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National contributions to climate change mitigation from agriculture: allocating a global target

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ABSTRACT

Globally, agriculture and related land use change contributed about 17% of the world's anthropogenic GHG emissions in 2010 (8.4 GtCO₂e yr⁻¹), making GHG mitigation in the agriculture sector critical to meeting the Paris Agreement's 2°C goal. This article proposes a range of country-level targets for mitigation of agricultural emissions by allocating a global target according to five approaches to effort-sharing for climate change mitigation: responsibility, capability, equality, responsibility-capability-need and equal cumulative per capita emissions. Allocating mitigation targets according to responsibility for total historical emissions or capability to mitigate assigned large targets for agricultural emission reductions to North America, Europe and China. Targets based on responsibility for historical *agricultural* emissions resulted in a relatively even distribution of targets among countries and regions. Meanwhile, targets based on equal future agricultural emissions per capita or equal per capita cumulative emissions assigned very large mitigation targets to countries with large agricultural economies, while allowing some densely populated countries to increase agricultural emissions. There is no single 'correct' framework for allocating a global mitigation goal. Instead, using these approaches as a set provides a transparent, scientific basis for countries to inform and help assess the significance of their commitments to reducing emissions from the agriculture sector.

Key policy insights

- Meeting the Paris Agreement 2°C goal will require global mitigation of agricultural non-CO₂ emissions of approximately 1 GtCO₂e yr⁻¹ by 2030.
- Allocating this 1 GtCO₂e yr⁻¹ according to various effort-sharing approaches, it is found that countries will need to mitigate agricultural business-as-usual emissions in 2030 by a median of 10%. Targets vary widely with criteria used for allocation.
- The targets calculated here are in line with the ambition of the few countries (primarily in Africa) that included mitigation targets for the agriculture sector in their (Intended) Nationally Determined Contributions.
- For agriculture to contribute to meeting the 2°C or 1.5°C targets, countries will need to be ambitious in pursuing emission reductions. Technology development and transfer will be particularly important.

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1. Introduction

The 2015 Paris Agreement on climate change for the first time commits nearly every country on the globe to lowering GHG emissions in order to keep global mean temperature increase well below 2°C in 2100, and possibly even below 1.5°C. Agricultural GHG emissions are highly relevant for meeting the Paris Agreement. Globally, agriculture and related land use change contributed about 17% of the world's anthropogenic GHG emissions in 2010 (8.4 GtCO₂e yr⁻¹) (Edenhofer et al., 2014), as CO₂, methane (CH₄) and nitrous oxide (N₂O). Agriculture alone contributes an average of 18% of the net GHG emissions of the large emerging economies (BRICS – Brazil, Russia, India, China and South Africa). Moreover, most scenarios consistent with the Paris Agreement show non-CO₂ emissions from agriculture comprising over 75% of remaining emissions by 2100 (Gernaat et al., 2015), because CO₂ emissions are projected to decline to zero. The implication is that, to have a chance of meeting the 1.5°C target, countries will need to tackle agricultural emissions. The alternative would be to rely even more heavily on negative emissions technologies – which may be risky (Anderson & Peters, 2016; Larkin, Kuriakose, Sharmina, & Anderson, 2017).

Despite its critical role in future emissions, action to reduce emissions from the agriculture sector has lagged behind other sectors. Policy and technology options for reducing agricultural GHG emission sources are currently poorly understood (Gernaat et al., 2015) and climate finance for mitigation of agricultural emissions is a fraction of that for other sectors (Buchner et al., 2017). Negotiations on agriculture under the UN Framework Convention on Climate Change (UNFCCC) have historically failed to make headway, but a recent decision to have the Subsidiary Body for Science and Technological Advice (SBSTA) and the Subsidiary Body for Implementation (SBI) review issues associated with agriculture in future negotiations may be an indication that countries are ready for more concerted action in this sector.

Since the adoption of the UNFCCC in 1992, many studies have proposed emissions allowances or reduction targets among countries based on 'effort-sharing' or 'burden-sharing' approaches. More recent studies have calculated allocations consistent with the Paris Agreement goals of a 2°C or 1.5°C warming scenario (Holz, Kartha, & Athanasiou, 2017; Meinshausen et al., 2015; Pan, den Elzen, Höhne, Teng, & Wang, 2017; du Pont et al., 2017) and thereby gauged the ambition of countries' Nationally Determined Contributions (NDCs).

This article proposes a range of country-level targets for mitigation of non-CO₂ emissions from the agricultural sector by applying the principles of effort-sharing, and using a global target for agricultural mitigation based on agriculture's necessary contribution in order to limit warming to 2°C as predicted by global integrated assessment models (Wollenberg et al., 2016). It further compares these normatively derived mitigation targets against countries' planned emission reductions in the agriculture sector, to the extent that countries have communicated such reductions in their NDCs. Most integrated assessment models focus only on non-CO₂ emissions from agriculture due to high variability in soil carbon, lack of data on carbon in on-farm biomass, and the reversibility of carbon sequestration (Powlson, Whitmore, & Goulding, 2011; Wollenberg et al., 2016). This analysis was therefore limited to non-CO₂ emissions from agriculture.

Although other recent studies have assessed the NDCs against normatively derived targets (Holz et al., 2017; Meinshausen et al., 2015; Pan et al., 2017; du Pont et al., 2017), this study is the first to do so for the agriculture sector in a way consistent with a 2-degree compliant pathway. Although the Paris Agreement directs countries to undertake economy-wide emission reductions, target ranges for emission reductions in the agriculture sector can provide the basis for more ambitious mitigation actions and inform implementation of NDCs (Wollenberg et al., 2016). Most mitigation actions will necessarily take place on a sector level, and sectors may have quite different mitigation potentials depending on available technologies and emission reduction opportunities. Because of this, NDCs largely reflect a bottom-up estimation of the mitigation that a country believes it can achieve, often calculated on a per-sector basis. The sectoral contributions by country presented here provide a transparent, scientific basis for ministries of agriculture and other agriculture sector actors to gauge the ambition of mitigation actions.

2. Methods

2.1. Global mitigation goal for agriculture

Wollenberg et al. (2016) calculated the reduction of agricultural GHG emissions by 2030 needed to avoid a 2°C increase in global temperature by 2100. Practically speaking, the 2°C pathway and the 1.5°C are near identical

with regards to agricultural non-CO₂ emissions, because the entire assumed abatement potential of these emissions was already exhausted in the 2°C scenario (Rogelj et al., 2016).

Given the uncertainties in future emissions and, among others, the political choices in timing of climate policy, many different emission pathways exist that are consistent with this goal. The Intergovernmental Panel on Climate Change (IPCC), using the 2°C threshold, estimated that global GHG emissions from all sources would have to decrease from 49 GtCO₂e in 2010 to about 42 GtCO₂e in 2030, i.e. mitigation of about 7 GtCO₂e (Edenhofer et al., 2014). To calculate a similar number for the agriculture sector, Wollenberg et al. (2016) used the Representative Concentration Pathway (RCP) 2.6 scenario from three integrated assessment models: Integrated Assessment of Global Environmental Change (IMAGE) (van Vuuren et al., 2011), Global Change Assessment Model (GCAM) (Wise, Calvin, Kyle, Luckow, & Edmonds, 2014) and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (Reisinger et al., 2013).

RCP2.6 is representative of the mitigation scenarios that would limit the increase of global mean temperature to 2°C by 2100. Under RCP2.6, emissions from agriculture are limited to 6.2–7.8 GtCO₂e in 2030. This figure includes CH₄ emissions from animals, manure, rice, agricultural waste burning and grassland burning; and N₂O emissions from fertilizer, manure, biological nitrogen fixation, crop residues, agricultural waste burning and grassland burning. Baseline agricultural emissions under a ‘no mitigation’ scenario estimated using the three modelling frameworks are 7.5–9.0 GtCO₂e in 2030. Thus, agriculture’s contribution to mitigation would need to be 0.9–1.4 GtCO₂e (in 2030) to meet the 2°C target; 1 GtCO₂e was selected as an approximate target. This target assumes that countries begin reducing emissions immediately. A delay would increase the mitigation required in the longer term. See Wollenberg et al. (2016) for a full description of the methodology for calculating the global mitigation target for agriculture.

2.2. Allocation of global mitigation goal to countries

In the text of the UNFCCC, Parties agreed to take action to mitigate climate change ‘on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities’ (CBDR-RC) (UNFCCC, 1992). The Paris Agreement affirmed the principle of CBDR-RC – qualifying it with the clause ‘in light of different national circumstances’ (Article 2.2) – and eliminated the distinction between Annex I (developed) and non-Annex I (developing) countries of the original Convention.

Although there is not currently consensus under the UNFCCC on how to define a fair and ambitious mitigation contribution for each country (Pan et al., 2017; Winkler et al., 2017), numerous allocation schemes have been proposed to operationalize the principles of equity and CBDR-RC. IPCC AR5 (Fleurbaey et al., 2014), using a review of existing approaches by Höhne, den Elzen, and Escalante (2014) grouped the approaches into six categories using particular definitions of equity principles (Pan et al., 2017): responsibility, capability, equality, responsibility-capability-need, equal cumulative per capita emissions and staged approaches.

This study used nine approaches (Table 1) to calculate a range of country-level mitigation goals, covering all categories of effort sharing approaches. The regional distribution of mitigation effort under these approaches was also compared to a least-cost approach to mitigation as modelled by van Vuuren et al. (2011). The least-cost approach is an empirical approach based on global economic efficiency rather than normative considerations of fairness. All the normative approaches would also fit into the ‘staged approaches’ category according to Höhne et al. (2014) because this category also includes sectoral approaches. Data sources used in calculating each approach are summarized in Table 2.

2.2.1. Responsibility: CE1890 and CA1960

Historical emission data from the ad-hoc group on the modelling and assessment of contributions to climate change (MATCH) (Höhne et al., 2011) were used to calculate national contributions to cumulative emissions for 1890–2010 as per Equation (1). This approach is referred to as CE1890.

$$m_{CE1890}(i, t) = \left(\frac{\sum_{1890}^{2010} e_H(i, t)}{\sum_{1890}^{2010} E_H(t)} \right) \times M(t), \quad (1)$$

Table 1. Description of allocation approaches used in calculating country-level mitigation targets for agricultural emissions in 2030.

Approach	Basis for calculating country-level agricultural mitigation targets
<i>Responsibility</i>	
CE1890	Cumulative emissions from all sectors from 1890–2010, including energy (CO ₂ , N ₂ O, CH ₄), industry (CO ₂ , N ₂ O, CH ₄), waste (N ₂ O, CH ₄), agriculture (N ₂ O, CH ₄), land use change and forestry (CO ₂)
CA1960	Cumulative agricultural emissions from 1960–2010 (N ₂ O, CH ₄)
<i>Capability</i>	
CAGDP	Cumulative agricultural emissions from 1960–2010 (N ₂ O, CH ₄) and gross domestic product in 2010, weighted equally
CAHDI	Cumulative agricultural emissions from 1960–2010 (N ₂ O, CH ₄) and human development index in 2010, weighted equally
<i>Equality</i>	
EQ2030	Equal agricultural emissions per capita, with convergence by 2030
EQ2050	Equal agricultural emissions per capita, with convergence by 2050
<i>Responsibility, capability and need</i>	
RCI	Responsibility and capability index as calculated by the Climate Equity Reference Calculator (Kemp-Benedict et al., 2017)
<i>Equal cumulative per capita emissions</i>	
EPPCE2030	Equal cumulative agricultural emissions per capita 1960–2030, per Pan et al. (2014)
EPPCE2050	Equal cumulative agricultural emissions per capita 1960–2050, per Pan et al. (2014)
<i>Cost-effectiveness (for comparison)</i>	
RCP2.6	Least-cost approach, using regional marginal abatement cost curves derived for all sectors, as implemented in the IMAGE model (van Vuuren et al., 2011); used for calculating regional targets only

here $m_{CE1890}(i, t)$ is the mitigation target for country i in year t , $e_H(i, t)$ denotes the total historical GHG emissions (from all sources) of country i in year t , $E_H(t)$ denotes total global historical GHG emissions (from all sources) in year t , and $M(t)$ is the global mitigation target for agricultural emissions in year t .

Countries' cumulative contributions to agricultural emissions were calculated using estimates from the Food and Agriculture Organization Statistical Database (FAOSTAT) (Tubiello et al., 2013). This approach (CA1960, Equation (2)) is essentially a linear scaling of the mitigation target according to historical agricultural emissions.

$$m_{CA1960}(i, t) = \left(\frac{\sum_{1960}^{2010} a_{BL}(i, t)}{\sum_{1960}^{2010} A_{BL}(t)} \right) \times M(t), \quad (2)$$

$m_{CA1960}(i, t)$ is the mitigation target for country i in year t , $a_{BL}(i, t)$ denotes the baseline or historical agricultural emissions of country i in year t , and $A_{BL}(t)$ denotes total baseline or historical global agricultural emissions in year t .

2.2.2. Capability: CAGDP and CAHDI

The global mitigation goal was allocated using a capability-based burden-sharing approach by scaling a country's share of cumulative agricultural emissions 1960–2010 by two indicators of capability to mitigate: gross

Table 2. Data sources.

Data	Sources
Historical emissions (all sources)	MATCH (Höhne et al., 2011) and EDGAR (JRC/PBL, 2013; Rogelj, McCollum, & Smith, 2014)
Historical agricultural emissions	FAOSTAT (Tubiello et al., 2013)
Gross domestic product (GDP)	United Nations Statistics Division National Accounts Main Aggregates Database (UN DESA, 2016)
Human development index (HDI)	United Nations Development Programme (Klugman, 2011)
Population	World Population Division of the United Nations Department of Economic and Social Affairs (UN DESA, 2015)
Future emissions (global)	Baseline and RCP2.6 scenario emissions as implemented in the IMAGE (van Vuuren et al., 2011), GCAM (Wise et al., 2014), and MESSAGE (Reisinger et al., 2013) models
Future emissions (country)	FAOSTAT (Tubiello et al., 2013), used only for downscaling emissions estimates from RCP2.6 as implemented in integrated assessment models
Responsibility–capacity–indicator	Climate Equity Reference Calculator (Kemp-Benedict et al., 2017)

domestic product (GDP) (CAGDP, Equation (3)) and human development index (HDI) (CAHDI, Equation (4)).

$$m_{CAGDP}(i, t) = \left[0.5 \times \left(\frac{\sum_{1960}^{2010} a(i, t)}{\sum_{1960}^{2010} A_{BL}(t)} \right) + 0.5 \times \left(\frac{GDP(i)}{\sum_{i=1}^I GDP(i)} \right) \right] \times M(t), \quad (3)$$

$m_{CAGDP}(i, t)$ is the mitigation target for country i in year t and $GDP(i)$ denotes the GDP of country i in 2010.

$$m_{CAHDI}(i, t) = \left[0.5 \times \left(\frac{\sum_{1960}^{2010} a(i, t)}{\sum_{1960}^{2010} A_{BL}(t)} \right) + 0.5 \times \left(\frac{HDI_N(i)}{\sum_{i=1}^I HDI_N(i)} \right) \right] \times M(t), \quad (4)$$

$m_{CAHDI}(i, t)$ is the mitigation target for country i in year t and $HDI_N(i)$ denotes the normalized HDI of country i in 2010 (Equation (5)).

$$HDI_N(i) = \frac{(HDI(i) - HDI_{\min})}{(HDI_{\max} - HDI_{\min})}, \quad (5)$$

$HDI(i)$ denotes the HDI of country i in 2010, HDI_{\min} and HDI_{\max} denote the minimum and maximum HDI values, respectively, among all countries in 2010.

2.2.3. Equality: EQ2030 and EQ2050

In this approach, per-capita agricultural emissions converge to the same level in all countries in a pre-defined convergence year, c . Each country's allocated emissions in year c were calculated by multiplying projected country population in year c by the same global per-capita emissions allocation, calculated by dividing the global agricultural emissions under the RCP2.6 scenario by projected global population in year c (Equation (6)). Emissions allocations in intermediate years (between the starting year, s and year c) were estimated by assuming a linear decrease from baseline emissions in year s to allocated emissions in year c (Figure 1(b), Equation (7)). This approach is ambitious in terms of emission reductions; modelled agricultural emissions under the RCP2.6 scenario actually *increase* between 2010 and 2030 in some integrated assessment models, before decreasing in the latter half of the century. To calculate country *mitigation* targets, the calculated emissions allocations were subtracted from FAOSTAT emissions projections, adjusted to match RCP2.6 baseline emissions (Equation (6)).

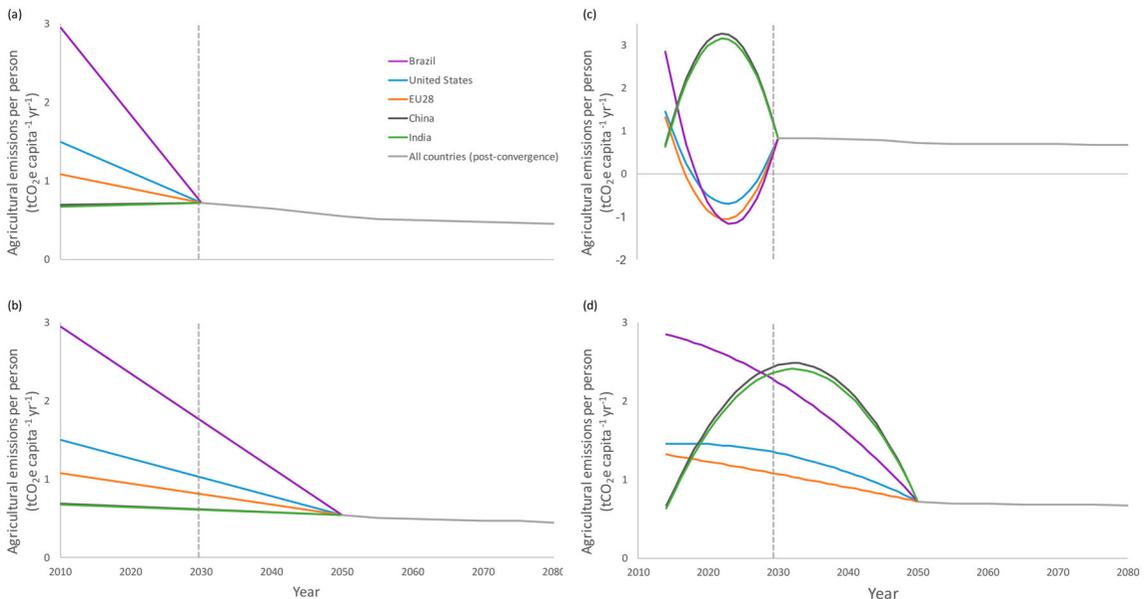


Figure 1. Schematic representation of the (a) EQ2030, (b) EQ2050, (c) EPPCE2030 and (d) EPPCE2050 approaches.

Two versions of this approach were tested: one with convergence in 2030 (EQ2030) and one with convergence in 2050 (EQ2050). Both used 2010 as a starting year.

Under a scenario that limits warming to 2 °C in 2100, RCP2.6 as implemented in the three integrated assessment models predicted agricultural non-CO₂ emissions of 6.2–7.8 GtCO₂e yr⁻¹ in 2030 and 5.3–8.4 GtCO₂e yr⁻¹ in 2050. This translates to per-capita emissions rates ranging from 0.7 to 1.0 tCO₂e person⁻¹ yr⁻¹ in 2030 and 0.5 to 1.0 tCO₂e person⁻¹ yr⁻¹ in 2050 to meet the 2°C target.

This approach is similar to a sectoral version of the contraction-and-convergence proposal (Meyer, 2000). After year *c*, all countries' emissions would continue to decline, at the same per-capita rate (Figure 1).

$$m_{EQ}(i, t) = a_{BL}(i, s) - p(i, t) \times \left(\frac{[A_{BL}(s) - A_M(t)]}{[A_{BL}(s) - A_M(c)]} \right) \times [a_{BL}(i, s) - a_M(i, c)], \quad (6)$$

$m_{EQ}(i, t)$ is the mitigation target for country *i* in year *t*, $p(i, t)$ denotes projected population of country *i* in year *t*, $A_M(t)$ and $A_M(c)$ denote global agricultural emissions under RCP2.6 for years *t* and *c*, respectively. $a_M(i, c)$ denotes the agricultural emissions allocation for country *i* in year *c* (Equation (7)).

$$a_M(i, c) = p(i, c) \times \left(\frac{A_M(c)}{\sum_{i=1}^I p(i, c)} \right). \quad (7)$$

2.2.4. Responsibility, capability and need: RCI

Shares of mitigation effort were allocated to countries using the responsibility–capacity indicator (RCI) of the Climate Equity Reference Framework (Baer, Fieldman, Athanasiou, & Kartha, 2008; Holz et al., 2017). As with CE1890, responsibility was based on cumulative emissions since 1890. Capability was based on GDP. However, unlike the CAGDP approach, the Climate Equity Reference Framework uses a progressive interpretation of GDP, exempting income below a particular per-capita income level (in terms of purchasing power parity) (Holz et al., 2017). For this analysis, the default cut-off value of PPP \$7500 was selected and capability and responsibility were weighted equally.

$$m_{RCI}(i, t) = RCI(i, t) \times M(t), \quad (8)$$

$RCI(i, t)$ denotes the Responsibility and Capacity Index for country *i* in year *t*, calculated in the Climate Equity Reference Calculator (Kemp-Benedict, Holz, Baer, Athanasiou, & Kartha, 2017) with parameters as described in Appendix S2 of the Supplemental Material.

2.2.5. Equal cumulative per capita emissions: EPPCE2030 and EPCCE2050

The equal cumulative per-capita emissions approach (EPPCE) was based on the scheme proposed by Pan, Teng, and Wang (2014). In this approach, all countries' per capita emissions converge at some future point, as in the EQ2030 and EQ2050 approaches. However, unlike the EQ2030 and EQ2050 approaches, every country's cumulative per capita emissions from some historical start year up to the convergence year must also be equal. To calculate each country's emissions trajectory, the remaining allowance for each country during the allocation interval, $\sum_{t=s}^c a_M(i, t)$, was first determined (Equation (9)). Per-capita allocations were determined by population in a single reference year, *s*.

$$\frac{\left[\sum_{t=s_0}^{s-1} a_{BL}(i, t) + \sum_{t=s}^c a_M(i, t) \right]}{p(i, s)} = \text{constant} = \frac{\left[\sum_{t=s_0}^{s-1} A_{BL}(t) + \sum_{t=s}^c A_M(t) \right]}{P(s)}, \quad (9)$$

here, start year s_0 was 1960, reference year *s* was 2015 and convergence year *c* was either 2030 (EPPCE2030) or 2050 (EPPCE2050).

Once the remaining allowance was determined, it was decomposed into annual values by assuming that future annual agricultural emissions per capita of each country *i* fit a quadratic polynomial

$\phi_i(t) = \alpha_i t^2 + \beta_i t + \gamma_i$, defined by Equation (10).

$$\left. \begin{aligned} \sum_{t=s}^c \phi_i(t) &= \frac{\sum_{t=s}^c a_M(t)}{p(i, s)} \\ \phi_i(s-1) &= \frac{a_{BL}(i, s-1)}{p(i, s)} \\ \phi_i(c) &= \frac{A_M(c)}{P(s)} \end{aligned} \right\} \quad (10)$$

Finally, the country-specific emissions trajectories were adjusted such that global annual agricultural emissions strictly follow the RCP2.6 pathway. This was done on a per-capita basis (Equation (11)).

$$a_M(i, t) = a_M(i, t) + \left(\left[A_M(t) - \sum_{i=1}^I a_M(i, t) \right] \times \left[\frac{p(i, s)}{P(i, s)} \right] \right). \quad (11)$$

The mitigation target for each country in year t was then calculated per Equation (12).

$$m_{EPPCE}(i, t) = a_{BL}(i, t) - a_M(i, t). \quad (12)$$

2.2.6. Cost effectiveness

The previous approaches reflect the distribution of mitigation effort according to various concepts of fairness. They do not, however, reflect what might be the most economically efficient distribution of emission reductions among countries. Studies using integrated assessment models have used marginal abatement cost (MAC) curves to distribute a global emission reduction objective over different regions, gases and sources following a least-cost approach.

It is impossible to directly compare the results of the nine allocation approaches based on fairness with a least-cost approach because integrated assessment models generally provide output at a regional level, not a national level. However, by clustering these country-level targets by the same regional boundaries used by the IMAGE model (van Vuuren et al., 2011), these allocation methods were compared with the results of the RCP2.6 scenario as implemented in the IMAGE model by van Vuuren et al. (2011).

2.3. Calculation of uncertainty ranges

Uncertainty ranges around these targets were calculated to reflect the range of mitigation that may be needed from each country's agricultural sector in 2030. Three sources of uncertainty were accounted for: (1) estimates of historical emissions by country, (2) population projections by country and (3) global mitigation of agricultural emissions needed by 2030. Full details of uncertainty calculations for each allocation approach can be found in Appendix S2 of the Supplemental Material.

3. Results

3.1. Comparison among approaches

Approaches based on responsibility, capability, and responsibility, capability and need assigned positive mitigation targets (i.e. emission reductions) to all countries; this feature is inherent in the calculations used to allocate targets. The responsibility approach based on historical agricultural emissions (CA1960) created the most even allocation in terms of percent reductions: it assigned all countries a mitigation target between 0 and 30% (Figures 2 and 3(b)). By comparison, using historical emissions from all sectors as an indicator of responsibility (CE1890) allocated more of the mitigation burden of agricultural emissions to industrialized countries. Europe, North America and China were collectively responsible for nearly half the mitigation required in 2030 (Table 3; Figure 2). This meant less of a burden for least developed countries (LDCs). Under CA1960, the

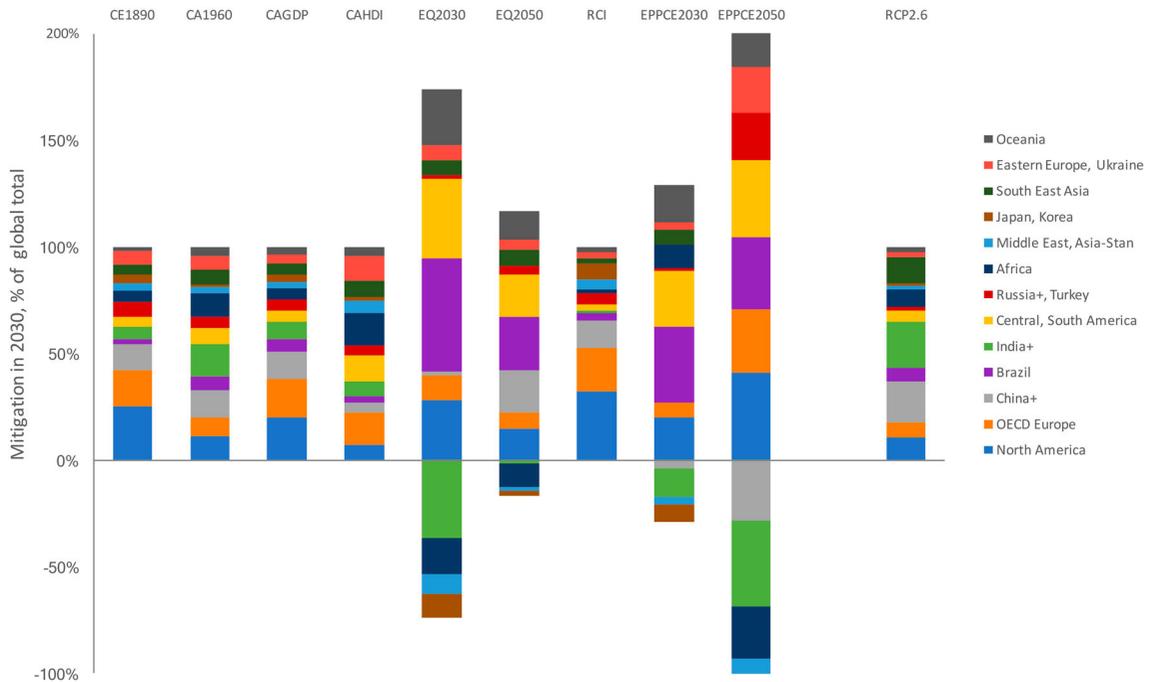


Figure 2. Regional distribution of a global mitigation target for agricultural emissions in order to meet the 2°C goal. Comparison of agricultural emission reductions using nine allocation approaches based on principles of fairness (CE1890, CA1960, CAGDP, CAHDI, EQ2030, EQ2050, RCI, EPPCE2030, EPPCE2050) and one least-cost approach using the RCP2.6 scenario implemented in the IMAGE model. Regions are defined in Stehfest et al. (2014).

collective mitigation target for LDCs was 109 MtCO₂e yr⁻¹, more than triple the 32 MtCO₂e yr⁻¹ target under CE1890 (Table 3).

The capability approach using GDP as an indicator (CAGDP) yielded mitigation targets similar to CE1890, both in terms of percent (Figure 2) and absolute reductions (Table 3; Figure 3(c)). Europe, North America and China assumed about half of the total mitigation target, and the remaining half was distributed about evenly among other regions. Targets calculated using HDI as an indicator of capability (CAHDI) created higher percent reduction targets for LDCs than CAGDP, likely due to the fact that HDI scores have less variance than GDP so there was less of a disparity in ‘capability’ between developed and less developed countries. Notably, several countries such as Saudi Arabia and Oman with high HDIs and low agricultural emissions had very high percent reduction targets under CAHDI (Figure 3(d)).

The responsibility, capability and need approach (RCI) created low percent mitigation targets for agricultural emissions in most of the global South and higher targets in the North (Figure 3(g)). The results were similar to those with CE1890, as would be expected, but the exclusion of individuals with low per-capita income from mitigation responsibilities further shifted the burden to wealthy countries in North America, Europe, Japan and Korea (Figure 2).

The two equality approaches (EQ2030 and EQ2050) yielded mitigation targets for agricultural emissions that were vastly different from those based on responsibility, capability, and responsibility, capability and need. Under EQ2030, if all countries’ agricultural emissions converged at the same per-capita emissions rate in 2030 (0.90 tCO₂e person⁻¹ yr⁻¹), four countries would be responsible for most of the mitigation required in the agricultural sector: Brazil, United States, Australia and Argentina (Figure 3(e)). These are all countries with large livestock populations and comparatively small human populations. Other countries with similar livestock and human and population profiles (Mongolia, former Sudan, most South American countries) also had high percent emission reduction targets. Meanwhile, countries with high projected populations (India), low baseline agricultural emissions per capita (Japan, South Korea) or very low agricultural emissions (much of the Middle East and North Africa) would

Table 3. Selected countries' annual GHG mitigation targets (MtCO₂e yr⁻¹) for agricultural emissions by 2030 calculated by distributing a global mitigation target of 1 GtCO₂ according to nine different approaches. Numbers in normal print are the targets for mitigation (emission reductions). Numbers in italics are the resulting *emissions* (2030 baseline emissions minus the mitigation target).

	2030 baseline emissions ^a	CE1890		CA1960		CAGDP		CAHDI		EQ2030		EQ2050		RCI		EPPCE2030		EPPCE2050	
		Mitigation	<i>Emissions</i>																
China	1225	115	<i>1110</i>	120	<i>1105</i>	127	<i>1098</i>	39	<i>1186</i>	9	<i>1216</i>	263	<i>961</i>	121	<i>1104</i>	-60	<i>1285</i>	-413	<i>1637</i>
Brazil	733	28	<i>706</i>	65	<i>668</i>	56	<i>678</i>	30	<i>703</i>	537	<i>196</i>	345	<i>389</i>	35	<i>699</i>	493	<i>240</i>	487	<i>246</i>
India	982	45	<i>938</i>	114	<i>868</i>	64	<i>918</i>	32	<i>950</i>	-330	<i>1312</i>	-47	<i>1029</i>	11	<i>971</i>	-200	<i>1182</i>	-427	<i>1409</i>
United States	520	223	<i>296</i>	84	<i>436</i>	164	<i>355</i>	40	<i>479</i>	214	<i>306</i>	141	<i>378</i>	276	<i>243</i>	204	<i>315</i>	483	<i>36</i>
EU28	587	208	<i>380</i>	132	<i>455</i>	202	<i>386</i>	216	<i>371</i>	150	<i>437</i>	129	<i>458</i>	218	<i>370</i>	110	<i>478</i>	564	<i>24</i>
Indonesia	233	17	<i>216</i>	23	<i>209</i>	19	<i>213</i>	17	<i>216</i>	-21	<i>254</i>	12	<i>221</i>	6	<i>226</i>	-4	<i>237</i>	-102	<i>335</i>
Russia	150	64	<i>86</i>	41	<i>109</i>	37	<i>113</i>	25	<i>125</i>	31	<i>119</i>	42	<i>109</i>	40	<i>111</i>	16	<i>134</i>	314	<i>-164</i>
Pakistan	231	6	<i>225</i>	18	<i>214</i>	8	<i>223</i>	11	<i>220</i>	21	<i>210</i>	30	<i>201</i>	0	<i>231</i>	52	<i>179</i>	-58	<i>289</i>
Argentina	206	8	<i>199</i>	26	<i>180</i>	16	<i>190</i>	20	<i>186</i>	164	<i>42</i>	114	<i>92</i>	6	<i>200</i>	151	<i>56</i>	256	<i>-50</i>
Australia	236	14	<i>221</i>	30	<i>205</i>	29	<i>207</i>	25	<i>211</i>	211	<i>24</i>	152	<i>84</i>	21	<i>215</i>	194	<i>42</i>	320	<i>-84</i>
LDCs	1222	32	<i>1190</i>	109	<i>1113</i>	36	<i>1186</i>	123	<i>1099</i>	84	<i>1138</i>	27	<i>1196</i>	3	<i>1219</i>	310	<i>912</i>	-80	<i>1303</i>

^aCalculated by downscaling median 2030 global agricultural baseline emissions from three integrated assessment models using FAOSTAT projected 2030 emissions by country.

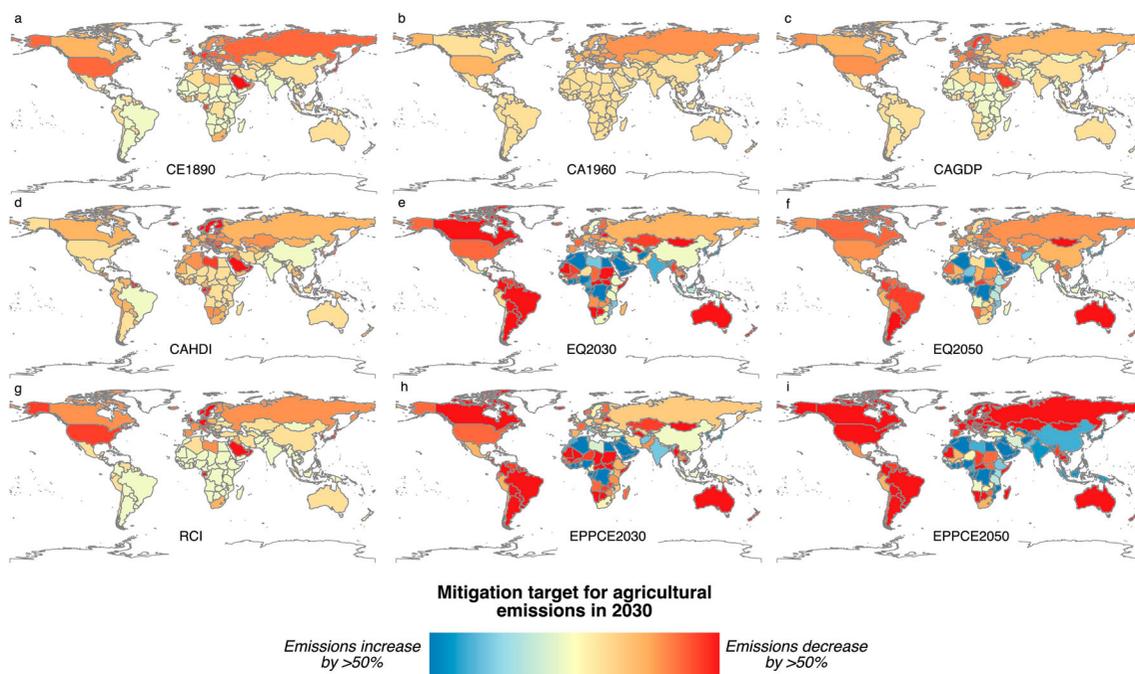


Figure 3. Countries' annual GHG mitigation targets (% of 2030 baseline emissions) for agricultural emissions by 2030 calculated by distributing a global mitigation target of $1 \text{ GtCO}_2\text{e yr}^{-1}$ on the basis of: (a) cumulative GHG emissions from all sectors since 1890 (CE1890), (b) cumulative agricultural GHG emissions since 1960 (CA1960), (c) cumulative agricultural GHG emissions since 1960 and current GDP (CAGDP), (d) cumulative agricultural GHG emissions since 1960 and current HDI (CAHDI), (e) equal agricultural emission per capita in 2030 (EQ2030), (f) equal agricultural emission per capita in 2050 (EQ2050), (g) responsibility and capability indicator (RCI) per Kemp-Benedict et al. (2017), (h) equal per capita cumulative agricultural emissions with convergence in 2030 (EPPCE2030), and (i) equal per capita cumulative agricultural emissions with convergence in 2050 (EPPCE2050). Emission reductions are calculated against baseline agricultural emissions of approximately $8.3 \text{ GtCO}_2\text{e yr}^{-1}$ in 2030.

be allowed to increase their agricultural emissions under this approach. Using 2050 as a convergence year (EQ2050), all countries would have agricultural emissions of $0.7 \text{ tCO}_2\text{e person}^{-1} \text{ yr}^{-1}$ in 2050, and be moving linearly towards this goal in 2030. This approach resulted in less stringent mitigation targets than EQ2030 for most countries (Table 3), and smaller emission increases for India, Japan, Korea and many African countries. However, this approach resulted in the largest mitigation target for China of all the methods tested in this analysis. This is likely because China's population is projected to peak around 2030 and decline thereafter; under EQ2050, China would be expected to start reducing agricultural emissions in 2030 in order to meet its lower emission allocation in 2050.

Mitigation targets under equal cumulative per capita emissions with convergence in 2030 (EPPCE2030) were similar to EQ2030 (Figure 3(h)) because with both approaches, all countries converge at the same per-capita emissions level in 2030. However, agricultural emission allocations (and mitigation targets) under EPPCE2030 would be quite different leading up to 2030, because the equal cumulative per capita approach specifies that emissions assume a quadratic function, rather than a linear decrease (Figure 1). For example, Australia had, as of 2015, already surpassed its cumulative per-person emission allocation for the period 1960–2030. Therefore, Australia would be assigned *negative* agricultural emissions during the years 2016 to 2029. Conversely, Ghana still had a large part of its cumulative allocation remaining in 2015, and would be allowed to increase its agricultural emissions substantially during the same period.

The implications of this approach became more apparent with convergence in 2050 (EQ2050); here, countries were at the top of their emission 'peak' or 'trough' in 2030. Most countries in Europe, the Americas, Oceania, and parts of Southeast Asia, having already exceeded their per-capita allocation, were assigned mitigation targets close to or more than 100% of their baseline agricultural emissions. China, India, Indonesia and parts of Africa with historically low agricultural emissions were assigned deeply negative mitigation targets (large emission increases) (Figure 3(i)).

3.2. Comparison with economic efficiency approach on a regional basis

The approach based on historical agricultural emissions (CA1960) bore the greatest similarity to the regional distribution produced by RCP2.6 in the IMAGE model, suggesting that this allocation method may result in greater economic efficiency than the others. This is likely because these mitigation targets are somewhat proportional to current – and future baseline – emissions from agriculture. Conversely, the large difference between the equality and equal cumulative per capita approaches and the economic efficiency approach suggests that these may be costly allocation schemes at the global scale. The economic efficiency approach allocates more of the mitigation effort to the India+ region (India, Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan and Sri Lanka) than any of the allocation approaches tested in this analysis, as well as a comparatively large proportion to the China +region (China, Taiwan and Mongolia) (Figure 3).

4. Discussion

Meeting the goal of a 1 GtCO₂e yr⁻¹ reduction in agricultural emissions in 2030 as calculated by Wollenberg et al. (2016) will require countries to be ambitious in selecting their mitigation targets. If all countries selected the minimum target among the approaches used in this analysis, global agricultural emissions would increase 1.9 GtCO₂e yr⁻¹ above the 2030 baseline because of emission increases allowed under the equality and equal cumulative emissions approaches. By contrast, if all countries selected the most ambitious target, global agricultural emissions would be reduced by 4.6 GtCO₂e in 2030, vastly exceeding the 1 GtCO₂e yr⁻¹ target.

4.1. Implications for food security

Trade-offs exist between food security and mitigation of agricultural emissions, and some countries may find that these trade-offs preclude mitigation in their agriculture sectors. Applying the Global Biosphere Management Model (GLOBIOM) to a range of mitigation scenarios, Kleinwechter et al. (2015) estimated that mitigation of emissions from agriculture, forestry and land use at the level required by RCP2.6 would reduce global food availability by 115 Kcal person⁻¹ day⁻¹. This decrease is negligible for regions with high food availability (e.g. United States or Canada, where consumption is about 3600 Kcal person⁻¹ day⁻¹) but may weigh heavily on countries with lower food availability (Kleinwechter et al., 2015). If LDCs were exempted from mitigation of agricultural emissions, the global reduction would fall short of the 1 GtCO₂e goal by 0.03–0.12 GtCO₂e yr⁻¹, meaning that other countries or other sectors would need to compensate for this shortfall. The impact of excluding LDCs from mitigation is lowest for CE1890 and CAGDP approaches. Under the EQ2050 approach, excluding LDCs would increase the global mitigation achieved in the agricultural sector by more than 1 GtCO₂e yr⁻¹ target, because it would mean eliminating emission increases above 2030 baselines allocated to most LDCs.

One limitation of this analysis is that it approaches mitigation of agricultural emissions purely on the basis of food production, not food consumption. Because it does not account for trade, it may disproportionately affect mitigation targets for countries that are net food exporters, particularly those that export livestock products. This is most apparent in the approaches using equal per capita emissions. The targets under EQ2030 would require stringent reductions in N₂O and CH₄ emissions from agriculture in many countries with large agricultural economies – such as Brazil, Argentina and Australia – by 2030. These emissions would instead be allocated to countries with historically low per-capita emissions, giving many developing countries room to grow their agricultural emissions to meet the food needs of their populations. However, it would also allow for substantial increases in agricultural emissions from countries where increased agricultural production may be impossible (and highly inefficient) due to water limitations, such as Egypt and Saudi Arabia.

4.2. Comparison with (Intended) Nationally Determined Contributions

If the (Intended) Nationally Determined Contributions (INDCs) and NDCs are any indication, LDCs have planned agricultural emission reductions commensurate with some of the targets presented here (Table 4). Of the 11

Table 4. Selected countries' projected mitigation contributions from agriculture and agriculture, forestry and other land use (AFOLU) as described in their (Intended) Nationally Determined Contributions, compared to mitigation targets calculated in this study. Sectoral mitigation contributions outlined in (I)NDCs do not reflect formal commitments from countries, they were primarily included as background information describing the process of calculating the economy-wide contribution, or in descriptions of mitigation actions the country plans to undertake.

		CE1890		CA1960		CAGDP		CAHDI		EQ2030		EQ2050		RCI		EPPCE2030		EPPCE2050		
		MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	MtCO ₂ e	%	
	2030 baseline ^a																			
Benin	20.9 MtCO ₂ e (20.6%) reduction against BAU, cumulative 2021–2030	8.6	1.6	19	0.6	7	0.9	10	0.3	4	1.9	22	-4.8	-56	2.3	26	-1.0	-12	-5.9	-68
Burundi	AFOLU: 12.94 MtCO ₂ e (17%) reduction against BAU in 2030, conditional	2.7	0.2	8	0.3	10	0.3	10	0.1	4	0.9	35	-12.3	-462	0.9	36	-6.1	-230	-10.9	-413
Chad	5.21 MtCO ₂ e reduction against cumulative BAU emissions 2016–2030, unconditional; 13.02 MtCO ₂ e reduction against cumulative BAU emissions 2016–2030, conditional	32.3	0.4	1	2.8	9	3.7	11	0.8	2	2.7	8	13.5	42	3.2	10	17.6	55	14.3	44
Comoros	Agriculture: 0.085 MtCO ₂ e reduction against BAU in 2030, conditional	0.3	0.0	5	0.0	12	0.0	12	0.0	6	0.5	150	-0.6	-171	0.5	148	-0.3	-98	-0.6	-163
Cote d'Ivoire	Agriculture: 2.33 MtCO ₂ e reduction against BAU in 2030, conditional	8.2	1.3	16	0.7	9	1.0	13	0.6	8	1.9	23	-19.4	-236	2.3	28	-11.8	-144	-21.0	-256
Ethiopia	Agriculture: 90 MtCO ₂ e (48.6%) reduction against BAU in 2030, conditional	114.3	1.9	2	12.3	11	12.9	11	2.6	2	6.9	6	-4.5	-4	7.2	6	20.4	18	-27.5	-24
Gambia	Rice production: 1.1 MtCO ₂ e reduction against BAU in 2025, conditional	1.7	0.0	2	0.2	9	0.2	11	0.1	3	0.9	52	-1.0	-58	0.9	56	-0.1	-7	-1.0	-60
Mali	Agriculture: 25.4 MtCO ₂ e reduction against 2030 BAU emissions, conditional	43.4	0.4	1	3.2	7	3.9	9	0.8	2	3.5	8	19.9	46	3.9	9	24.8	57	8.5	20
Nigeria	74 MtCO ₂ e reduction against BAU in 2030, conditional	98.3	6.6	7	7.5	8	9.9	10	7.7	8	6.9	7	-127.2	-129	8.1	8	-61.8	-63	-154.2	-157

^aCalculated by downscaling median 2030 global agricultural baseline emissions from three integrated assessment models using FAOSTAT projected 2030 emissions by country.

countries that estimated mitigation contributions from the agriculture or AFOLU sectors, all demonstrate levels of ambition that approach or surpass the allocations specified in this analysis. Benin, for example, estimated a cumulative mitigation reduction of 20.9 MtCO₂e for its agriculture sector between 2021 and 2030. That reduction, equal to about 2 MtCO₂e annually, surpasses the targets for Benin calculated in this analysis, which ranged from an increase of 4.8 MtCO₂e yr⁻¹ (EQ2030) to a reduction of 1.9 MtCO₂e yr⁻¹ (CAHDI) (Table 4). Ethiopia plans to reduce agricultural emissions by 90 MtCO₂e yr⁻¹ in 2030, also surpassing the targets from this analysis (a maximum of 20.4 MtCO₂e yr⁻¹ reduction) (Table 4). These countries' ambitions are therefore aligned with reaching the 2° C – or perhaps even the 1.5°C limit, assuming baseline 2030 emissions similar to those used in this analysis.

None of the largest agricultural emitters included sector-specific contributions from the agriculture sector in their NDCs, but most included agriculture in their economy-wide targets. The exception is India, which excluded agriculture from its mitigation target. This exclusion is consistent with the equality and equal cumulative per-capita approaches, which would allow India to increase its agricultural emissions, but not with the responsibility or capability approaches.

5. Conclusion

For countries with high agricultural emissions, the challenge will be to ramp up the ambition of their mitigation targets for the agriculture sector over time. Currently available mitigation options based on improved efficiencies and best farming practices such as improved nutrition and health management of ruminant livestock (Gerber et al., 2013), reduction of water use in paddy rice (Yan, Akiyama, Yagi, & Akimoto, 2009) and more efficient use of nitrogen fertilizers (Gerber et al., 2016) could be the entry points. Meeting the 2°C goal will require widespread uptake of such existing options. In countries where GHG intensity per unit of production is already low, further mitigation will depend on new technologies such as breeding ruminants for lower emissions (Pickering et al., 2015). The Technology Mechanism under the UNFCCC – which will also serve the Paris Agreement – can support the transfer of more advanced technologies to developing countries, including those that may provide adaptation benefits as well.

Developed countries should provide financial support for developing countries to meet their conditional goals in the agriculture sector, while undertaking ambitious domestic reductions. Climate finance for mitigation of emissions from agriculture and land use lags behind other sectors (Buchner et al., 2017), and many farmers in developing countries lack access to financial services. Greater access to finance will enable farmers to make investments that increase efficiency and reduce emissions. Ultimately, countries, and farmers and food companies operating within them, will chart their own courses towards low-emission agricultural systems, bearing in mind both their own capabilities and the collective effort necessary to meet the Paris Agreement goals.

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