Fair contributions to reduce global GHG emissions from agriculture

FABLE Policy Brief
August, 2025

Headlines

- **Food systems are major contributors to climate change and highly vulnerable to its impacts**, threatening global agricultural productivity, livelihoods, and food security worldwide.
- **We estimate 'fair shares' for agricultural emissions among regions by 2050** to comply with the Paris Agreement, based on Current Trends and Global Sustainability pathways developed in the latest FABLE Scenathon.
- **We calculate fair allowances based on three equity principles:** ability to pay, historical responsibility, and population size.
- **Under Current Trends, only Sub-Saharan Africa meets its fair share** under the ability to pay principle.
- **In the Global Sustainability scenario, Asia meets its fair share** under the historical responsibility principle, as well as **North Africa & the Middle East** under both historical responsibility and population-based approaches.
- **Europe, North America & Australia, and Central & South America remain far from meeting their fair share** across all pathways and equity approaches.
- **Production-based emissions accounting can unfairly penalize food-exporting countries**, making a strong case for integrating consumption-based accounting into fairness frameworks.
- **Future steps** for improving the methodology include additional food security indicators, combining equity approaches into a composite measure, and accounting for consumption-based emissions.

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About FABLE

The Food, Agriculture, Biodiversity, Land-Use, and Energy (FABLE) Consortium is a collaborative initiative to support the development of globally consistent mid-century national food and land-use pathways that could inform policies towards greater sustainability. The Consortium brings together teams of researchers from 26 countries and international partners from Sustainable Development Solutions Network (SDSN), the International Institute for Applied Systems Analysis (IIASA), the Alliance of Bioversity International and CIAT, and the Potsdam Institute for Climate Impact Research (PIK).

https://www.fableconsortium.org/
info.fable@unsdsn.org

1. General background

Food systems lie at the heart of the climate crisis, accounting for one-third of global anthropogenic GHG emissions,[1] and using 50% of the world's habitable land for agriculture.[2,3] They are also among the most vulnerable sectors to the impacts of climate change. Higher temperatures, changing precipitation patterns, and extreme atmospheric phenomena,[4] such as floods, hurricanes, and droughts, contributed to the slowdown in global agricultural productivity growth over the past 50 years, disproportionately impacting mid and low-latitude regions,[2] and posing a direct threat to agricultural output.[5,6]

This vulnerability also threatens the livelihoods of millions, with 26.6% of the world's workforce employed in agriculture as of 2021.[7] Climate change disrupts farm income stability and productivity and destabilizes the national food supply, markets, food security, and broader economic conditions.[8] Globally, climate-induced shocks in crucial food-producing regions can trigger price spikes, market volatility, and trade disruptions, disproportionately affecting the accessibility of global markets for the poorest nations and populations.[2,8–10]

The Paris Climate Agreement's 'common but differentiated responsibilities and respective capabilities' (CBDR-RC) principle establishes that each country should contribute to the 1.5 °C global mitigation goal based on its 'capacity and highest possible ambition'.[11] By considering national capacities and vulnerabilities, this principle enables countries to voluntarily determine the extent of their commitment to reducing emissions. It also requires countries to increase their ambition progressively every five years, through Nationally Determined Contributions (NDC).

Without clear guidelines on what counts as 'highest possible ambition', and as countries try to achieve global climate goals while balancing national interests, addressing fairness and equity is imperative to tackling the climate crisis effectively. In agriculture, mitigation efforts often compete with other priorities, such as food security, expanding commodity-based value chains, and protecting rural employment.[12] This challenge is particularly high for the least-developed countries, where the expectation to allocate resources for reducing emissions must be weighed against pressures to secure economic growth, and the responsibilities of the world's highest emitters.

This brief presents a framework to assess equity in mitigation efforts for agriculture and address the gaps between countries' trajectories and the ambition needed to meet global goals. We draw on 22 national long-term pathways for food and land-use systems developed by the Food, Agriculture, Biodiversity, Land Use and Energy (FABLE) Consortium, which aim to meet global sustainability goals, including ambitious emission reductions from agriculture, which could contribute to achieving the Paris Agreement. We assess current and projected agricultural emissions through 2050, against fair share principles and proposed emission allowances. The findings can improve the FABLE Scenathon process to align local priorities with global sustainability and support the operationalization of the CBDR-RC principle in climate negotiations.

2. Methodology

Fair share approaches

This fair share framework consists of three approaches: Ability to Pay, Historical Responsibility, and Immediate per Capita Convergence.

Achieving global climate goals requires clarity on how much each country needs to contribute. Yet, this is particularly challenging in agriculture and land use, where efforts must also support food security, healthy diets, and economic development. While fair share methodologies are not new,[13] few have been applied to agriculture. Based on earlier efforts to assess fairness in economy-wide GHG emission reduction targets,[14] we identified three approaches applicable to agricultural emissions through 2050, drawing on FABLE Scenathon results.[12]

The Ability to Pay (AP) approach grants higher allowances to vulnerable countries with a lower sum of annual GDP and a higher total population summed over the period 1961-2049. The AP approach derives from the capability principle, which states that countries with greater economic, technical, or environmental capacity to address the common challenge of climate change should contribute more to mitigation efforts.[14,15]

Under AP, fair emissions allowances by 2050 are allocated inversely to each country's cumulative per-capita GDP from 1961 to 2049 to give higher allowances to poorer countries. These are then adjusted using the Notre Dame Global Adaptation Initiative (ND-GAIN) Country Index,[16] which reflects climate vulnerability and resilience, ensuring that more vulnerable countries receive greater allowances, all else being equal. The ND-GAIN index accounts for differences in climate exposure, resilience, and adaptive capacity that are not fully captured in GDP projections (cf. Appendix A).

The Historical Responsibility (HR) approach grants fewer emission allowances to countries with higher historical emissions and lower cumulative populations. HR is based on the responsibility principle, which distributes mitigation efforts among countries according to their past contributions to global warming.[14,15] Under HR, fair emissions allowances are allocated to countries at the target year (2050) in an inversely proportional manner to their cumulative per-capita emissions from 1961 to 2049. While using CO_2-equivalent values do not fully capture the temporal dynamics and differing warming impacts of long-lived gases like CO_2 versus short-lived gases like CH_4, it facilitates comparability across gases. We use cumulative CO_2-equivalent emissions as a practical and widely accepted proxy for historical responsibility, given data availability and consistency across countries and emission sources.

The Immediate Per Capita Convergence (IEPC) approach grants higher emission rights to highly populated countries. It derives from the equality principle, which holds that every individual is entitled to the same right to emit.[14,15,17] Under IEPC, fair emission allowances for 2050 are proportionally assigned based on the country's share of the world population, and immediate because allocations begin the year following the calculation period (i.e., 2049).

In all approaches, fair allowances are applied starting in 2050, following their calculation based on data up to 2049. They are then adjusted by the yield gap and self-sufficiency ratio to safeguard food security while reducing agricultural emissions (cf. Appendix A).

Applying 'fairness' to scenathons

We use GHG emissions results from the pathways developed by the FABLE Consortium during the 2023 'Scenathon'.[18] Scenathons ('scenario marathon') are a collaborative, iterative process where FABLE country teams use modelling tools to develop mid-century national pathways for sustainable food and land-use systems, aligned with global objectives and national priorities, and interconnected through trade. FABLE teams also consult with stakeholders to ensure scenarios are relevant and accurate.

As part of the Scenathon, the FABLE Consortium sets global sustainability targets for the food and land-use system that need to be met collectively. For GHG emissions from agriculture (cf. Appendix B), FABLE agreed on collectively reducing them below 4 $GtCO_2e$ per year by 2050. This target reflects an ambitious mitigation effort for agriculture that contributes to limiting global warming to 1.5 degrees Celsius (cf. Appendix D).[12]

Twenty-two FABLE country teams participated in this exercise (Figure 1), modeling the following pathways:[a]

a) **Current Trends:** based on historical trends and existing practices and policies.

b) **Global Sustainability**: aligned with national and global sustainable goals, such as the Paris Agreement, reflecting stronger ambition.

Using the FABLE Calculator,[19] teams modeled alternative national scenarios, adjusting assumptions on population growth, food demand, diets, agricultural practices, trade, land use, and productivity, among others, in consultations with local stakeholders.

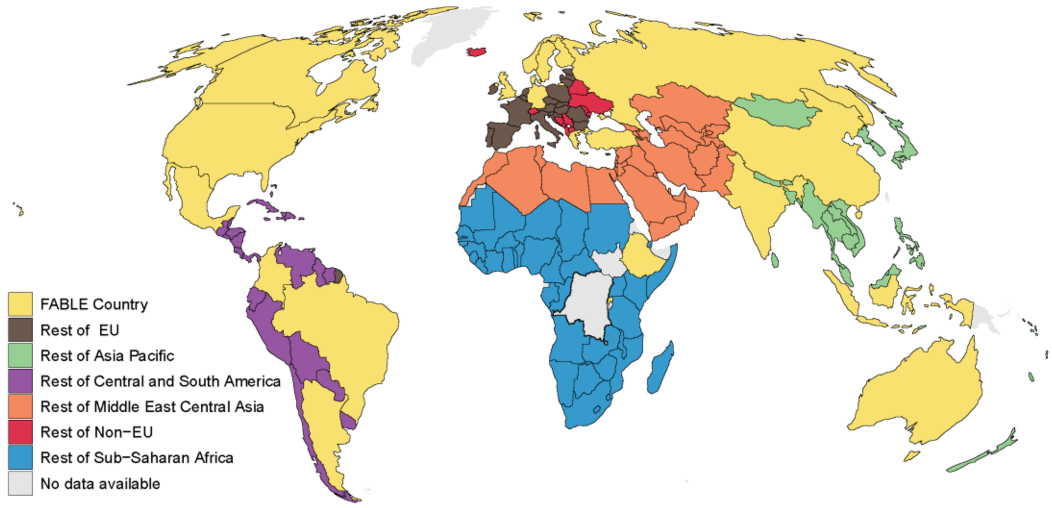
To reflect countries without a FABLE team, the FABLE Secretariat modelled regional pathways for six 'rest-of-the-world' regions (Figure 1).[b]

Teams submitted their pathway results to the Scenathon online platform, which corrects inconsistencies in agricultural trade, and aggregates the national results from the food and land-use system of each country and region, showing whether global sustainability goals are met.

While the Scenathon helps countries align national pathways and global targets, even the most ambitious scenarios may fall short. When global targets are not met, country teams are encouraged to revise their assumptions and raise their ambition within realistic bounds. But which country should contribute more, and by how much? The fair share framework offers a starting point to guide these discussions and revisions, beginning with agricultural emissions.

[a] FABLE teams also modelled a third scenario 'National Commitments' which is not considered in this brief.
[b] The 'six rest-of-the-world' regions are: Rest of EU, Rest of Asia Pacific, Rest of Central and South America, Rest of Middle East Central Asia, Rest of Non-EU, Rest of Sub-Saharan Africa.

Figure 1: FABLE countries participating in the 2023 Scenathon



Source: FABLE (2024) in Sachs et al. (2024) Sustainable Development Report.

3. Results

Global distribution of agricultural emissions

By 2050, global agricultural GHG emissions under the 'Current Trends' pathway are projected to reach 7.34 $GtCO_2e$, nearly double the mitigation target of 4 $GtCO_2e$. In contrast, the 'Global Sustainability' pathway, brings emissions down to 4.79 $GtCO_2e$, moving closer to the target. However, reaching this goal 'fairly' requires a more equitable distribution of mitigation efforts across countries and regions.

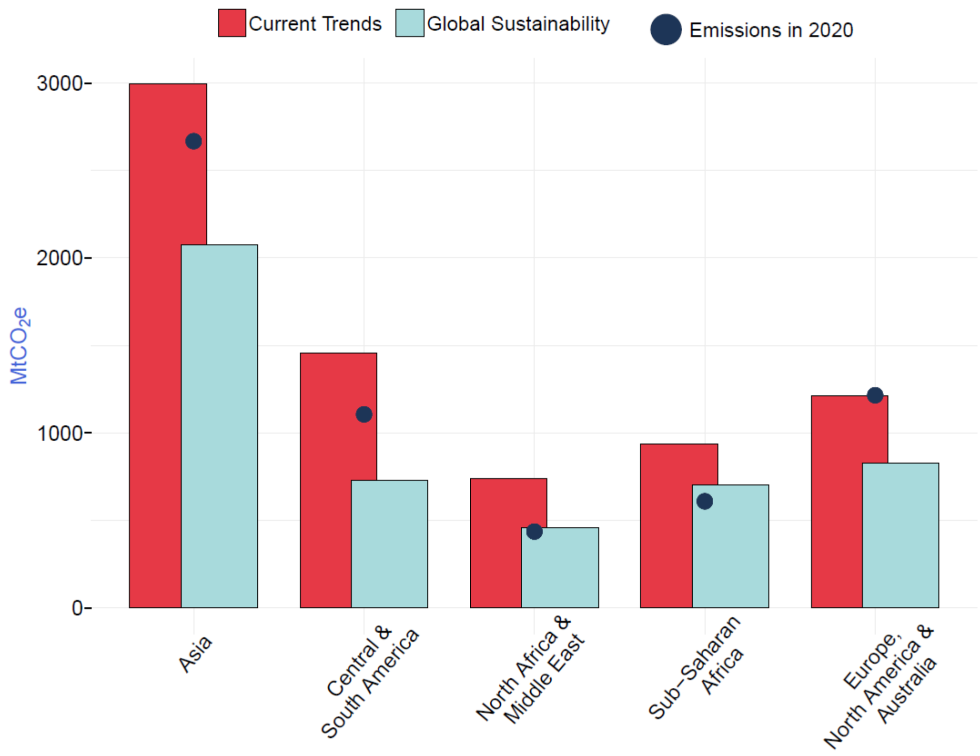
We grouped the countries and regions participating in the Scenathon, into five clusters based on geographical proximity and economic similarities: (i) Asia; (ii) Central & South America; (iii) North Africa & Middle East; (iv) Sub-Saharan Africa; and (v) Europe, North America & Australia (cf. Appendix B).[c]

In 2020, Asia was the largest emitter from the agricultural sector, with around 2.7 $GtCO_2e$ per year, followed by Europe, North America & Australia (around 1.2 $GtCO_2e$), Central & South America (around 1.1 $GtCO_2e$), Sub-Saharan Africa (around 0.6 $GtCO_2e$), and North Africa & the Middle East (around 0.5 $GtCO_2e$).

When projecting emissions by 2050, all clusters, except Europe, North America & Australia, are expected to experience an increase in emissions, largely driven by rising demand and population growth. While in Global Sustainability, the cluster projecting the largest relative decrease (or the 'highest ambition') compared to 2020 is Asia, followed by Central & South America, and Europe, North America & Australia (Figure 2).

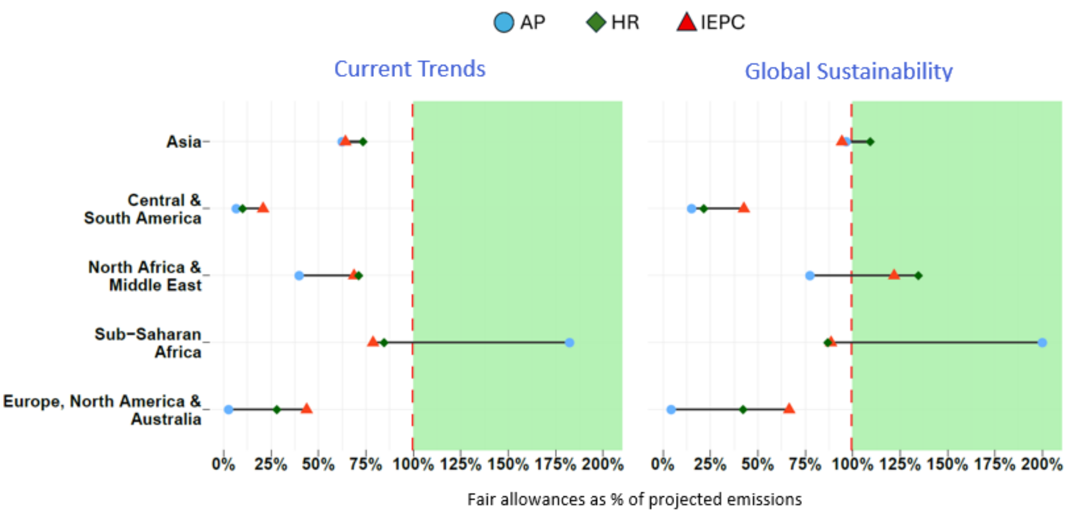
[c] For this analysis, FABLE countries and regions were grouped into clusters as follows: (i) **Asia**: India, Nepal, Indonesia, China, Russia, and the 'Rest of Asia Pacific'. (ii) **Central & South America:** Brazil, Mexico, Colombia, Argentina, with the 'Rest of Central and South America'. (iii) **North Africa and the Middle East** only covers the 'Rest of North Africa and Middle East', with no individual FABLE country. (iv) **Sub-Saharan Africa**: Ethiopia, Rwanda, and the 'Rest of Sub-Saharan Africa'. (iv) **Europe, North America & Australia**: United States, Canada, Australia, the United Kingdom, Germany, Denmark, Finland, Sweden, Greece, Norway, Turkey, the Rest of EU, and the Rest of Non-EU.

Figure 2: Global distribution of emissions from agriculture in 2020 and 2050 by cluster



Source: Authors.

Figure 3: Fair allowances for emissions from agriculture compared to projected emissions, based on three fair share approaches



Source: Authors

Fair allowances

Under the Ability to Pay (AP) approach, Sub-Saharan Africa is the only group projected to meet its fair share by 2050 in a Current Trends scenario (Figure 3). The AP fair allowance for Sub-Saharan Africa would be over 80% higher than its projected emissions, due to its low cumulative GDP per capita (the lowest among all regions) and high vulnerability, measured as a country's exposure, sensitivity, and capacity to adapt to the negative effects of climate change.[16]

Under the HR approach, no region would meet its fair share by 2050, whereas the IEPC approach results in less pronounced discrepancies between clusters.

However, the region's allowance slightly decreases when we account for the yield gap. This is because a large yield gap indicates significant potential for productivity increase and reduced emissions, especially through efficient land use. Across all approaches, regions with greater potential for improvement see their fair shares reduced, as they are expected to contribute more to mitigation through efficiency gains. On the other hand, the self-sufficiency ratio did not alter significantly Sub-Saharan Africa's AP fair share.

All the other regions emit more than their AP fair share. Europe, North America & Australia, as well as Central & South America, exceed their AP fair share by the widest margins, with their allowances representing only 3% and 7% of their projected emissions, respectively. This means that over 90% of their projected emissions from agriculture would go beyond what is considered a fair contribution to the global mitigation effort. These results are due to the regions' higher cumulative GDP per capita, which substantially limits their AP allowances. In the case of Central & South America, although their cumulative GDP per capita is five times lower than Europe, North America & Australia, their projected emissions are significantly higher, further widening the gap from their AP fair share.

If we follow the Historical Responsibility (HR) approach, none of the regions would meet their fair share by 2050 in the Current Trends scenario. Asia, North Africa & the Middle East, and Sub-Saharan Africa have relatively similar outcomes, with HR fair allowances covering only 70% to 85% of their projected emissions. For North Africa & the Middle East, and Sub-Saharan Africa, this is mainly driven by low cumulative historical emissions. Asia, on the other hand, has the highest total historical emissions (1961–2049), but still receives high HR fair allowances due to its large population, resulting in the lowest per capita historical emissions among all regions.

Europe, North America & Australia, and Central & South America, which rank second and third in historical emissions, are in a much less favorable position under the HR approach. Their high historical emissions combined with their relatively smaller populations result in low allowances, representing respectively 28 and 10% of their 2050 emissions. The HR allowances of Europe, North America & Australia are slightly improved due to a low yield gap, which reflects limited room for further productivity gains. In the case of Central & South America, they have a high agricultural self-sufficiency ratio, which slightly decreases their emission allowance.

Under the Immediate Per Capita Convergence (IEPC) approach, discrepancies between clusters are less pronounced. Since fair allowances are determined solely based on

In the Global Sustainability pathway, regions get closer to staying within their fair share allowances, showing a more optimistic outlook compared to Current Trends.

projected population size in 2050, Asia receives the largest allowance (over 1.9 $GtCO_2e$). However, this covers only about 65% of its projected emissions in 2050, which are expected to exceed 3 $GtCO_2e$. Sub-Saharan Africa comes closer to meeting its IEPC fair share, with allowances covering nearly 80% of its projected emissions (0.75 $GtCO_2e$ in allowances vs. 0.94 $GtCO_2e$ in emissions). The lowest share is observed for Central & South America, which is projected to have the smallest population among the regions in 2050.

In the IEPC approach, Europe, North America & Australia perform slightly better than under other frameworks, due to their medium-sized population and low yield gap, which slightly increase their allowance. However, their IEPC fair share still falls short, covering less than 50% of their projected emissions in 2050.

In a Global Sustainability scenario, regions get closer to staying within their fair share allowances, showing a more optimistic outlook compared to Current Trends (Table 1). Asia meets its fair share across almost all three approaches, with allowances under the IEPC and AP approaches remaining slightly below projected emissions for 2050. The Central & South America group also improves their position but remains far from their fair share. Their fair allowances range from only 15% (AP) to 43% (IEPC) of projected emissions, indicating a persistent gap.

North Africa & the Middle East show notable progress. While they do not meet any of the fair share thresholds under Current Trends, in the Global Sustainability scenario, they meet their fair share under two approaches. This shift is largely driven by lower projected emissions in 2050 and relatively low cumulative emissions from 2020 to 2049. As a result, their fair allowances exceed their 2050 projected emissions by 22% (IEPC) and 35% (HR).

For Sub-Saharan Africa, the picture remains largely unchanged. The region was already close to, or exceeding, its fair share under Current Trends, and it performs even better under Global Sustainability. This is especially notable under the AP approach, where Sub-Saharan Africa's relative advantage compared to the other clusters grows.

Finally, for Europe, North America & Australia, the gap remains wide. Even in the Global Sustainability scenario, this cluster still falls significantly short of its fair share across all approaches, with little improvement compared to Current Trends.

Table 1: Overview of Fair Share compliance

Region	**Current Trends**			**Global Sustainability**		
	AP	HR	IEPC	AP	HR	IEPC
Asia	62%	73%	64%	97%	109%	94%
Central & South America	7%	10%	21%	15%	21%	43%
North Africa and the Middle East	40%	71%	69%	77%	135%	122%
Sub-Saharan Africa	182%	85%	79%	213%	87%	89%
Europe, North America & Australia	3%	28%	44%	4%	42%	67%

(green) Projected emissions are lower than fair allowances in 2050, meaning the cluster respects its fair share.
(red) Emissions exceed the fair share allowance, signaling an overshoot.
The % indicates fair allowances as share of projected emissions.

Source: Authors.

4. Testing methods across countries

India

With about 17% of the world's population and the world's fifth-largest economy, India is the third-largest emitter of GHG economy-wide, surpassing 4 $GtCO_2e$ in 2023 (excluding LULUCF). The country faces the dual challenge of fostering economic growth while minimizing its climate impact, due to the strong link between energy consumption and economic expansion.[21,22]

While India's historical emissions are lower than the global average,[23] it aims to achieve net-zero emissions by 2070. Although India's voluntary declarations do not specifically target mitigation in the agricultural sector,[24] the government has recognized agriculture's significance through initiatives to reduce emissions through sustainable agricultural practices, improved productivity, and innovations in rice cultivation.[24]

Under the AP approach, India's fair share is over 1.3 $GtCO_2e$ in Current Trends (Figure 4), representing close to 32% of the global agricultural emissions budget. Since this approach grants higher allowances to countries with low per capita economic power and high vulnerability, India is entitled to a high allocation due to its low cumulative GDP from 1961 to 2049, similar to countries like Canada, Brazil, and Russia, and its large cumulative population, amounting to nearly 100 billion people during the same period.

India's AP allowance in 2050 would represent 125% of its projected agricultural emissions (Figure 4). This means India would be entitled to emit 25% more than its anticipated agricultural emissions in 2050.

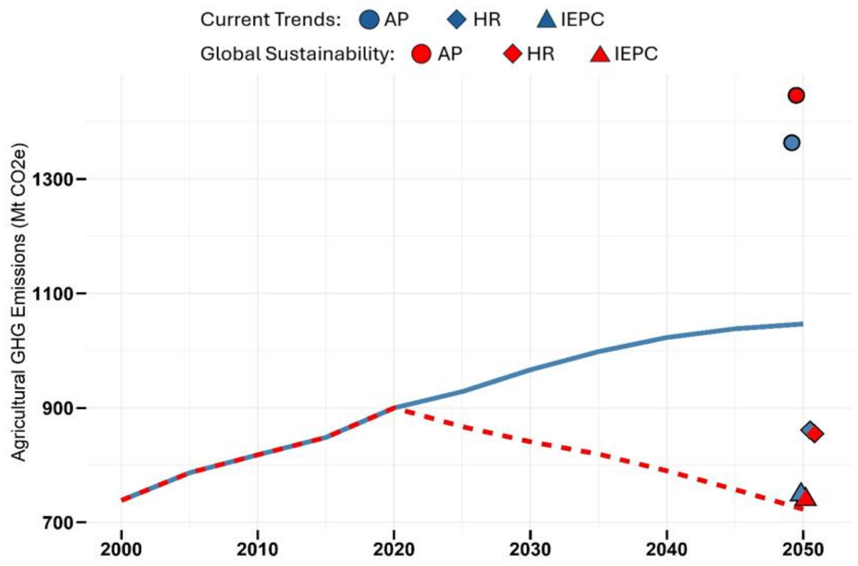
However, India's emission allowance decreases under the HR and IEPC approaches. Under HR, India's fair share drops to 0.85 $GtCO_2e$, reflecting its substantial historical agricultural emissions from 1961 to 2049—approximately 65 $GtCO_2e$, the highest globally, slightly ahead of China. In this case, India's fair share would cover just over 80% of its projected agricultural emissions in 2050, implying that its actual emissions would exceed its allocated allowance by around 20%. IEPC further reduces India's allowance to around 0.75 $GtCO_2e$, which represents about 70% of its projected emissions for 2050.

In the Global Sustainability scenario, India would align with its fair emission allowances across all three approaches. Under the AP approach, India's allowances in 2050 are double its projected emissions, while the HR approach grants an allowance 25% higher than its estimated emissions. Under IEPC, India's emissions are in line with its fair share. Compared to Current Trends, this shift is driven by a decline in India's emissions from 1 to 0.72 $GtCO_2e$ by 2050.[25]

India has expressed its commitment to addressing the global challenge of climate change, guided by the CBDR-RC. In its Biennial Update Report 4,[24] submitted to the UNFCCC in December 2024, India reports a 36% reduction in emissions intensity of its GDP between 2005 and 2020.[26] This places the country on track to meet its NDC target of reducing the emissions intensity by 45% by 2030 compared to 2005 levels.[26]

For India, the AFOLU sector offers significant cost-effective, near-term mitigation potential,[27] where LULUCF (65%) contributes the most, followed by demand-side measures (19%), such as shifting to sustainable healthy diets and reducing food waste, and agricultural measures (16%).[28] The results show that adopting a holistic approach across the AFOLU sector offers substantial mitigation potential, which would support India's ability to remain within its fair share of global emissions allowances and strengthen its role in contributing to equitable global efforts.

Figure 4: India's agricultural emissions trends and fair share allowances in 2050 under the Current Trends and Global Sustainability pathways



Source: Authors

Brazil

A global leader in agricultural production, Brazil ranks among the top producers and exporters of beef, soy, sugarcane, and maize.[29] However, the expansion of cattle ranching and soybean farming drives significant biodiversity loss, the former affecting the Brazilian Amazon rainforest,[30] the latter, threatening mostly the ecosystems like the Cerrado biome.[31] These activities also contribute massively to Brazil's GHGs, with land-use change accounting for approximately 66% of CO_2 emissions in Brazil in 2020.[32]

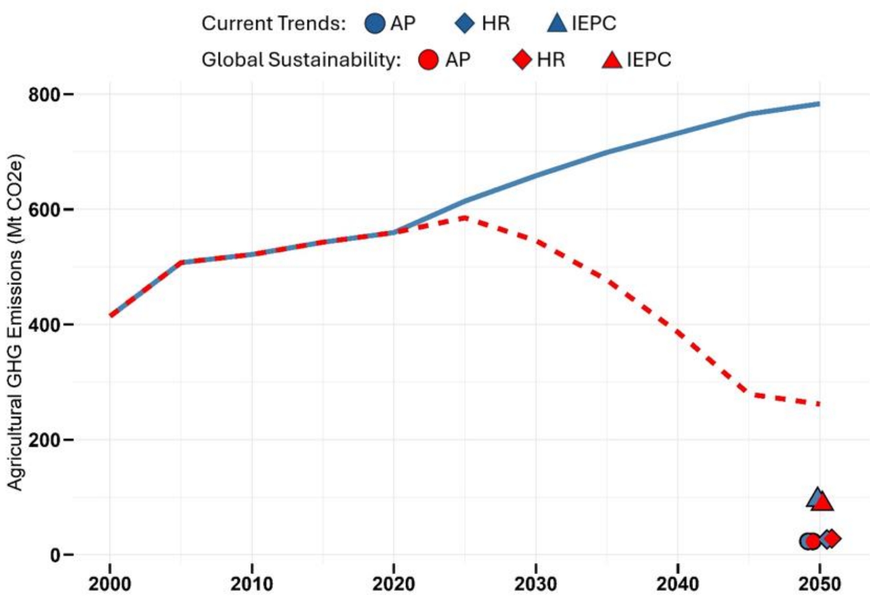
Brazil's projected emissions significantly exceed its fair emission allowances by 2050 (Figure 5). Under the AP approach, Brazil is allocated just 23 $MtCO_2e$, amounting to only 3% of its 2050 emissions. This small share is mainly due to its high-income level (fifth out of 22 countries). The HR slightly increases allowances to 27 $MtCO_2e$, but this is still low because of Brazil's historically high cumulative emissions (the third highest among the 22 countries), still covering just 3% of 2050 emissions. Under IEPC, emission allowances rise to 95 $MtCO_2e$, reflecting Brazil's large population in 2050, yet still only accounting for 12% of its projected emissions in 2050.

In the Global Sustainability scenario, Brazil's 2050 emissions are projected to be around 260 $MtCO_2e$, compared to 780 $MtCO_2e$ under the Current Trends, mainly due to a reduction in livestock driven by projected dietary shifts towards EAT-*Lancet* recommendations.[33]

However, fair allowances remain limited relatively to projected emissions: under the AP approach, they account for only 9%, under HR 11%, and IEPC 33%.

As a major agricultural exporter, Brazil plays a fundamental role in global food supply chains. Fair shares emission allowances based solely on production could disproportionately burden producer countries like Brazil, requiring them to limit high-emission activities such as cattle ranching or invest more heavily in mitigation technologies than consumer countries. This could increase production costs and reduce output of key export commodities, such as beef and soy. While such measures may reduce emissions, they could also raise international food prices, potentially threatening food security in import-dependent, lower-income countries. To account for this dynamic, fairness methodologies should incorporate a consumption-based perspective, recognizing the role of importing countries in driving emissions.

Figure 5: Brazil's agricultural emissions trends and fair share allowances in 2050 under the Current Trends and Global Sustainability pathways



Source: Authors

5. Discussion

By applying different methodologies based on projections for agricultural emissions, we present several approaches to bridge the gap between current trajectories and the achievement of global goals in a more equitable manner. In this brief, we provide a structured approach to closing these gaps following equity principles and fostering discussion among researchers, policymakers, and climate negotiators, recognizing the importance of agriculture to many societies, not just economically but also socially, culturally, and politically which can pose challenges for countries aiming to decarbonize agricultural emissions.

There is no universal solution or uniform approach that works for all. Different fairness approaches lead to significantly different outcomes for the same region. This highlights how political and ethical choices in determining what is 'fair' can have large implications and spark debates.

These results are intended to serve as an informative tool, a platform to foster dialogue and reflect on how countries might equitably raise their ambition to collectively stay within planetary boundaries. They should not be seen as absolute truths or definitive prescriptions for emission allocation, but rather as illustrative examples of how emissions could be allocated under fair share approaches grounded in ideal equity principles.

The Global Sustainability pathway helps close the gaps, especially for vulnerable or historically low-emitting regions, but fairness gaps remain under all approaches, especially for wealthier and more polluting regions. For these countries, it may be necessary to consider offsetting mechanisms or financial compensation, whereby they purchase emission allowances from those achieving their fair share, helping to balance global efforts and support a more equitable distribution of mitigation responsibilities.

Methodology improvements are needed to better capture the complexities of food systems by integrating additional food-related indicators that reflect the capacity to reduce emissions without compromising food security and availability. Further work should explore other fair share approaches such as 'equal cumulative per capita emissions', 'cost-optimal', 'greenhouse development rights',[15,34,35] and develop an integrated measure that assigns equal weight to AP, HR, and IEPC.

Applying the same methodology to consumption-based emissions would provide a more comprehensive understanding of a country's overall carbon footprint and the role that consumers and diets in each country can play in reducing agricultural emissions. Relying solely on production-based accounting means that food-exporting countries are penalized with a lower allowance than they would be entitled to if we considered that they are avoiding the GHG emissions that would otherwise occur in food-importing countries, had they produced the imported food domestically. This case applies particularly well to Argentina[36] and Brazil. A possible solution could be to equitably distribute emissions along the entire value chain of each exported food product.

Achieving fairness in emission reduction requires considering cross-sectoral flexibility and synergies with other sectors and sources of emissions. There is no predefined 'agricultural carbon budget' assigned to countries. Instead of being isolated efforts that could lead to unintended consequences or inefficiencies, emission reduction strategies should recognize the interconnected nature of sectors like agriculture, energy, transportation, and land use.

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This brief was prepared by Davide Cozza [a], Maria Diaz [a], and Aline Mosnier [a].

Contributors include Ankit Saha [b], Vartika Singh [c], Wanderson Costa [d], Alex Koberle [d], Guillaume Lafortune [a], Isabella Massa [a], Clara Douzal [a], John Lynch [e], Hisham Zerriffi [f], Adrian Monjeau [g], Konstantinos Dellis [h], Emil Fraas [i], Simone Højte [i], Michella Molin [i], and Michael Obersteiner [e].

External reviewer: Kirian Mischke-Reeds [j].

[a] Sustainable Development Solutions Network (SDSN)
[b] Indian Institute of Management Ahmedabad (IIM-A)
[c] International Food Policy Research Institute (IFPRI)
[d] University of Lisbon
[e] Oxford University
[f] University of British Columbia
[g] Fundación Bariloche
[h] AE4RIA
[i] CONCITO
[j] World Resources Institute (WRI)

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Appendix A

Methods and equations

The methodology is a result of a revision of the equations used by Yuwono et al. 2023.[37]

Historical Responsibility (HR)

$$\forall E_{W,t} \geq 0, \qquad E_{i,t} = E_{W,t} \cdot \frac{|RI_{i,t-1}|}{\sum_{\forall i} |RI_{i,t-1}|}$$

where:

$$RI_{i,t-1} = Pop_{i,t-1} \cdot \frac{\sum_{t_h}^{t} Pop_{i,t-1}}{\sum_{t_h}^{t} E_{i,t-1}}$$

$\boldsymbol{E_{i,t}}$: Emissions of country i at time t

$\boldsymbol{E_{W,t}}$: Global Carbon Budget at time t

$\boldsymbol{Pop_{i,t}}$: Population of country i at time t

$\boldsymbol{RI_{i,t-1}}$: Responsibility Index, that is the inverse share of cumulative per-capita emissions, multiplied by the population size at year t -1

t = 2050

Ability to Pay (AP)

$$\forall E_{W,t} \geq 0, \quad E_{i,t} = E_{W,t} \cdot \frac{CI_{i,t-1} * VI^{\beta}{}_{i,t-1}}{\sum_{\forall i}(CI_{i,t-1} * VI^{\beta}{}_{i,t-1})}$$

where:

$$CI_{i,t-1} = Pop_{i,t-1} \cdot \frac{\sum_{t_h}^{t} Pop_{i,t-1}}{\sum_{t_h}^{t} GDP_{i,t-1}}$$

$\boldsymbol{GDP_{i,t}}$: GDP of country i at time t

$\boldsymbol{CI_{i,t-1}}$: Capability Index, that is the inverse-share of cumulative per-capita GDP, multiplied by the population size at year t

$\boldsymbol{VI^{\beta}{}_{i,t-1}}$: Vulnerability Index, it can range from 0 to 1, where higher values indicate greater vulnerability. The ND-GAIN Country Index have been used[16] and adapted.

$\boldsymbol{\beta}$ is a parameter to control the weight given to the Vulnerability Index. If β=1, the Vulnerability Index is applied linearly. If β>1, the Vulnerability Index has a greater impact on the distribution. If β <1, the Vulnerability Index has a smaller impact. In our study, β=1.

The Vulnerability index is used to reflect that it's not just about how much wealth a country produces, but how much of that wealth it may need to allocate to address its own vulnerability. In this way, for two countries with similar GDP levels, the more vulnerable one will receive more emission allowances, because a greater share of its resources is likely to be needed to cope with the impacts of climate change. The index helps to account for differences in climate exposure, resilience, and adaptive capacity that are not fully captured in GDP projections.

Immediate per capita convergence (IEPC)

$$\forall t > t_0, \; \frac{E_{i,t}}{Pop_{i,t}} = \frac{E_{W,t}}{\sum_{\forall i} Pop_{i,t}}$$

then:

$$E_{i,t} = E_{W,t} \cdot \frac{Pop_{i,t}}{\sum_{\forall i} Pop_{i,t}}$$

Integration of food and agriculture indexes

After having computed the fair allowances according to the three approaches, food and agriculture-related indicators, namely the **Yield Gap and Self-Sufficiency ratio (SSR),** have been incorporated into the methodology to adjust the fair allowances and not compromise agricultural production, while aiming at reducing agricultural emissions.

A large yield gap indicates substantial potential for enhancing food production through improved practices or technology. Therefore, a large yield gap necessitates a downward adjustment of emissions allowances. This is based on the premise that the negative impacts of reduced emissions allowances on food production can be offset by a country's capacity to increase productivity.

SSR reflects a country's ability to meet its food demand through domestic agricultural production. Countries with lower SSRs are less capable of fulfilling their food needs domestically, which correlates with potentially lower food security. Therefore, countries with lower SSRs should receive more emissions allowances to support their food production and not rely even more on imports.

To incorporate these two indicators into the formula for fair share allowances, both the SSR and yield gap scores have been normalized on a scale of 0 to 1 using the following formulas:

$$SSRNorm_i = 1 - \frac{SSR_i - Min(SSR_i)}{Max\ (SSR_i) - Min\ (SSR_i)}$$

and

$$YieldGapNorm_i = \frac{Max(YieldGap_i) - YieldGap_i}{Max\ (YieldGap_i) - Min\ (YieldGap_i)}$$

Next, equal weights (0.5) have been assigned to these indicators. The formula for adjusted allowances will be:

$$AdjAllowances_i = IniAllowances_i \times (1 + 0.5 \times YieldGapNorm_i + 0.5 \times SSRNorm_i)$$

To ensure the respect of the global carbon budget of 4 $GtCO_2e$ yr-1, the following adjustment has been applied:

$$FinAllowances_i = AdjAllowances_i \times (\frac{GlobalCarbonBudget}{\sum_i AdjAllowances_i})$$

Appendix B

Countries and regions

We test the fair share approaches using the results from the FABLE Consortium,[38] which includes 22 countries and 6 regions. These countries encompass Argentina, Australia, Brazil, Canada, China, Colombia, Denmark, Ethiopia, Finland, Germany, Greece, India, Indonesia, Mexico, Norway, Nepal, Russia, Rwanda, Turkey, the UK, and the USA.

Recognizing that the FABLE consortium does not include all nations globally, models were developed for 6 additional "rest of the world" regions: Rest of Asia Pacific, Rest of Central and South America, Rest of Non-EU, Rest of EU, Rest of Sub-Saharan Africa, and Rest of Middle East and Central Asia, which results are not showed in this study.

The results are finally aggregated at the five clusters level, based on geographical proximity and economic similarities: (i) Asia (India, Nepal, Indonesia, China, Russia, 'Rest of Asia Pacific'; (ii) Central & South America (Brazil, Mexico, Colombia, Argentina, 'Rest of Central and South America'); (iii) North Africa & Middle East ('Rest of North

Africa and Middle East'); (iv) Sub-Saharan Africa (Ethiopia, Rwanda, 'Rest of Sub-Saharan Africa'); and (v) Europe, North America & Australia (United States, Canada, Australia, the United Kingdom, Germany, Denmark, Finland, Sweden, Greece, Norway, Turkey, 'Rest of EU', 'Rest of Non-EU').

Appendix C

Data sources

The data used in this analysis originates from various sources:

Projections for future emissions are sourced from the Scenathon 2023 dataset [18] and consider GHG emissions from crop production—such as CO_2 and N_2O from energy use, N_2O from manure applied to cropland and synthetic fertilizers, and CH_4 from rice cultivation—as well as emissions from livestock, including CH_4 from enteric fermentation and manure management, and N_2O from manure left on pastures.

For historical emissions data, particularly pertinent to the HR, the PRIMAP Database is referenced [39]. This database is constructed around production-based emissions. Global agricultural emissions have been considered (entity = "Kyoto greenhouse gases (AR6)" and category code = "M.AG").

Historical GDP [40] and historical population size [41] (1961-2019) are sourced from the World Bank data. Future GDP and future population size (2020-2050) are also extracted from the Scenathon 2023, with values subject to change based on the pathways. The values are directly dependent on the assumptions that the country teams in the FABLE Consortium made.

Appendix D

Global target for reducing agricultural emissions

The target on which the fair share methodology has been applied is limiting global agricultural emissions to 4 $GtCO_2e$ e yr-1 by 2050. To ensure that the collective national and regional pathways align with sustainable development objectives, it is imperative to establish global benchmarks across food and land-use system domains [42]. These benchmarks draw heavily on planetary boundaries [43]and are formulated through a combination of science-based and political targets.

Scenathons' Climate targets adhere to the Paris Agreement's stipulation of staying within 1.5 °C of global warming, informed by Integrated Assessment Models (IAM) scenario ensembles [44-46]. Additional sources to design the GHG emissions target include International Energy Agency 2021; Roe et al. 2021; 2023a; UNEP 2021.