FABLE CONSORTIUM

The Food and Land Use Coalition

National food and land mitigation pathways for net zero

FABLE Policy Brief
October 2022

Headlines

- Net zero climate commitments from countries represent nearly 90% of current greenhouse gas (GHG) emissions and if achieved, **global warming could be held within 2°C above pre-industrial levels**.
- The **Agriculture, Forestry and Other Land Uses (AFOLU) sector is critical** to increasing land-based carbon removals and reducing non-CO_2 GHG emissions. However, sectoral targets and a clear action map are often lacking in current nationally determined contributions (NDCs) and net zero targets.
- This brief proposes a **typology of six profiles for countries to facilitate the prioritization of actions** that can deliver significant climate change mitigation from the food and land use systems.
- Actions required range from **changes in food consumption patterns** and **in agricultural productivity**; to **halting deforestation** and **agricultural land expansion**; to **restoring former agricultural land** and **conducting large-scale afforestation**.
- It is critical that countries implement tailored actions promoting sustainable consumption and production to **be on track with 2050 climate mitigation goals**.
- The degree of the contribution to net zero climate targets is greatly determined by the land-based CO_2 removal potential and the overall CO_2 intensity of the economy. Therefore, **transparency around a country's global role and responsibility on GHG emissions is needed, as well as investments in innovation and technology-based solutions**.

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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[1]. FABLE is convened as part of the Food and Land Use Coalition (FOLU). The Consortium brings together teams of researchers from 20 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). Reports published in 2019 and 2020 describe the FABLE approach to developing pathways to sustainable food and land-use systems.

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

1. Net zero targets: Why and how?

To achieve the communicated net zero targets, countries need to incorporate emissions from their food and land use systems into their long- and short-term climate strategies.

The Paris Agreement sets a long-term temperature goal of holding global warming to well **below 2°C above pre-industrial levels and ideally below 1.5°C**; otherwise, climate change impacts are likely to be severe[2,3,4]. Global warming is mainly driven by carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions. Pathways compatible with the Paris Agreement achieve **carbon neutrality (net zero CO_2) by 2050**. Net negative CO_2 emissions alongside significant reductions in other GHG emissions need to follow, thereinafter to achieve **climate neutrality (net zero GHG) ideally by 2070**[5,6]. "Net" indicates that residual emissions are still possible if they are offset by removals[5,6].

As of today, **129 countries have communicated net zero targets** representing 88% of current total GHG emissions[7,8] (Figure 1, Annex). If achieved, the world could be close to meeting the Paris Agreement (Box 1). However, less than half are transcribed in law or policies, and many are not well-defined (Figure 1). The documents lack sectoral details to inform implementation roadmaps. Urgent action is needed to limit global warming below 2°C as the remaining carbon budget will be depleted within decades under the current level of emissions[9].

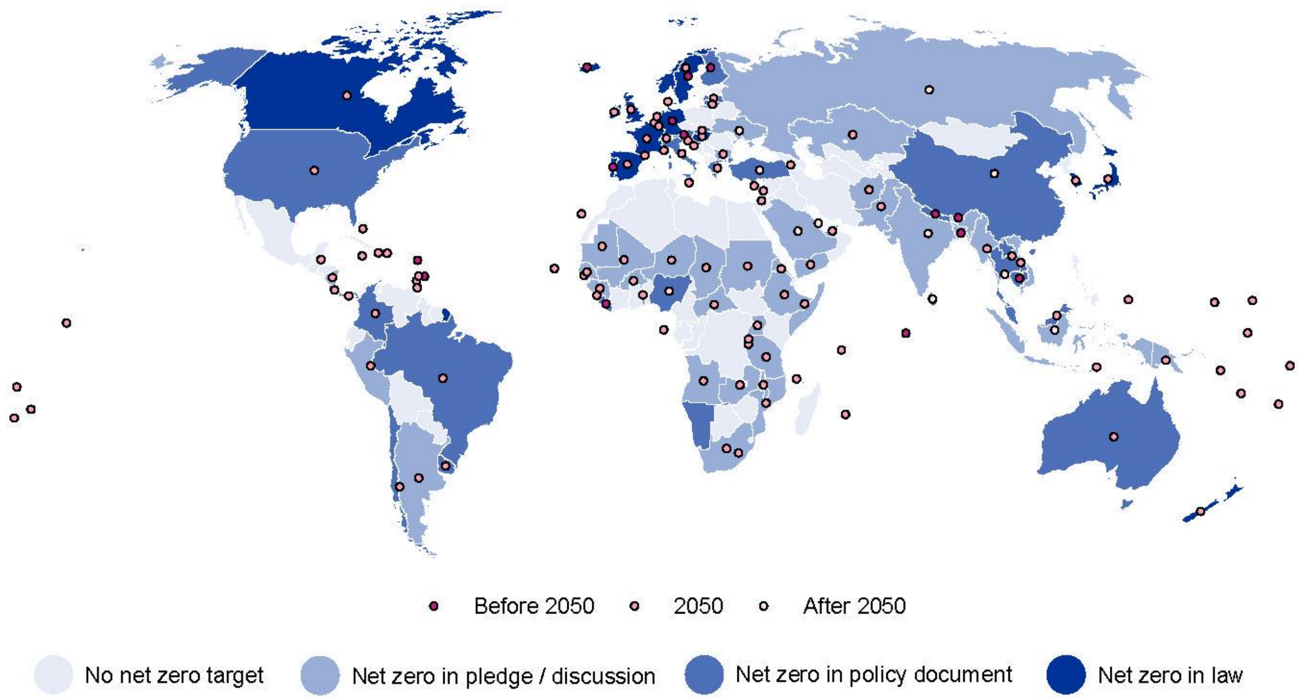
To reach carbon neutrality, countries need to decarbonize their energy systems and extend their carbon sinks[10]. Land carbon sinks such as soils and forests play an essential part. It is estimated that emissions from the Land use, Land-use change, and Forestry (LULUCF) sector need to be carbon negative by 2050[11]; a stark contrast to the sector's current global net emissions of ˜5.5 Gt CO_2e mainly caused by deforestation, peat drainage, and human-induced fires[12].

The highest GHGs in volume, next to CO_2, are methane (CH_4) and nitrous oxide (N_2O). **Pathways to climate neutrality must also cut those emissions**[4,14]. Agriculture accounts for 41% and 75% of global CH_4 and N_2O emissions respectively[13] with the main emission sources being livestock production, mineral fertilizers use, and rice cultivation[14].

Under the Intergovernmental Panel on Climate Change (IPCC), anthropogenic GHG emissions from Agriculture and LULUCF are aggregated as Agriculture, Forestry, and Other Land Use (AFOLU)[15]. In 2019, the AFOLU sector accounted for 22% of global GHG emissions[12,16]. The volume as well as the discussed impacts make it essential to incorporate the AFOLU sector when developing long- and short-term climate strategies (Box 1). We adopt a food and land use system lens to emphasize the critical role of demand- and supply-side actions and to ensure other sustainable development goals are considered.

This brief **enables countries to identify priority actions in their food and land use systems** to help meet net-zero targets and hold global warming below 2°C. It guides the countries to a set of tailored actions through the use of the FABLE modelling framework[17] and highlights the extent to which the food and land use systems can contribute to net zero targets.

Figure 1: Overview of the political depth of net zero targets and net zero target year by country



Source: Net Zero Tracker (2022); Climate Watch (2022); Authors (cf. Annex for data harmonization)

Box 1: Are nationally determined contributions aligned with net zero commitments?

Under the Paris Agreement, countries have committed to develop, enhance and communicate their post-2020 nationally determined contributions (NDCs) every five years. NDCs are critical strategic policy documents that set national emission targets and mitigation priorities considering national circumstances[18]. Up to the end of 2021, most countries had submitted first or updated NDCs to the UNFCCC covering 94.3% of global GHG emissions with AFOLU-related actions making up about 25% of planned GHG reductions by 2030[8,19].

It is estimated that should all announced targets – including net zero targets, long-term strategies (LTS), and NDCs – be fully implemented global warming could be limited to ~1.95°C (estimates range from 1.3 to 3°C) by the end of the century. Full implementation of only the immediate actions under current NDCs, however, would have the world experience a global warming of ~2.6°C (estimates range from 1.9 to 3.7°C) by 2100[4,18]. Based on the analysis of the Climate Action Tracker and other researchers, the actions contained in current NDCs are not ambitious enough and not aligned with mid-century net zero commitments. To achieve these net zero targets, ambitious actions need both to start this decade and to be reflected in NDCs[4,20].

The Food, Environment, Land and Development (FELD) Action Tracker reveals that most countries mention the AFOLU sector in their NDCs, but only few specify sectoral targets, concrete policy measures and mitigation actions across the whole range of food and land use systems[21]. An updated analysis of 24 NDCs from G20 and FOLU partner countries indicates that countries need to integrate and align their NDCs and net zero strategies around effective policy action with operational implementation and adequate financing[21].

2. Food and land use mitigation profiles

We use a typology that groups countries according to their food consumption patterns, their land-based CO_2 removal potential and their current AFOLU emissions.

Actions impact food and land use systems on the supply and demand side, differing between countries. Therefore, three criteria are used to group countries according to common properties of their food and land use systems (Figure 2):

- **Food consumption patterns**
- **Land-based CO_2 removal potential**
- **AFOLU emission patterns**

Reducing excessive food consumption and/or changing diets can cut pressure from Agriculture on resources, avoid the destruction of natural ecosystems and lead to reduced GHG emissions as well as co-benefits for health[22]. In this brief, we use a threshold of 3,000 kcal/cap/day to highlight excessive food consumption in a country. Using the EAT-Lancet Commission recommendations, a threshold of 60 kcal/cap/day is applied to define excessive red meat consumption[a,25].

To achieve the climate targets, large CO_2 removals from land will be required to offset residual emissions[10]. We consider the land-based CO_2 removal potential as substantial in a country if it can abate at least 20% of current GHG emissions (excluding LULUCF)[b].

The composition of the current AFOLU emissions reveals whether countries currently have land-based CO_2 removal (LULUCF < 0 CO_2e) to build on, and whether LULUCF removals can compensate for agricultural emissions (Agricultural emissions CO_2e > LULUCF removals CO_2e).

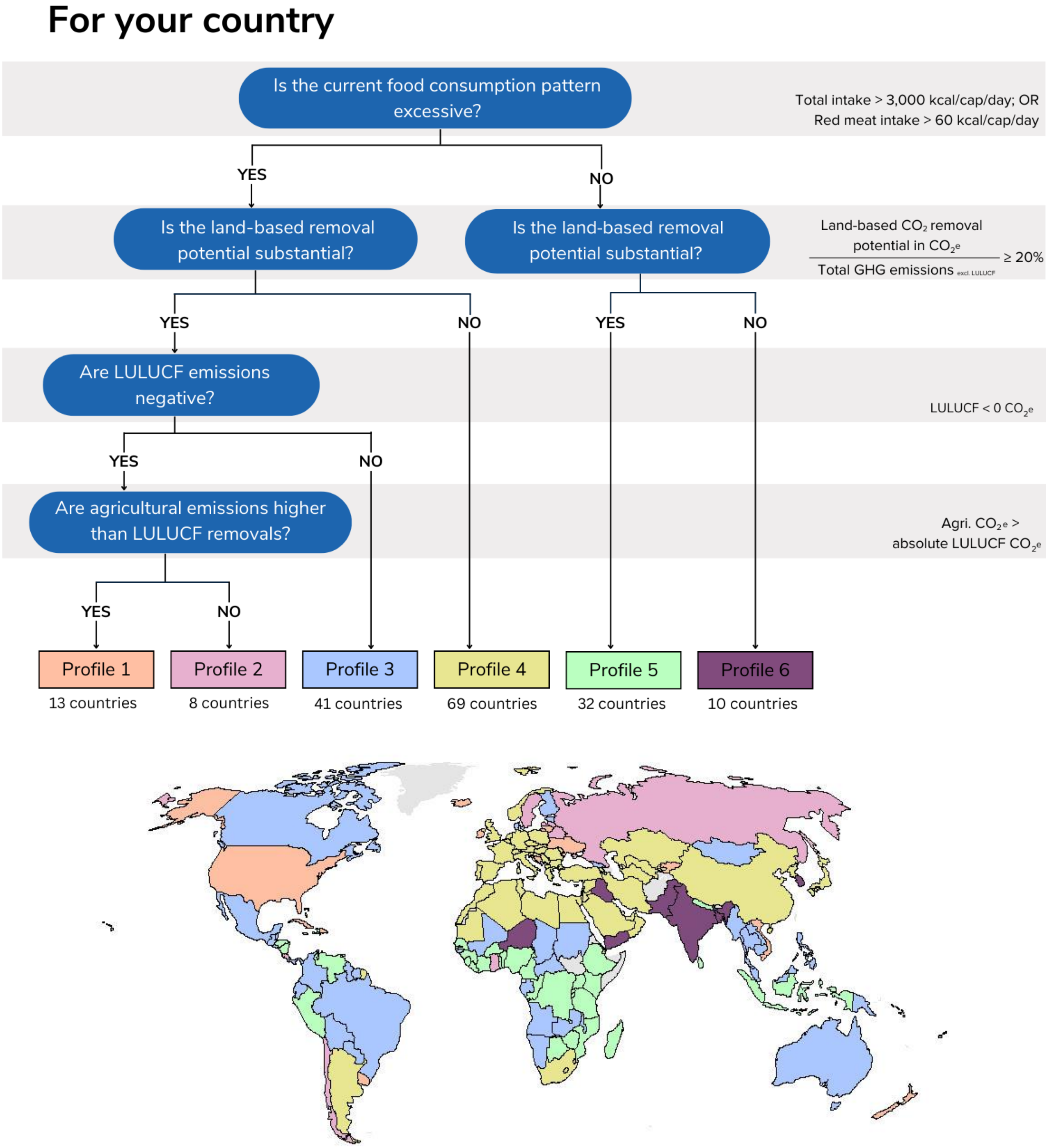
These three criteria group countries where similar actions must be prioritized in order to significantly reduce GHG emissions and increase GHG removals from the food and land use systems. From these criteria, six country profiles emerge (Figure 2).

In this brief, we are using FAO data from 2019 for GHG emissions and food consumption as well as data on the technical annual land CO_2 removal potential from Roe et al. (2021) for the typology. A country's allocation to a profile is determined highly by the data sources used and the thresholds applied. The implications of different input data and/or threshold choices on the country allocation to the profiles can be tested in the FABLE Profile tool provided as supplementary material.

[a] The recommended average daily intake reflecting the country's age and gender structure is between ~2,000 and 2,200 kilocalories (kcal)[23]. Red meat includes beef, sheep and goat, and pork meat. Red meat production is one of the main sources of emissions from agriculture and has the highest GHG footprint compared to other food products[24].

[b] Here, land-based CO_2 removal potential includes the technical potential from forests and other ecosystems such as re/afforestation, forest management, management, and restoration of peatland and wetland. CO_2 removal on agricultural land (e.g., through agroforestry and soil carbon sequestration) is excluded as it can quickly be reversed with changes in agricultural practices, and data uncertainty is very large.

Figure 2: Typology of food and land use mitigation profiles and respective country mapping



Notes: Food and land use mitigation profile dashboards are provided as supplementary material to easily find ones country. Countries are allocated under each profile based on 2019 emission data from FAOSTAT and land-based CO_2 removal potential from Roe et al. (2021). Small Islands in the Pacific are not visible on the map but are found under Profile 6.

While land-based CO_2 removal potential is high for countries in profiles 3 and 5, LULUCF currently contributes significantly to total AFOLU emissions.

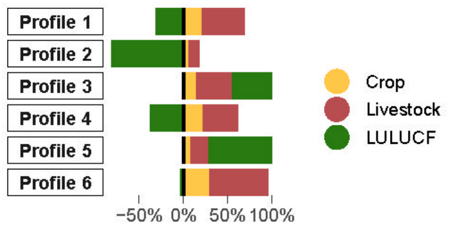
Profile 1: Despite LULUCF being a carbon sink, AFOLU is a net emitter with significant livestock emissions (Figure 3). Both total food and red meat consumption is excessive[14]. The land-based CO_2 removal potential could abate ~43% of the current total GHG emissions (excl. LULUCF) mainly through re/afforestation[19].
FABLE country: USA.

Profile 2: CO_2 removals offset the emissions from Agriculture resulting in AFOLU being a net sink (Figure 3). Land-based CO_2 removal potential could abate ~86% of the current total GHG emissions (excl. LULUCF) mainly through forest management, restoration of peatland, and re/afforestation[19]. In almost all countries, both, total food and red meat consumption are excessive[14]. Most countries are in temperate and polar climate zones.
FABLE countries: Russia, Sweden.

Profile 3: AFOLU is a net emitter with significant emissions from LULUCF (Figure 3). In many countries, the total food consumption is not excessive, but red meat consumption needs to be reduced. The land-based CO_2 removal potential could abate more than the current total GHG emissions (excl. LULUCF) mainly through re/afforestation[19]. This is the second largest group, and it is spread over the continents.
FABLE countries: Brazil, Canada, Colombia, Finland, Malaysia, Mexico.

Profile 4: AFOLU is a net emitter with agricultural emissions being higher than CO_2 removals (Figure 3). On average, current LULUCF emissions are negative but it is estimated that land-based CO_2 removal potential remains limited (~5% of the current total GHG emissions excl. LULUCF)[19]. The share of crop emissions tends to be higher than in the other profiles. About half of the countries overconsume both total food and red meat, while the other countries overconsume only red meat with sometimes low total food intake. This is the largest group of countries and mostly lies in sub-tropical and temperate zones.
FABLE countries: Argentina, China, Germany, Norway, South Africa, United Kingdom.

Figure 3: Composition of AFOLU emissions by profile



Source: Authors' calculation based on FAOSTAT (2022).

Profile 5: LULUCF emissions largely dominate AFOLU emissions (Figure 3). The food consumption pattern is below excessive limits[14]. The land-based CO_2 removal potential could abate more than the current GHG emissions (excl. LULUCF) mainly through re/afforestation and restored peatland[19]. This is the third largest group of countries with most in tropical zones.
FABLE countries: Ethiopia, Indonesia, Rwanda.

Profile 6: Agricultural emissions largely dominate AFOLU emissions. Food consumption is not in excess[14]. The land-based CO_2 removal potential could only abate ~6% of the current total GHG emissions (excl. LULUCF)[19]. It includes countries in sub-tropical and tropical zones, with a high population density and many small islands.
FABLE country: India.

3. How to reduce AFOLU emissions?

AFOLU mitigation levers

Actions on both the demand and supply side of food and land use systems are required to maximize the contribution of AFOLU to net zero targets and to avoid potential negative impacts of mitigation measures on food security and environmental sustainability.

The levers can reduce the need for agricultural land, creating opportunities for increased land-based CO_2 removals.

This brief uses results from the FABLE Scenathon 2021[17] (cf. Annex) to assess the impact of main levers on AFOLU emissions for the identified profiles. Mitigation levers represented in our models – the FABLE Calculator and MAgPIE – are dietary shifts, decreases in food waste and/or post-harvest losses, increases in crop and livestock productivity, constraints on agricultural land expansion, and re- or afforestation (cf. Annex)[17, 26].

Other mitigation levers such as the implementation of regenerative agricultural techniques and/or climate change adaptation and mitigation measures, bioenergy with carbon capture and storage (BECCS), or improved forest management are not being assessed further in this brief. This leads to a possible underestimation of GHG emissions abatement from AFOLU which will be discussed in the context of the country case studies.

Constraints on trade are introduced in each national and regional model to ensure estimated future import quantities are balanced at these levels against global exports[1].

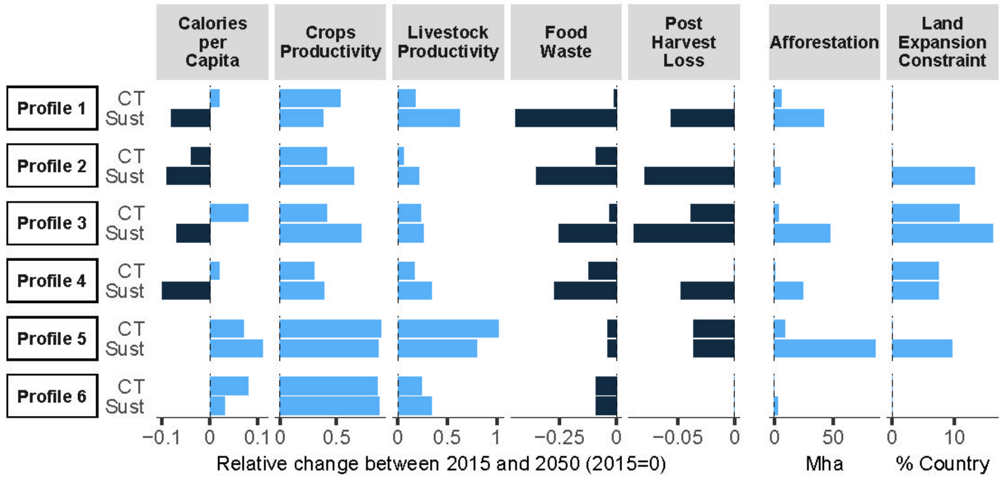
We compare the results of two pathways by 2050 that have been computed for 20 countries and six rest-of-the-world regions: the ***Current Trends*** pathway depicts a low ambition of feasible action towards environmental sustainability; the ***Sustainable*** pathway corresponds to a higher ambition towards environmental sustainability.

Our results show that our *Sustainable* pathway could be compatible with the Paris agreement where global emissions from Agriculture are limited at 4 Gt CO_2e and LULUCF emissions are negative by 2050[11].

Results by profile

Figure 4 shows for each profile the average changes for the modelled mitigation levers. The resulting AFOLU abatement by source, calculated as the difference between the cumulative AFOLU emissions over 2020 to 2050 in the *Sustainable* pathway relative to the *Current Trends* pathway are found in Figure 5.

Figure 4: Levers implemented up to 2050 by profile



Source: Authors' calculation based on FABLE Scenathon 2021.

Notes: CT= Current Trends pathway and Sust = Sustainable pathway. Productivity is measured in average kcal per ha for crops and average kcal per livestock unit. Food waste is measured as the change in the share of wasted kcal consumption. Post-harvest loss is measured as the change in the share of production that is lost. Afforestation is measured in absolute change (Mha). Land expansion constraint is measured in the percentage of countries in a profile that has set a constraint.

The mitigation levers implemented to achieve more sustainable food and land use pathways vary across countries.

Compared to the current situation, in the *Sustainable* pathway, countries with excessive food consumption (Profiles 1,2,3, and 4) reduce their average calorie consumption and food waste and loss and countries with consumption below excessive limits (Profiles 5 and 6) increase their calorie consumption per capita while reducing food waste (Figure 4). These shifts lead to a reduction in global demand, production, and trade of animal-sourced food, resulting in reduced livestock emissions between 2020 to 2050 (Figure 5).

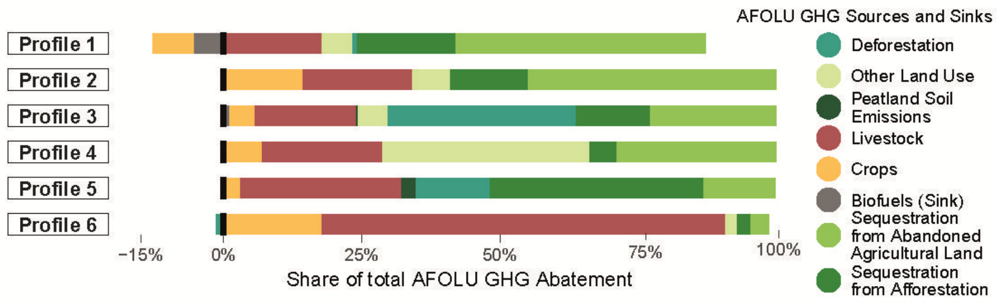
In most countries, agricultural productivity will increase more in the *Sustainable* pathway than in the *Current Trends* pathway (Figure 4). This leads to a lower emission intensity per ton of product in 2050. Countries in Profile 1 will foster extensive agricultural production in the *Sustainable* pathway with a relatively lower increase in crop productivity compared to *Current Trends*.

Overall, these changes would reduce agricultural emissions between 2020 to 2050 in the *Sustainable* pathway relative to the *Current Trends* pathway while keeping production at a sustainable level (Figure 5). Livestock emissions would be reduced by 20% to 30% for Profiles 1 to 5 and by 74% for Profile 6 up to 2050. For Profiles 2 to 6, crop emissions would reduce by 3% to 17% in the *Sustainable* pathway. Under Profile 1, countries experience an increase in crop emissions (10%) due to higher production of fruits and vegetables, nuts, and pulses (Figure 5). The transformation of agricultural production enables a reduction of agricultural land where natural vegetation could regrow and remove up to 61% of cumulative AFOLU emissions in the *Sustainable* pathway (Figure 5).

Except for countries in Profile 6, LULUCF accounts for more than half of the total AFOLU mitigation between our *Current Trends* and *Sustainable* pathways (Figure 5). In countries from Profiles 1 and 2, LULUCF emissions mitigation is mainly achieved through agricultural land abandonment and increased afforestation targets; under Profile 3 and 5 it is through avoided deforestation and afforestation; and under Profile 4 through avoided non-forest natural land conversion and agricultural land abandonment (Figure 5).

As countries under Profile 6 improve their food and nutrition status, they also increase agricultural production. Therefore, slightly higher deforestation occurs under the *Sustainable* pathway (Figure 5).

Figure 5: Main AFOLU GHG sources of abatement for Sustainable pathway relative to Current Trends by profile (2020–2050)



Source: Authors' calculation based on FABLE Scenathon 2021.

Notes: Profile 1 includes country results for the US, Profile 2 for Russia and Sweden, Profile 3 for Brazil, Canada, Colombia, Finland, and Mexico, Profile 4 for Argentina, China, Germany, Norway, South Africa, and the United Kingdom, Profile 5 for Ethiopia, Indonesia, and Rwanda, and Profile 6 for India. The rest of the world regions are included as a weighted average based on the number of countries from a region included in each profile. Negative numbers mean that this source has led to higher emissions.

In the next section, we use the results from four country case studies with different profiles to give further insights into the main actions needed to reduce AFOLU emissions and how this can contribute to meeting the country's net zero target.

4. Country case studies

Argentina's current emissions and climate targets

Note: The 2030 NDC target applies to all GHG emissions while the net 2050 zero target applies to CO_2 emissions only.

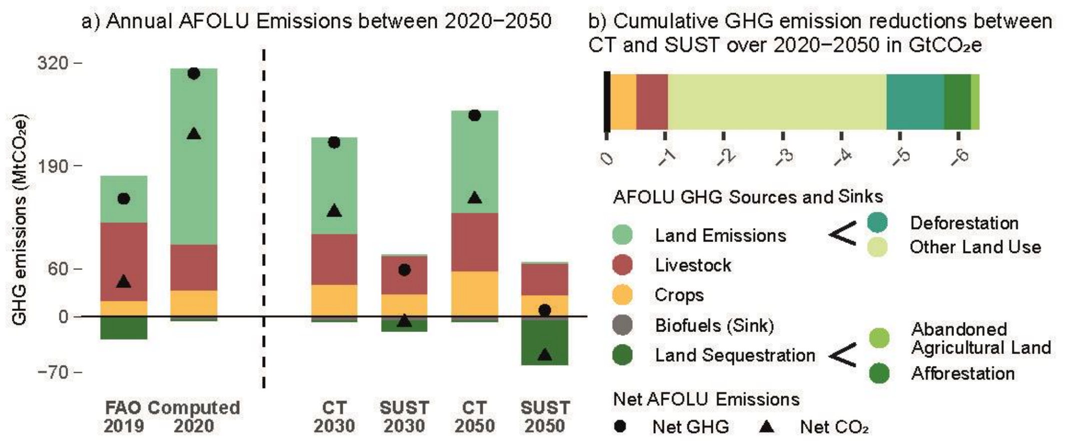
Argentina

In 2019, food consumption patterns were excessive with a total calorie intake of 3304 kcal/cap/day and an intake of red meat of 421 kcal/cap/day[14]. The land-based CO_2 removal potential is not substantial (11% of current total GHG emissions excl. LULUCF)[19,14]. AFOLU is a net emitter (149 Mt CO_2e) with Agriculture accounting for the vast majority of AFOLU emissions (67%), mainly from livestock production[14] (Figure 6). According to our typology, Argentina is grouped under Profile 4.

Under a *Sustainable* pathway, Argentina is projected to reduce net AFOLU emissions to 7 Mt CO_2e, remaining a net GHG emitter by 2050 while LULUCF turns into a carbon sink (-56 Mt CO_2e). **By 2050, AFOLU could be carbon negative**. Livestock emissions reduce by 47% compared to the current trend. The main sources of abatement are avoided emissions from converting natural land and from deforestation, avoiding 74% of AFOLU emissions (Figure 6). Reducing pressure on land enables this mitigation potential.

The changes are mainly driven by limiting agricultural land expansion (especially halting deforestation and increasing protected areas), increasing afforestation targets as well as agricultural productivity.

Figure 6: Argentina's AFOLU emissions and abatement (2020–2050)



Notes: CT = Current Trends pathway and SUST = Sustainable pathway
GHG emissions are converted by using the IPCC Second Assessment Report GWP. FAO 2019 emissions exclude energy on farm. FABLE computation for 2020 is calibrated by using official data and expert knowledge data from country teams, excluding GHG fluxes in managed forests.

From other studies[27], it is estimated that reaching overall carbon neutrality by 2050 would require reduced emissions of around 235 Mt CO_2e from transport, industry, household demand reductions, energy generation, industrial processes and residues, and land-based CO_2 removal of 120 Mt CO_2e. Our results show that the LULUCF sector can become a carbon sink by 2050 (-56 Mt CO_2e). Meeting the target would require additional afforestation on 2.5 Mha[27]. This would involve embarking on a land use change trajectory very different from the one that has occurred during the last 20 years.

Ethiopia's current emissions and climate targets

Note: The 2030 NDC target applies to all GHG emissions while the 2050 net zero target applies to CO_2 emissions only.

Ethiopia

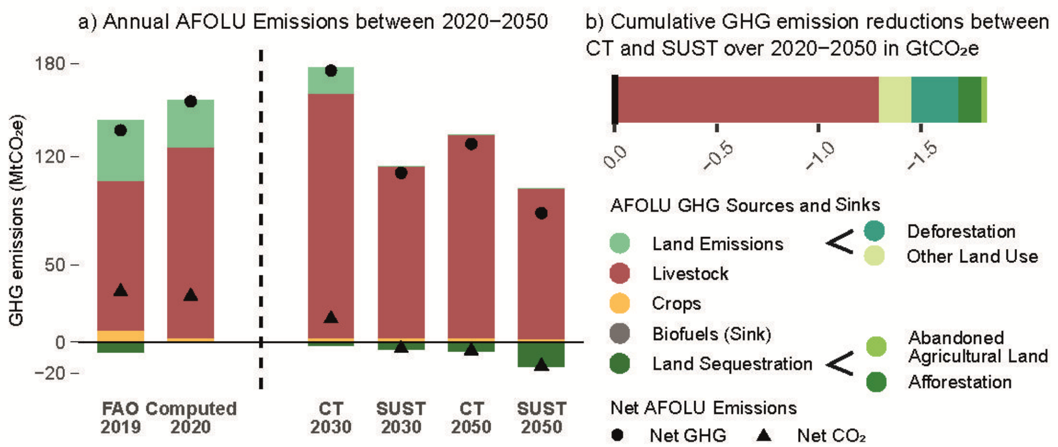
In 2019, food consumption patterns were not excessive with a total calorie intake of 2439 kcal/cap/day and a red meat intake of 30 kcal/cap/day[14]. The CO_2 removal potential on land is substantial (76% of current total GHG emissions excl. LULUCF)[19,14]. AFOLU is a net emitter (137 Mt CO_2e) and accounts for 81% of total GHG emissions with the vast majority caused by livestock production[14] (Figure 7). According to our typology, Ethiopia is included in Profile 5.

Under a *Sustainable* pathway, AFOLU is projected to remain a net GHG emitter (83 Mt CO_2e) by 2050.

However, emissions can be reduced by 45 Mt CO_2e compared to the current trend and LULUCF turns into a carbon sink (-15 Mt CO_2e). **By 2050, AFOLU could be carbon negative**. The main sources of abatement are reduced livestock emissions (70%), avoided emissions from deforestation (13%) and other land conversion (8%) as well as removed emissions through increased afforestation (6%) (Figure 7).

The changes are mainly driven by the increase in agricultural productivity, limiting agricultural land expansion (especially halting deforestation and increasing protected areas), and increased afforestation targets.

Figure 7: Ethiopia's AFOLU emissions and abatement (2020–2050)

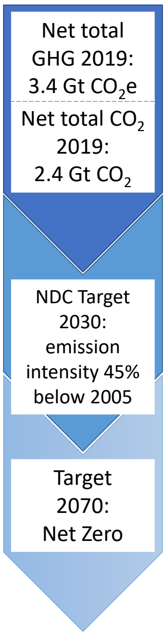


Notes: CT = Current Trends pathway and SUST = Sustainable pathway.
GHG emissions are converted by using the IPCC Second Assessment Report GWP. FAO 2019 emissions exclude energy on farm. Computed emissions exclude GHG fluxes in managed forests.

Under the NDC, it is projected that 86% of total mitigation by 2030 will be achieved through reduced LULUCF emissions[18]. This would require LULUCF to turn into a carbon sink (-99 Mt CO_2e) by 2030[18]. Our results show that this will be hard to realize. We identify a gap of 95 Mt CO_2e which matches the gap foreseen between unconditional and conditional emission reduction. The livestock sector exhibits a reduction of 15 Mt CO_2e per year under the NDC by 2030[18]. Our results show a higher potential of 40 Mt CO_2e yearly by 2030.

Realizing both potentials would reduce total GHG emissions but the achievement of the 2030 and 2050 targets would require more ambitious shifts in the levers represented in our analysis and/or deployment of other measures.

India's current emissions and climate targets



Note: The 2030 NDC target applies to all GHG emissions while the 2050 net zero target applies to CO_2 emissions only.

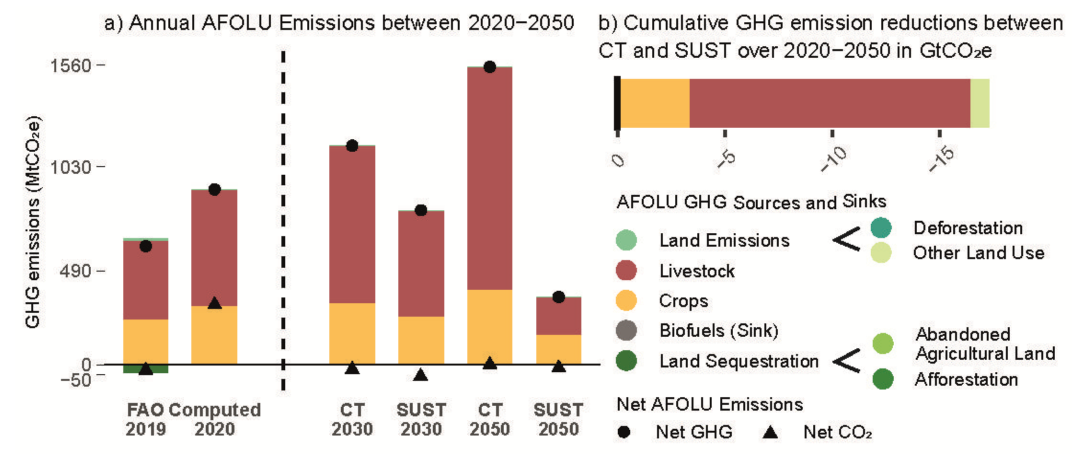
India

In 2019, food consumption patterns were not excessive with a total calorie intake of 2581 kcal/cap/day and an intake of red meat of 9 kcal/cap/day[14]. The land-based CO_2 removal potential is not substantial (12% of current total GHG emissions excl. LULUCF)[19,14]. AFOLU is a net emitter (618 Mt CO_2e) mainly resulting from livestock production (67%). LULUCF is a small carbon sink (-31 Mt CO_2e)[14] (Figure 8). According to our typology, India is included in Profile 6.

Under a *Sustainable* pathway, India's net AFOLU emissions are projected to decrease by -1214 Mt CO_2e in 2050 compared to the current trend but will remain a net GHG emitter (Figure 8). LULUCF remains a carbon sink (-16 Mt CO_2e) wherefore, **AFOLU could be carbon neutral by 2050**. The main sources of abatement are reduced livestock emissions (75%) and crop emissions (19%) (Figure 8).

The main levers inducing the changes are shifts in diets, the increase in agricultural productivity (e.g., increase in nitrogen uptake efficiency and feed use efficiency), and increased afforestation targets.

Figure 8: India's AFOLU emissions and abatement (2020-2050)



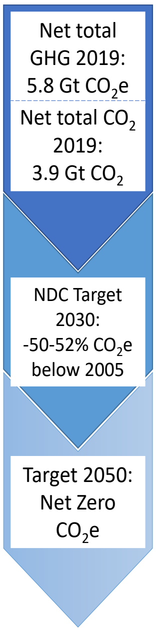
Notes: CT = Current Trends pathway and SUST = Sustainable pathway.
GHG emissions are converted by using the IPCC Second Assessment Report GWP. FAO 2019 AFOLU emissions exclude energy on farm. Computed emissions exclude GHG fluxes in managed forests.

As the land-based mitigation potential is limited, the AFOLU sector can only contribute marginally to India's net zero target by reducing its agricultural emissions. Offsetting residual emissions from other sectors will be daunting. Mitigation needs to occur in the energy sector through technology-based emission removals to achieve the net zero target by 2070.

Reducing agricultural emissions is particularly challenging given the population's high dependency on the sector for both nutritional and livelihood requirements. A move away from traditional rice-wheat production practices towards a more diversified crop production system could contribute. Improving livestock feed efficiency and production system presents a major opportunity to reduce emissions from the livestock sector. This would require overcoming feed and fodder scarcity and improving animal health and breeding.

USA

USA's current emissions and climate targets:



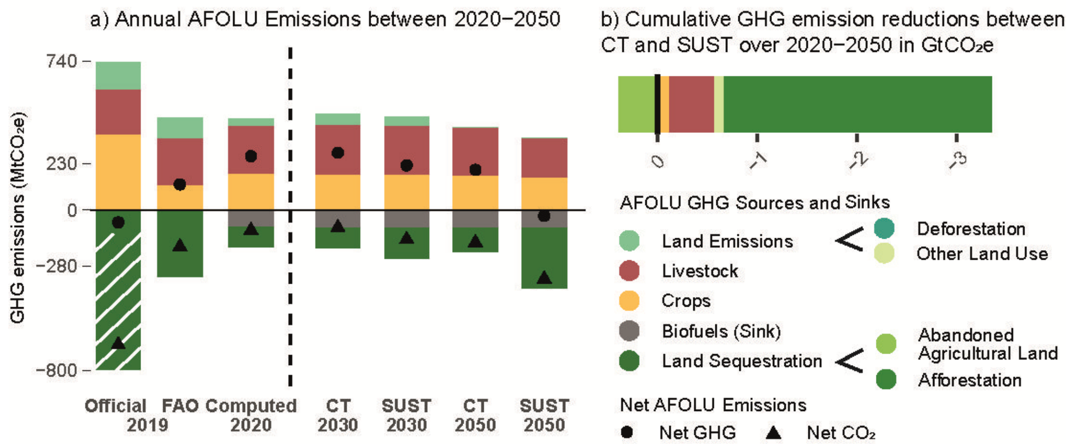
Note: Climate (CO_2e) neutrality by 2050 implicates carbon neutrality.

In 2019, food consumption patterns were excessive with a total calorie intake of 3862 kcal/cap/day and an intake of red meat of 313 kcal/cap/day[14]. The land-based CO_2 removal potential on land is substantial (23% of current total GHG emissions excl. LULUCF)[19,14]. AFOLU is a net emitter (126 Mt CO_2e). According to our typology, the US is grouped under Profile 1 (Figure 9). Using official GHG reporting data would allocate the US to Profile 2 due to sequestration from managed forest.

Under a *Sustainable* pathway, **AFOLU is projected to be a net sink** (-31 Mt CO_2e) **by 2050** (Figure 9). Emissions are reduced by 230 Mt CO_2e compared to the current trend with LULUCF becoming a large carbon sink (-305 Mt CO_2e). Livestock emissions would be reduced by 40%. Afforestation activities result in the largest mitigation potential under the *Sustainable* pathway (81%). Livestock emissions make up 15% and crop production only contributes to 3% of the mitigation potential. Emissions from crop production reduce as dietary shifts result in a strong reduction in feed commodity production. Abandoned land is used for managed afforestation under the *Sustainable* pathway matching the increased afforestation target (Figure 9).

Changes are mainly driven by an increased afforestation target, dietary shifts, and increased productivity.

Figure 9: USA's AFOLU emissions and abatement (2020–2050)



Notes: CT = Current Trends pathway and SUST = Sustainable pathway.
GHG emissions are converted by using the IPCC Second Assessment Report GWP. The white hatched area accounts for sequestration from managed forest. FAO 2019 AFOLU emissions exclude energy on farm. Computed emissions exclude GHG fluxes in managed forests.

Another study estimating the economy-wide mitigation required for climate neutrality by 2050 identified the following mitigation needed[28]: -5 Gt CO_2e/yr from the energy sector (including transportation), -1 Gt CO_2e/yr from the land sink and -1 Gt CO_2e/yr through CO_2-removal technologies. Our results show a gap between required and potential LULUCF CO_2 removal. It should be noted that additional carbon stored in existing forests is not included in our results. Other modelling efforts have found that this would account for around 330 Mt CO_2/yr[28]. Adding this to our CO_2 removal increases the total net sink of land to around 600 Mt CO_2e, leaving a gap of 400 Mt CO_2e by 2050.

5. Towards a food and land mitigation action agenda

The key mitigation actions are tailored to the profiles' food and land use systems properties and are a first step towards a mitigation action agenda

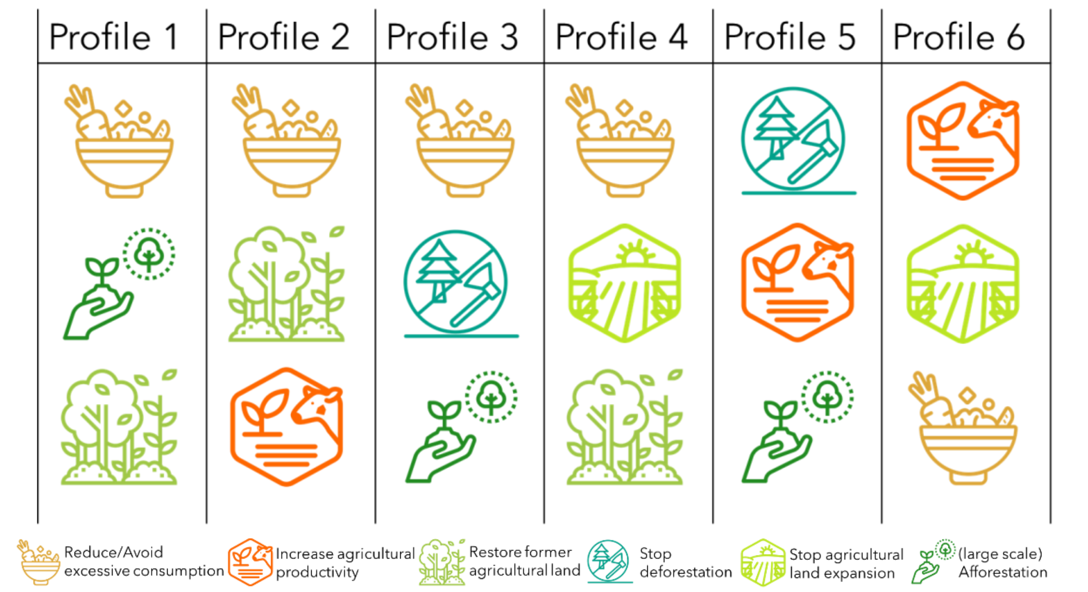
As countries enter the next round of NDCs and need to operationalize their net zero targets, the role of AFOLU should be clarified. Depending on countries' characteristics, the AFOLU mitigation potential and the most important levers vary. Figure 10 summarizes our recommendations on **key mitigation actions that need to be prioritized by each profile and adapted to the national context**. A section on those actions should be systematically included in national climate strategic documents.

Reducing food and red meat overconsumption has large co-benefits for health and spill-over effects for climate mitigation (Profiles 1, 2, 3, and 4). According to our results, this leads to significant carbon sinks on abandoned agricultural land. Climate strategies must include measures to incentivize or compensate farmers, in relation to the national biodiversity strategy.

Zero hunger (Sustainable Development Goal 2) might still be a challenge, even in countries where the average food and/or red meat consumption is above recommended levels. In these contexts, reducing inequalities and increasing access to affordable alternatives will be needed.

In countries without current food and/or red meat overconsumption (Profiles 5 and 6), gains in crop and livestock productivity as well as avoided further conversion of natural ecosystems must be prioritized. In the context of high agricultural commodity prices, enforcement of such policies might be particularly challenging and financial support will be required. Implementing an effective pricing system for AFOLU emissions[16] could facilitate carbon trade.

Figure 10: Recommended Key Mitigation Actions by profile



The **AFOLU sector can play a significant role** in achieving net zero targets in countries where the land-based CO_2 removal potential is substantial (Profiles 1, 2, 3, and 5). But as the country studies show, land-based mitigation alone might not be enough to reach net zero by mid-century. For countries with low land-based CO_2 removal potential (Profiles 4 and 6), **investing in innovation and technology-based removals in other sectors would be crucial** to reach the overall net zero targets. Financial offsetting of emissions by other countries would be another possibility.

Additional mitigation options not considered in this study, i.e., forest management, mitigation technologies in agriculture, agricultural soils, and BECCS, would potentially increase the contribution of AFOLU to climate targets, especially for countries with a low land use CO_2 removal potential. However, uncertainty remains about their actual mitigation potential. In their analysis, Roe et al. (2021) estimates a substantial technical CO_2 removal potential for agricultural soil. Globally, this would more than double the land-based CO_2 removal potential in this brief and more than threefold it for countries under Profiles 4 and 6.

Nonetheless, actions to decarbonize the rest of the economy cannot be delayed[29,20] as carbon stocks in new vegetation and soils will take time to build, and initial CO_2 removal on land can be reversed, including by fire, pests, or disease[29].

Future work should consider the role of adaptation measures in the transition to net zero. By enhancing resilience against diverse risks, weather events, and natural disasters[16], they can buffer the economic impact of immediate climate change on the agricultural sector and protect land carbon stocks. This will enable a smoother transition of the food and land systems onto a net zero trajectory.

To maximize the AFOLU emission reduction potential, countries need to work together. Members of the **FABLE Consortium can support more detailed national mitigation roadmaps for the food and land systems** that are consistent with national priorities and context and that consider actions in other countries.

The **FABLE framework can also be used in the future to highlight the need for more ambitious AFOLU targets** depending on countries' historical responsibilities and current capacity to implement transformations on the land use side.

Acknowledgments

This policy brief was developed with support from the Norwegian Climate and Forest Initiative (NICFI) and World Resources Institute (WRI). The contents and opinions expressed herein are those of the authors and do not necessarily reflect the views of the associated and/or supporting institutions. The usual disclaimer applies.

Supplementary Material

FABLE Profile tool

Food and Land use mitigation profile dashboards

Recommended citation

FABLE (2022). National food and land mitigation pathways for net zero. FABLE Policy Brief. Sustainable Development Solutions Network (SDSN), Paris.

This brief was prepared by Lucie Adenäuer, Aline Mosnier, Clara Douzal, Federico Frank, Adrian Monjeau, Christopher Wade, Gordon McCord, Justin Baker, Grace Wu, Chandan Kumar Jha, Ranjan Kumar Ghosh, Vartika Singh, Prantika Das, Barbara Garza Fuentes, Maria Diaz, Fernando Orduña-Cabrera, Morvarid Bagherzadeh. The brief is based on the FABLE consortium results from the 2021 Scenathon.

Contributors include Livia Rasche, Jan Steinhauser, Alison Smith, Paula Harrison, Hisham Zerriffi, Marcela Olguin, Ingo Fetzer, Valeria Javalera-Rincon, Sarah Jones, Raymundo Marcos-Martinez, Javier Navarro Garcia, Wanderson Costa, Marluce Scarabello, Aline Cristina Soterroni, Fernando Ramos, René Reyes, Avery Maloney, Xinpeng Jin, Zhaohai Bai, Lin Ma, John Chavarro, Andrés Peña, Kiflu Gedefe Molla, Firew Bekele Woldeyes, Heikki Lehtonen, Janne Rämö, Satyam Saxena, Miodrag Stevanovíc, Hermann Lotze-Campen, Habiburrachman A H Fuad, Nurul L. Winarni, Jatna Supriatna, Rizaldi Boer, Gito Immanuel, Wai Sern Low, Andrew Chiah Howe Fan, Charlotte E. Gonzalez-Abraham, Anne Sophie Daloz, Robbie Andrew, Bob van Oort, Anton Strokov, Vladimir Potashnikov, Dative Imanirareba, Fidèle Niyitanga, François Xavier Naramabuye, Odirilwe Selomane, Shyam Basnet, Nicholas Leach, Michael Obersteiner, Katya Pérez-Guzmán, Fabrice DeClerck, Scarlett Benton, Morgan Gillespy, Talia Smith, Sophie Mongalvy, Ed Davey, Cecil Haverkamp, Ryan Swaney, John Flynch, Sofia Ahmed, Alessandro Caprini, Emilie Perge, Seth Cook, Guillaume Lafortune, Trevor Donnellan, Olaf Erenstein, Hugo Valin.

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Annex

Data sources and methodology for the net zero targets' data harmonization

According to Climate Watch, there are 76 countries with net zero targets. On the other hand, Net Zero Tracker Beta indicated 174 countries with targets, where 112 were net zero related (Table A1). The difference in these numbers can be explained by the categorization each source gives to certain targets, the varying definitions in Nationally Determined Contributions and the type of target described. A literature review was carried out to define criteria for a global net zero target definition regarding differences between each country's targets (e.g. zero emissions, climate neutrality, carbon neutral, etc.) to reconcile these differences. The four categories ("Net zero in law", "Net zero in policy document", "Net zero in pledge/discussion" and "No net zero law") were defined after fitting best the targets' status. Countries designated as "achieved" were also revised, so that they could be better understood through any of these four categories depending on their targets.

Table 1: Target category harmonization

Target Category	Climate Watch	Net Zero Tracker Beta	Final Categories
Achieved (self-declared)	0	9	0
In Law	14	17	**17**
In Policy Document	38	57	**42**
In Political Pledge	24	0	0
Proposed or in Discussion	0	71	0
Declaration or Pledge	0	20	0
Pledge / Discussion	0	0	**70**
Total (as of May 2022)	76	174	**129**

Overview of the FABLE modelling framework

We have developed four steps for coordinating bottom-up national pathways to address national priorities, collectively achieve global sustainability objectives, and balance international trade in agricultural commodities: 1) the country teams jointly decide on global targets to be achieved collectively, and each country team applies them to its country context; 2) each FABLE country team integrates national data from many different sources and develops mid-century pathways towards sustainable land-use and food systems; the FABLE Secretariat develops pathways for the rest of the world regions; 3) imports and exports are balanced and key results from the national and regional pathways are aggregated to determine if the global targets are met. Throughout these first three steps, 4) FABLE country teams consult stakeholders to test and refine assumptions, support a shared understanding of food and land use systems, and develop shared ownership of the results. This process is called Scenathon and is repeated annually. The latest version is Scenathon 2021.

Two models have been used: the FABLE Calculator for 20 countries and the rest of the world regions, and MAgPIE for India. The FABLE Calculator is an Excel accounting tool[c] used to study the potential evolution of food and land-use systems over the period 2000–2050 for each five-year time step. It includes 76 raw and processed agricultural

[c] The FABLE Calculator has a very similar structure as the GLOBAGRI[30] and TYFA[31] models

products from the crop and livestock sectors and relies extensively on the FAOSTAT (2021) database for input data. All details are provided in the model documentation [32] and the FABLE Calculator can be downloaded here. It focuses on agriculture as the main driver of land use change and tests the impact of different policies and changes in the drivers of these systems through the combination of a large number of scenarios[32]. MAgPIE is a recursive dynamic cost-minimization model of global land systems developed at PIK. The model simulates crop production, land use patterns, water use for irrigation, and carbon stock changes at a spatial resolution of 0.5° × 0.5° [33]. Associated with the REMIND energy-economy model, it is used in global integrated assessments to support the IPCC.

Each pathway is defined by a combination of scenarios that allow for variation across key parameters of the models. Each of our country teams could select different values for the following parameters: affecting demand (GDP, diets, biofuel use), trade, food loss and waste, productivity, land use restrictions, afforestation, and climate change. In the MAgPIE model, carbon tax is an additional scenario.

Dietary shifts and reductions in food loss and waste decrease livestock and crop emissions by reducing agricultural production, especially of animal-based products. Changes on the demand side also impact AFOLU emissions in exporting countries through trade. Increasing productivity in livestock and crop production, e.g. by nitrogen uptake efficiency, feed use efficiency, or sustainable ruminant density per hectare, lowers the emission intensity per ton of product which reduces AFOLU emissions while keeping production at a sustainable level. Changes through these levers enable a lower conversion of natural land – forests and other ecosystems – to agriculture (avoiding AFOLU emissions), and in some countries, even a reduction of agricultural land where natural vegetation could regrow (removing AFOLU emissions) despite increases in urban land. Limiting agricultural land expansion (including no deforestation beyond 2030 and increasing protected areas) avoids a further increase in CO_2 emissions. Afforestation targets actively remove CO_2. However, we note that this can cause indirect land use change that needs to be carefully monitored.

GHG emissions from Agriculture include emissions from enteric fermentation, manure management, rice cultivation, agricultural soils, and other sources. For all countries, GHG emissions from LULUCF include carbon stock changes due to the conversion of forest and other natural land to cropland, grassland, and urban area, and changes in biomass after grassland and cropland abandonment. GHG emissions from the cultivation of organic soils are included for Finland and Indonesia. Changes in carbon in land not being converted as well as commercial forestry are not included in these pathways.

Changes in country model assumptions to Scenathon 2020

For the US: Under the Sustainable pathway, afforestation targets have been increased from 20 million ha to 40 million ha and it is assumed that livestock productivity increases.

For India: Under the Sustainable pathway, the main assumptions follow a "green road" with higher income per capita and slower growth in population, progressive environmental protection, and faster technological change. The Sustainable Pathway is highly ambitious in meeting the national sustainability objectives, extending dietary shifts, afforestation targets, and bioenergy demand beyond a sustainable level. Sustainable Development Goals (SDGs) are considered a priority and the policy landscape is favorable for the attainment of these goals specifically: SDG2, SDG7, SDG12, SDG13, and SDG15[34]. Efficient technologies in agricultural production are incorporated and dietary transitions follow the recommendations made by the EAT-Lancet Commission[25]. Population growth in this scenario is lower while afforestation targets are higher, as compared to the other scenarios. India's participation in the Paris Agreement and Bonn Challenge are accounted for. Other aspirational goals such as production and greater dependence on biofuels and higher technological change with lower costs of technology change are included. The Sustainable pathway uses a global GHG concentration trajectory that aims to keep global warming below 2°C above pre-industrial temperatures by 2100 (RCP 2.6)[35]. This pathway includes mitigation strategies in the form of GHG prices and second-generation bioenergy demand to make our climate policies more ambitious[36]. The modeled scenarios are harmonized from the model initialization for the year 1995 till 2015, while different scenario policy setups are projected from the year 2020 onwards.