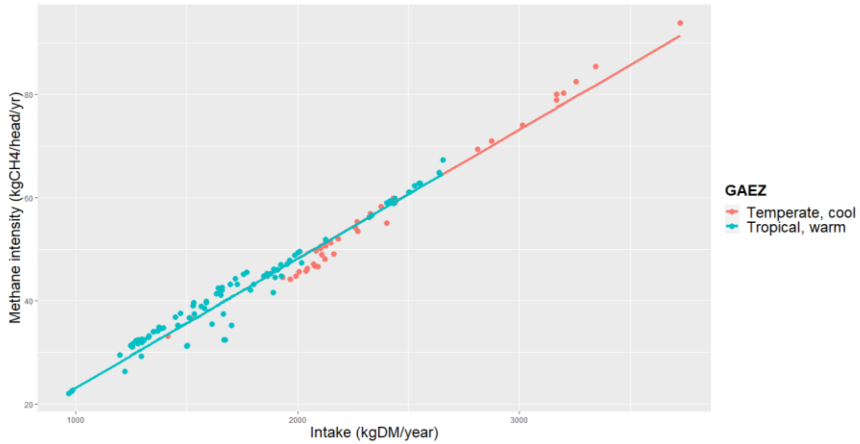


a. Relation between milk yield and concentrate intake per Global Agro-ecological Zones (GAEZ)



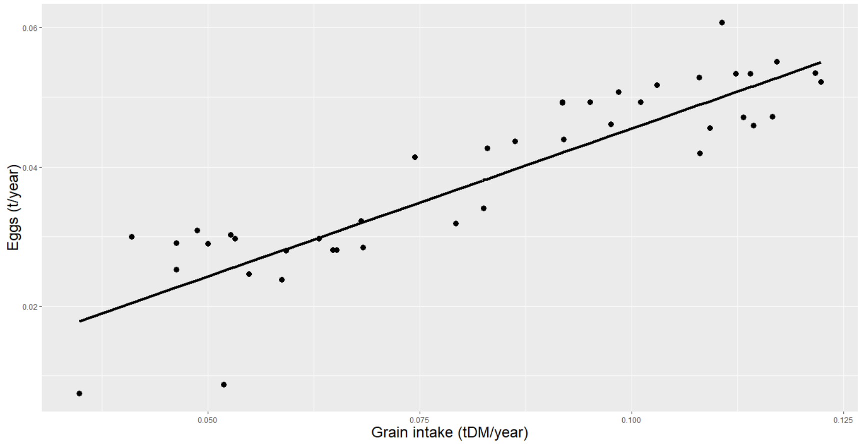
b. Relation between emission intensity and concentrate intake per Global Agro-ecological Zones (GAEZ)



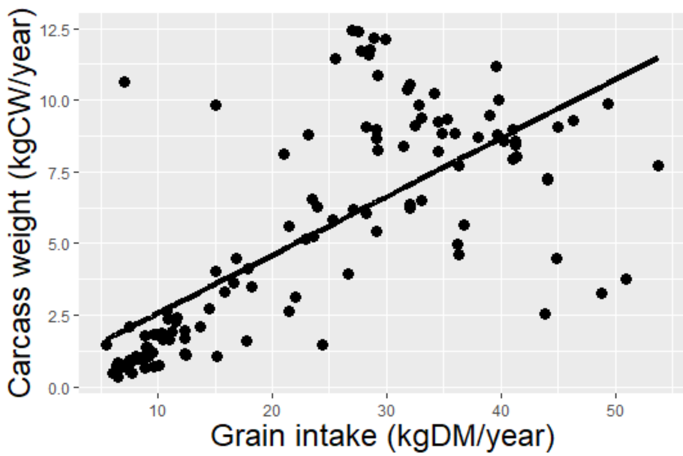


c. Relation between carcass yield of non-dairy cattle and total intake per Global Agro-ecological Zones (GAEZ)

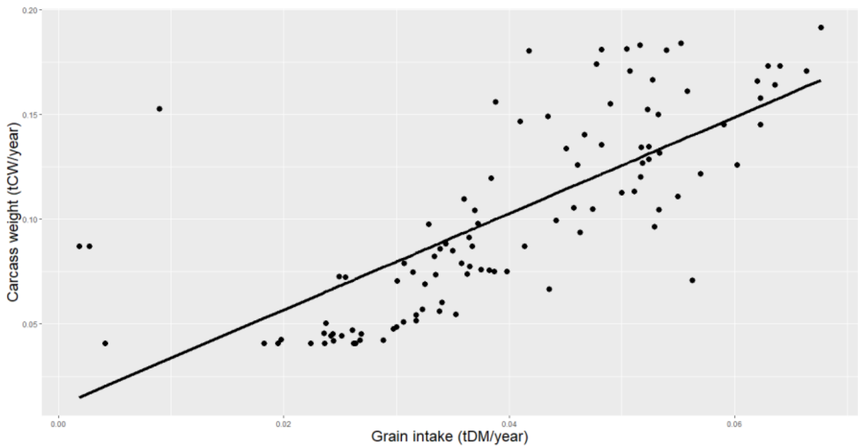
d. Relation between emission intensity of non-dairy cattle and total intake per Global Agro-ecological Zones (GAEZ)



e. Relation between eggs yield of chicken and grain intake



f. Relation between carcass yield of chicken and grain intake



g. Relation between carcass yield of pig and grain intake

Fig S2.1: Relation between yields and intakes for different cohort based on GLEAM.

To define the intensification level of the ‘improved’ pathway, we take:

For dairy cattle, the maximum milk yield for dairy cattle and the corresponding emission intensity. The choice of this efficiency level is based on the concave shape of the intensification function.

For non-dairy livestock, poultry and pigs, the meat yield and emission intensity of the country with a meat yield matching the 9th decile of meat yields within the same GAEZ. The choice of the 9th decile is due to the linear relationship between carcass yield and intake. We do not take the highest yield, as it may correspond to a yield that is too high and unsustainable.

S2.2. Production levels

Table S2.2.1 Size and CH_4 emissions in 2010 for CH_4-intensive food production systems in Brazil, France, India and Ireland based on FAOSTAT (2015) data.

Food system	Emission source/Activity	Brazil	France	India	Ireland
Cattle	Number (M heads)	209.5	19.6	194.2	6.6
	Enteric fermentation (ktCH_4)	12101	1338	6568	440.4
	Manure management	209.5	185.9	516	55.7
Sheep and goats	Number (M heads)	26.7	9.4	205.1	4.8
	Enteric fermentation (ktCH_4)	133.5	70.9	1025	38.0
	Manure management (ktCH_4)	4.2	1.7	35.2	0.9
Pigs	Number (M heads)	39	14.3	10.6	1.5
	Manure management	40.0	90.8	55.0	9.5
Poultry	Number (M heads)	1270	281	588	15.8
	Manure management (ktCH_4)	25	16.5	13.8	1.1
Rice	Harvested area (kha)	2723	24	42862	0
	Rice cultivation (ktCH_4)	176.9	12	4524	0

Table S2.2.2: Production unit (PU) for animal products (number of head).

		UP 2010	Production Unit											
			GDP			Grand-parenting			Population			Protein		
			Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI
Brazil	Cattle, dairy	2.29E+07	2.04E+07	2.11E+07	2.57E+07	1.54E+07	1.59E+07	1.94E+07	4.38E+06	4.52E+06	5.52E+06	6.13E+06	6.33E+06	7.73E+06
	Cattle, non-dairy	1,87E+08	1,66E+08	1,73E+08	1,25E+08	1,25E+08	1,31E+08	9.42E+07	3.56E+07	3.72E+07	2.67E+07	4.99E+07	5.21E+07	3.75E+07
	Chickens, layers	2,85E+08	2,54E+08	2,54E+08	2,54E+08	1,92E+08	1,92E+08	1,92E+08	5.44E+07	5.44E+07	5.44E+07	7.62E+07	7.62E+07	7.62E+07
	Poultry Birds	1,27E+09	1,13E+09	1,13E+09	5,08E+08	8,54E+08	8,54E+08	3,84E+08	2,42E+08	2,42E+08	1,09E+08	3,4E+08	3,4E+08	1,53E+08
	Sheep and Goats	2.67E+07	2.38E+07	2.38E+07	2.38E+07	1.79E+07	1.79E+07	1.79E+07	5.10E+06	5.10E+06	5.10E+06	7.14E+06	7.14E+06	7.14E+06
	Swine	3.90E+07	3.47E+07	3.47E+07	2.12E+07	2.62E+07	2.62E+07	1.60E+07	7.44E+06	7.44E+06	4.55E+06	1.04E+07	1.04E+07	6.38E+06
France	Cattle, dairy	3.72E+06	961926,2	1.14E+06	1.08E+06	2.50E+06	2.96E+06	2.81E+06	1.81E+06	2.14E+06	2.03E+06	2.56E+06	3.03E+06	2.88E+06
	Cattle, non-dairy	1.58E+07	4.10E+06	5.42E+06	4.68E+06	1.06E+07	1.41E+07	1.22E+07	7.71E+06	1.02E+07	8.81E+06	1.09E+07	1.44E+07	1.25E+07
	Chickens, layers	5.65E+07	1.46E+07	1.46E+07	1.46E+07	3.80E+07	3.80E+07	3.80E+07	2.75E+07	2.75E+07	2.75E+07	3.89E+07	3.90E+07	3.90E+07
	Poultry Birds	2,82E+08	7.30E+07	7.30E+07	4.41E+07	1,9E+08	1,9E+08	1,15E+08	1,37E+08	1,37E+08	8.29E+07	1,94E+08	1,95E+08	1,18E+08
	Sheep and Goats	9.40E+06	2.43E+06	2.43E+06	2.43E+06	6.32E+06	6.32E+06	6.32E+06	4.57E+06	4.57E+06	4.57E+06	6.48E+06	6.48E+06	6.48E+06
	Swine	1.43E+07	3.70E+06	3.70E+06	3.70E+06	9.61E+06	9.61E+06	9.61E+06	6.95E+06	6.95E+06	6.95E+06	9.85E+06	9.85E+06	9.85E+06
India	Cattle, dairy	4.28E+07	4.03E+07	6.40E+07	6.49E+07	2.87E+07	4.57E+07	4.63E+07	3.58E+07	5.69E+07	5.77E+07	1.97E+07	3.12E+07	3.17E+07
	Cattle, non-dairy	1,51E+08	1,43E+08	3,52E+08	1,19E+08	1,02E+08	2,51E+08	8.49E+07	1,27E+08	3,13E+08	1,06E+08	6.97E+07	1,72E+08	5.81E+07
	Chickens, layers	3,04E+08	2,86E+08	2,86E+08	2,86E+08	2,04E+08	2,04E+08	2,04E+08	2,54E+08	2,54E+08	2,54E+08	1,4E+08	1,4E+08	1,4E+08
	Poultry Birds	6,89E+08	6,49E+08	6,49E+08	1,7E+08	4,63E+08	4,63E+08	1,21E+08	5,77E+08	5,77E+08	1,51E+08	3,17E+08	3,17E+08	8.29E+07

	Sheep and Goats	2,05E+08	1,93E+08	2,19E+08	2,19E+08	1,38E+08	1,57E+08	1,57E+08	1,72E+08	1,95E+08	1,95E+08	9.44E+07	1,07E+08	1,07E+08
	Swine	1.06E+07	1.00E+07	1.00E+07	3.73E+06	7.15E+06	7.15E+06	2.66E+06	8.91E+06	8.91E+06	3.31E+06	4.90E+06	4.90E+06	1.82E+06
Ireland	**Cattle, dairy**	1.07E+06	780878,4	9.48E+05	942056,4	7.20E+05	8.74E+05	868612,3	116540,9	1.42E+05	140595,6	444725,2	540134,1	536519,1
	Cattle, non-dairy	5.54E+06	4.04E+06	4.15E+06	3.96E+06	3.72E+06	3.83E+06	3.65E+06	602490,7	6.20E+05	591099,5	2.30E+06	2.37E+06	2.26E+06
	Chickens, layers	3.80E+06	2.77E+06	2.81E+06	2.81E+06	2.56E+06	2.59E+06	2.59E+06	413574,3	419079,4	419079,4	1.58E+06	1.60E+06	1.60E+06
	Poultry Birds	1.58E+07	1.15E+07	1.17E+07	6.05E+06	1.06E+07	1.08E+07	5.58E+06	1.71E+06	1.75E+06	903044,7	6.54E+06	6.67E+06	3.45E+06
	Sheep and Goats	4.76E+06	3.47E+06	3.47E+06	3.47E+06	3.20E+06	3.20E+06	3.20E+06	5.18E+05	518009,6	518009,6	1.98E+06	1.98E+06	1.98E+06
	Swine	1.52E+06	1.11E+06	1.12E+06	1.12E+06	1.02E+06	1.03E+06	1.03E+06	1.65E+05	166631,3	166631,3	629750,4	635872,2	635872,2

S2.3. Mitigation potentials

Table S2.3: Mitigation measure extracted from MACC curves of Ireland, Brazil, France and India (Lanigan and Donnellan 2018; Moraes et al. 2012b; Pellerin et al. 2017; Sapkota et al. 2019) **used to compute CH_4 and N_2O intensity**

Country	Emission	Measure	Indicator	Unit	Mitigation potential	Production change	gas	Item
India	enteric	Molasses Urea Product (MUP) for large ruminants	share	-	0.11	0	CH4	Cattle, dairy
India	enteric	Increased concentrate feeding for large ruminants	share	-	0.15	0	CH4	Cattle
India	enteric	Monensin pre-mix for large ruminants	share	-	0.22	0	CH4	Cattle, dairy
India	enteric	Green fodder supplement for large ruminants	mitigation per head	tCH_4/head	0.0094	0	CH4	Cattle
India	enteric	Improved diet management for small ruminants	mitigation per head	tCH_4/head	0.00062	0	CH4	Sheep and Goats

India	manure	High fiber diet for pigs	mitigation per head	tN2O/head	0.0004	0	N2O	Swine
India	rice	Improved water management in rice	mitigation per ha	tCH_4/head	0.081	0	CH4	Rice
India	manure	Improved Manure management	mitigation per head	tCO2e/head	0.03063	0	both	Cattle
India	fertilizer	Fertilizer consumption	mitigation per ha	tN2O/head	0.00066	0	N2O	Synthetic Nitrogen fertilizers
India	fertilizer	Nitrogen Use Efficiency (NUE)	mitigation per ha	tN2O/ha	0.017	0	N2O	Synthetic Nitrogen fertilizers
India	fertilizer	Laser land levelling	share	-	0.28	0	N2O	Synthetic Nitrogen fertilizers
Brazil	rice	Improved water management in rice	share	-	0.5	0	CH4	Rice
Brazil	enteric	Increased concentrate feeding for large ruminants	mitigation	tCH4	196429	0	CH4	Cattle
Brazil	enteric	Additives in ration	mitigation	tCH4	125000	0	CH4	Cattle
Brazil	enteric	Breeding	mitigation	tCH4	171429	0	CH4	Cattle
Brazil	manure	manure management	mitigation	tCO2e	16778	0	both	Cattle
Ireland	enteric	Improved live weight gain	mitigation	tCH4	1794	0	CH4	Cattle, non-dairy
Ireland	enteric	Improvement of beef maternal replacement index (MRI)	mitigation	tCH4	744	1.1	CH4	Cattle, non-dairy
Ireland	enteric	Improvement of dairy economic breeding index	mitigation	tCH4	12647	1.15	CH4	Cattle, dairy
Ireland	enteric	Extended grazing	mitigation	tCH4	2823	0	CH4	Cattle
Ireland	enteric	Animal health	mitigation	tCH4	4323	0	CH4	Cattle
Ireland	enteric	Sexed semen	mitigation	tCH4	714	0	CH4	Cattle
Ireland	enteric	Fatty acids	share	-	0.103	0	CH4	Cattle, dairy
Ireland	rice	Rice management	share	-	0.5	0	CH4	Rice

Ireland	manure	Slurry amendments	mitigation	tCO2e	27000	0	both	Cattle, dairy
Ireland	manure	Low emission slurry spreading	mitigation	tCO2e	117000	0	both	All animals
Ireland	manure	Crude proteins in pig diet	mitigation	tN2O	169	0	N2O	Swine
Ireland	manure	Improved manure management	mitigation	tCO2e	4900	0	both	All animals
Ireland	fertilizer	Clover	mitigation	tN2O	231	0	N2O	Synthetic Nitrogen fertilizers
Ireland	fertilizer	Nitrogen Use Efficiency (NUE)	mitigation	tN2O	375	0	N2O	Synthetic Nitrogen fertilizers
Ireland	fertilizer	Fertiliser type	mitigation	tN2O	1748	0	N2O	Synthetic Nitrogen fertilizers
Ireland	fertilizer	Mineral soil drainage	mitigation	tN2O	661	0	N2O	Synthetic Nitrogen fertilizers
France	rice	Improved rice management	share	-	0.5	0	CH4	Rice
France	enteric	Additives in feed	mitigation	tCH4	212800	0	CH4	Cattle
France	fertilizer	Adjusting fertilizer application	mitigation	tN2O	2.8	0	N2O	Synthetic Nitrogen fertilizers
France	manure	Use of organic fertilizer	mitigation	tN2O	6.3	0	N2O	All animals
France	fertilizer	Adjusting application date	mitigation	tN2O	1.4	0	N2O	Synthetic Nitrogen fertilizers
France	fertilizer	Nitrification inhibitor	mitigation	tN2O	2.0	0	N2O	Synthetic Nitrogen fertilizers
France	fertilizer	Incorporate fertiliser in the soil	mitigation	tN2O	1.9	0	N2O	Synthetic Nitrogen fertilizers

France	fertilizer	Incorporate grain legumes	mitigation	tN2O	3.0	0	N2O	Synthetic Nitrogen fertilizers
France	fertilizer	Incorporate legumes in temp grassland	mitigation	tN2O	1.6	0	N2O	Synthetic Nitrogen fertilizers
France	enteric	Extend the grazing period	mitigation	tCO2e	0.7	0	both	Cattle
France	fertilizer	Intensive permanent and temporary grassland less intensive	mitigation	tN2O	1.7	0	N2O	Synthetic Nitrogen fertilizers
France	enteric	Carbohydrates by unsaturated fats in diets	mitigation	tCH4	55	0	CH4	Cattle
France	enteric	Incorporate an additive (nitrate based)	share	tCH4	0.1	0	CH4	Cattle
France	manure	Reduce the nitrogen content in the diet of dairy cows	mitigation	tN2O	0.7	0	N2O	Cattle, dairy
France	manure	Reduce the nitrogen content in the diet of pigs and sows	mitigation	tN2O	0.7	0	N2O	Swine
France	manure	Extend methanisation	mitigation	tCO2e	5780	0	both	All animals
France	manure	Cover storage tanks and install flares	mitigation	tCH4	100	0	CH4	All animals

S2.4. Land area requirements & land sparing

Table S2.4: Average national grass and feed yield per country

	France	Ireland	Brazil	India
Average national grass yield (tDM/ha)	3.2	3.4	2.5	35.7
Average national feed yield (tDM/ha)	6.0	6.5	5.8	7.3
Average yield of imported feed (tDM/ha)	2.8	3.1	4.6	5.1

Table S2.5: Forest growth rate for afforestation in the different biomes (boreal, temperate and tropical) and for different forest use (plantation or natural)

	Natural Forest Growth Rate (MgC $ha^{-1}yr^{-1}$)	Plantation Forest Growth Rate (MgC $ha^{-1}yr^{-1}$)	Percent of regrowth allocated to plantations	Average Forest Growth Rate (MgC $ha^{-1}yr^{-1}$)	Literature Sources
Boreal	0	0	0	0	(Li et al. 2015)
Temperate	2.0	5.8	22%	2.8	(IPCC, Penman, and IPPC National Greenhouse Gas Inventories Programme 2003; Powers et al. 2011; Richards and Stokes 2004)
Tropical	4.8	6.2	4%	4.86	(Bonner, Schmidt, and Shoo 2013)

Table S2.6: Emission factor (tCO2/ha/year) of national deforestation computed based on FAOSTAT data.

	France	Ireland	Brazil	India
Emission factor (tCO_2/ha/year)	13.9	10.8	21.8	23.8

Table S2.7: Computation of the average deforestation rate at the agricultural margin

	Agricultural expansion 2008-2017 (M ha)	Lost habitat	Soil organic C loss (kg ha^{-1} yr^{-1})	Soil N mineralisation (kg ha^{-1} yr^{-1})	Biomass C loss (kg ha^{-1} yr^{-1})	Global warming potential (kg CO_2e ha^{-1} yr^{-1})
Indonesia	8.3	Tropical rain forest	1222	82	11378	385956
Kazakhstan	6.14	Temperate grassland	977	65	90	25485
Democratic Republic of the Congo	5.8	Tropical dry forest	987	66	4710	122560
Brazil	5.7	Tropical moist forest	1222	82	6570	164567
Argentina	4.44	Temperate grassland	977	65	90	18429
Weighted mean (per hectare)			**1092**	**73**	**5272**	**23601**

S2.5. Reference biogenic methane emissions for eGWP*

Table S2.8: Equations used to calculate target and reference level CH_4 emissions across different allocation methods. CH_4 reference emisisons are presented in the Table S2.9.

	${CH_4^i}_{2050}$	${CH_4^i}_{ref}$
Equal-per-capita allocation of national CH_4 quota and reference level of CH_4 for the country i	${CH_4^i}_{2050} = \frac{Pop_i^{2010}}{Pop_w^{2010}} \times \alpha_E^{world} \times {CH_4^{world}}_{2010}$	${CH_4^i}_{ref} = \frac{Pop_i^{2010}}{Pop_w^{2010}} \times {CH_4^{world}}_{2010}$
Equal-per-protein produced allocation of national CH_4 quota and reference level of CH_4 for the country i	${CH_4^i}_{2050} = \frac{Prot_i^{2010}}{Prot_w^{2010}} \times \alpha_E^{world} \times {CH_4^{world}}_{2010}$	${CH_4^i}_{ref} = \frac{Prot_i^{2010}}{Prot_w^{2010}} \times {CH_4^{world}}_{2010}$
GDP based allocation of national CH_4 quota and a zero-CH_4 reference level for the country i	${CH_4^i}_{2050} = \frac{GDP_i^{2010}}{GDP_w^{2010}} \times {CH_4^{world}}_{2010} \times \left(\alpha_E^{world} - 1\right) + {CH_4^i}_{2010}$	${CH_4^i}_{ref} = {CH_4^i}_{2010} + Debt_{1961-2010}^{CH_4^i}$
Grand-parenting allocation of national CH_4 quota and a zero-CH_4 reference level for the country i	${CH_4^i}_{2050} = \frac{{CH_4^i}_{2010}}{{CH_4^{world}}_{2010}} \times {CH_4^{world}}_{2010} \times \left(\alpha_E^{world} - 1\right)$	${CH_4^i}_{ref} = {CH_4^i}_{2010}$

Table S2.9: Methane reference used in eGWP* for different fairness approach per country

Rule used for the reference year	Indicator for the reference methane level	Ireland	France	India	Brazil
Grand Fathering/GDP	Methane emissions in 2010 (tCH_4)	550610	1755995	19369452	13472652
Equal-per-capita	Equal methane emissions per capita in 2010 (tCH_4)	28420	405267	7692337	1219734
Equal-per-protein	Equal methane emissions per protein produced in 2010 (tCH_4)	108452	574219	4227436	1708726

S2.5. Supplementary results

Table S2.10. Production in 2010 and 2050 under different biogenic methane allocation rules

		Production in 2010 (Mt)	Production in 2050 (Mt)											
			GDP			Grand-parenting			Population			Protein		
			2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base
Brazil	**Eggs**	2.1	1.9	2.8	1.9	1.4	2.1	1.4	0.4	0.6	0.4	0.6	0.8	0.6
	Milk	3.4	3.1	5.6	3	2.4	4.3	2.3	0.7	1.2	0.6	0.9	1.7	0.9
	Monogastric Meat	14.4	12.8	12.2	12.8	9.7	9.2	9.7	2.7	2.6	2.7	3.8	3.7	3.8
	Rice	11.2	20	20	10	15.1	15.1	7.6	4.3	4.3	2.1	6	6	3
	Ruminant Meat	9.2	8.5	8.1	8.2	6.5	6.2	6.2	1.8	1.7	1.8	2.6	2.4	2.5
France	**Eggs**	0.9	0.2	0.2	0.2	0.6	0.6	0.6	0.5	0.5	0.5	0.7	0.7	0.7
	Milk	4.6	1.3	2.3	1.2	3.7	6.4	3.1	2.6	4.6	2.2	3.8	6.6	3.2
	Monogastric Meat	4	1	1	1	2.7	2.7	2.7	2	1.9	2	2.8	2.7	2.8
	Rice	0.1	0.1	0.1	0	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.1
	Ruminant Meat	1.7	0.5	0.5	0.4	1.4	1.4	1.1	1	1	0.8	1.5	1.4	1.1
India	**Eggs**	3.4	3.3	3.8	3.2	2.3	2.9	2.3	2.8	3.3	2.8	1.6	2	1.6
	Milk	26.9	33.4	48.2	25.3	26.4	41.4	18.1	30	45.1	22.5	19.4	31.8	12.4
	Monogastric Meat	2.6	2.5	2.5	2.4	1.8	1.8	1.7	2.2	2.1	2.2	1.2	1.2	1.2
	Rice	144	260.1	269.3	135.6	298.9	306.4	96.8	282.2	291.2	120.6	263.8	266.8	66.3
	Ruminant Meat	3.3	4.8	5.3	3.1	4	4.5	2.2	4.4	4.9	2.8	3	3.4	1.5
Ireland	**Eggs**	0	0	0	0	0	0	0	0	0	0	0	0	0
	Milk	0.9	0.9	1.3	0.6	0.8	1.2	0.6	0.1	0.2	0.1	0.5	0.7	0.4
	Monogastric Meat	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0	0.1	0.1	0.1
	Rice	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ruminant Meat	0.6	0.5	0.5	0.4	0.5	0.5	0.4	0.1	0.1	0.1	0.3	0.3	0.3

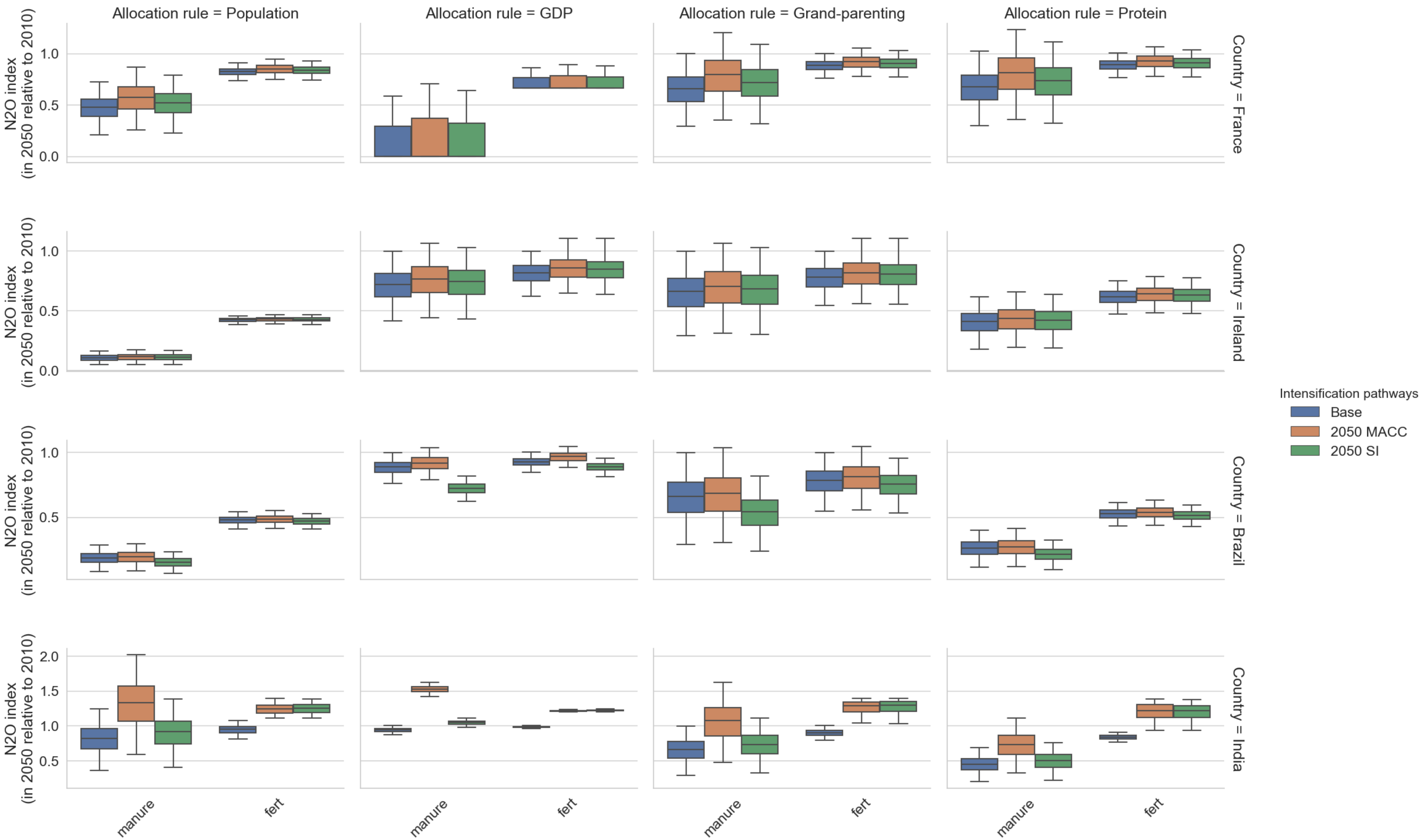


Figure S2.1. Impact of national biogenic CH_4 quota on N_2O emissions

Table S2.11. Areas required for agricultural production in 2010 and 2050 under different biogenic methane allocation rules

		Area in 2010 (Mha)	Area in 2050 (Mha)											
			GDP			Grand-parenting			Population			Protein		
			Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI
Brazil	**Feed**	16.7	15.1	16.1	14.8	11.4	12.2	11.2	3.2	3.5	3.2	4.5	4.8	4.5
	Grass	169.9	157.3	126.4	151.2	118.9	95.5	114.2	33.8	27.1	32.4	47.3	38	45.4
	Rice	2.7	4.8	4.8	2.4	3.7	3.7	1.8	1	1	0.5	1.5	1.5	0.7
	Total	**231.5**	**219.5**	**189.6**	**210.6**	**176.2**	**153.5**	**169.5**	**80.2**	**73.8**	**78.3**	**95.5**	**86.5**	**92.8**
France	**Feed**	3.6	0.9	0.9	0.9	2.5	2.5	2.4	1.8	1.8	1.7	2.6	2.5	2.5
	Grass	13.1	4	3.6	3.3	11	9.9	8.8	8	7.2	6.4	11.3	10.2	9
	Rice	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**32.4**	**20.6**	**20.3**	**19.9**	**29.3**	**28.1**	**26.9**	**25.5**	**24.7**	**23.8**	**29.6**	**28.4**	**27.2**
India	**Feed**	4.4	4.5	4.8	4.1	3.3	3.6	3	3.9	4.2	3.7	2.3	2.6	2
	Grass	10.3	15.5	10.1	9.7	13	7.1	7	14.3	8.6	8.7	9.9	4.8	4.8
	Rice	42.9	107.4	112.5	40.4	100	103.1	28.8	104.3	108.6	35.9	80.8	81.9	19.7
	Total	**179.6**	**249.4**	**249.4**	**176.2**	**238.3**	**235.8**	**160.7**	**244.5**	**243.4**	**170.2**	**214.9**	**211.2**	**148.5**
Ireland	**Feed**	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0	0.1	0.1	0.1
	Grass	4.2	3.3	3.2	3.1	3	3	2.8	0.5	0.5	0.5	1.9	1.8	1.8
	Rice	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**5.2**	**4.3**	**4.2**	**4**	**4**	**3.9**	**3.8**	**1.4**	**1.4**	**1.3**	**2.8**	**2.8**	**2.7**

Table S2.12. CO_2 offset ($MtCO_2$) due to land-sparing following national emission reduction of methane

		CO_2 offset ($MtCO_2$)											
		GDP			Grand-parenting			Population			Protein		
		Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI	Base	2050 MACC	2050 SI
Brazil	Feed	29.9	10.4	35.5	101.4	86.7	105.7	260.9	256.8	262.1	235.6	229.9	237.3
	Grass	238.7	843.2	360.9	982.3	1440.5	1074.6	2639.3	2768.1	2665	2376.9	2557.4	2412.9
	Rice	-50.5	-50.5	5.8	-22.8	-22.8	17.2	32.7	32.7	42.8	24.6	24.6	38.8
	Total	218.1	803.1	402.2	1060.9	1504.4	1197.5	2932.9	3057.6	2969.9	2637.2	2811.9	2689
France	Feed	28.8	28.7	28.6	11.9	12.3	13	19.8	20.1	20.6	11.1	11.6	12.3
	Grass	95.7	100	104.4	20.8	34	47.5	56.7	65.7	75	17.4	31	44.9
	Rice	0.1	0.1	0.2	-0.2	-0.2	0.1	0	0	0.1	-0.2	-0.2	0.1
	Total	124.6	128.9	133.2	32.4	46.1	60.6	76.4	85.7	95.8	28.2	42.3	57.3
India	Feed	-3	-10.5	4.9	21	14.9	27.8	8.6	2	12.8	40.8	35.8	46.2
	Grass	-128.1	6.4	11.4	-78.3	62.1	64.6	-120.1	33.5	29.8	0.7	105.2	107.2
	Rice	-1533	-1654.2	48	-1358.1	-1432.5	270.9	-1460.9	-1562.6	124.9	-902.1	-928.2	449.8
	Total	-1664	-1658.3	64.4	-1415.3	-1355.5	363.3	-1572.4	-1527.1	167.6	-860.6	-787.2	603.2
Ireland	Feed	0.3	0.4	0.5	0.5	0.5	0.6	1.5	1.5	1.6	1	1	1
	Grass	9.9	11	12.7	12.9	13.9	15.5	41.6	41.8	42.1	25.9	26.5	27.6
	Rice	0	0	0	0	0	0	0	0	0	0	0	0
	Total	10.2	11.3	13.2	13.4	14.3	16.1	43.2	43.3	43.6	26.8	27.5	28.6

Table S2.13. Emissions of individual greenhouse gases from the AFOLU sector in 2050 under different biogenic CH_4 accounting rules

		GWP (tCO2eq)			
		GDP	**Grand-parenting**	**Population**	**Protein**
Brazil	**GWP_{100}**	1.16E+08	-8.10E+08	-2.90E+09	-2.50E+09
	eGWP*	3.43E+08	-1.50E+09	-2.70E+09	-2.40E+09
France	**GWP_{100}**	-1.00E+08	2.17E+07	-3.40E+07	2.69E+07
	eGWP*	-5.40E+08	-6.70E+07	8.36E+06	8.66E+07
India	**GWP_{100}**	1.82E+09	1.44E+09	1.66E+09	8.88E+08
	eGWP*	2.13E+09	2.56E+08	1.82E+09	1.16E+09
Ireland	**GWP_{100}**	7.18E+06	2.73E+06	-4.00E+07	-1.60E+07
	eGWP*	-1.20E+07	-2.60E+07	-3.70E+07	-4.78E+06

Table S2.14: Kruskal Wallis test of difference between the median of each biogenic methane allocation

			H	Pvalue	Significant
Brazil	**Grand-parenting**	**carbon**	352,3869	0.0001	Significant differences
		yield	249,4182	< 0.0001	Significant differences
		mitigation	257,9231	< 0.0001	Significant differences
	Population	**carbon**	65,9437	1	No Significant differences
		yield	250,0378	< 0.0001	Significant differences
		mitigation	257,6074	< 0.0001	Significant differences
	Protein	**carbon**	113,2859	0,9129	No Significant differences
		yield	249,6507	< 0.0001	Significant differences
		mitigation	257,7658	< 0.0001	Significant differences
	GDP	**carbon**	364,5017	< 0.0001	Significant differences
		yield	153,0453	0,1372	No Significant differences
		mitigation	211,977	< 0.0001	Significant differences
France	**Grand-parenting**	**carbon**	394,2738	< 0.0001	Significant differences
		yield	256,4017	< 0.0001	Significant differences
		mitigation	268,04	< 0.0001	Significant differences
	Population	**carbon**	350,0661	< 0.0001	Significant differences
		yield	257,8146	< 0.0001	Significant differences
		mitigation	267,9306	< 0.0001	Significant differences
	Protein	**carbon**	396,0136	< 0.0001	Significant differences
		yield	256,3666	< 0.0001	Significant differences
		mitigation	268,0448	< 0.0001	Significant differences
	GDP	**carbon**	284,7399	< 0.0001	Significant differences
		yield	259,412	< 0.0001	Significant differences
		mitigation	269,0999	< 0.0001	Significant differences
India	**Grand-parenting**	**carbon**	403,128	< 0.0001	Significant differences
		yield	270,7603	< 0.0001	Significant differences

		mitigation	183,4276	0,0035	Significant differences
	Population	**carbon**	405,1091	< 0.0001	Significant differences
		yield	270,0669	< 0.0001	Significant differences
		mitigation	189,2459	0,0014	Significant differences
	Protein	**carbon**	393,4633	< 0.0001	Significant differences
		yield	270,935	< 0.0001	Significant differences
		mitigation	181,5444	0,0047	Significant differences
	GDP	**carbon**	402,2736	< 0.0001	Significant differences
		yield	266,3075	< 0.0001	Significant differences
		mitigation	204,2129	0,0001	Significant differences
Ireland	**Grand-parenting**	**carbon**	379,3976	< 0.0001	Significant differences
		yield	256,4491	< 0.0001	Significant differences
		mitigation	261,3116	< 0.0001	Significant differences
	Population	**carbon**	50,8465	1	No Significant differences
		yield	260,9418	< 0.0001	Significant differences
		mitigation	259,3507	< 0.0001	Significant differences
	Protein	**carbon**	288,2987	< 0.0001	Significant differences
		yield	256,812	< 0.0001	Significant differences
		mitigation	261,3411	< 0.0001	Significant differences
	GDP	**carbon**	380,0885	< 0.0001	Significant differences
		yield	247,2089	< 0.0001	Significant differences
		mitigation	254,9508	< 0.0001	Significant differences

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