Roadmap for achieving net-zero emissions in global food systems by 2050

Ciniro Costa Jr (c.costajr@cgiar.org)
The Alliance of Bioversity International and CIAT – Multifunctional Landscapes
Eva Wollenberg
The Alliance of Bioversity International and CIAT – Multifunctional Landscapes
Mauricio Benitez
responsAbility
Richard Newman
The Alliance of Bioversity International and CIAT – Sustainable Finance
Nick Gardner
U.S. Dairy
Federico Bellone
UNFCCC Climate Champions

Article

Keywords: low-emissions practices, diet shifts, agriculture value-chains, climate targets

Posted Date: April 19th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1552029/v1

Abstract

Food systems (FSs) emit ~20 $GtCO_2e/y$ (~35% of global greenhouse gas emissions). This level is supposed to raise given the expected increases in food demands, which may threaten global climate targets. By evaluating 60+ scenarios based on existing low-emission and carbon sequestration practices, we estimate that intensifying FSs could reduce its emissions from 21.4 to -2.0 $GtCO_2e/y$ and address increasing food demands without relying on carbon offsets. However, given historical trends and regional contexts, a more diverse portfolio of practices, including diet shifts and new-horizon technologies, will be needed to increase the feasibility of achieving net-zero FSs. One likely pathway consists of implementing practices that shift food production to the 30^{th}-percentile of least emission-intensive FS (~45% emissions reduction), sequester carbon at 50% of its potential (~5 $GtCO_2e/y$) and adopt diet shifts and new-horizon technologies (~6 $GtCO_2e/y$). For a successful transition to happen, the global FS would, in the next decade (2020s), need to implement cost-effective mitigation practices and technologies, supported by improvements in countries' governance and technical assistance, innovative financial mechanisms and research focused on making affordable technologies in the following two decades (2030-2050). This work provides options and a vision to guide global FSs to achieving net-zero by 2050.

Introduction

The Paris Agreement's goal of limiting the increase in global temperature to 1.5° above pre-industrial levels requires rapid and ambitious reductions in global greenhouse gas (GHG) emissions. This can only be achieved by drastic emissions reductions across the energy; industry; transport; buildings; and agriculture, forestry and other land-use (AFOLU) sectors (IPCC, 2014).

Clark et al. (2020) showed that even if fossil fuel emissions stopped now, current trends in global food systems (FSs) would prevent the achievement of the 1.5°C target and threaten the achievement of the 2°C target by the end of the century. However, carbon budgets or net-zero emissions are often only discussed for CO_2 emissions and not for non-CO_2 emissions, such as CH_4 and N_2O, in which FSs, especially agriculture production, are the main source (Hasegawa et al., 2021; Clark et al., 2020; Roe et al., 2021).

Today, FS GHG emissions contribute to roughly a third of global emissions. In 2015, FSs emitted 18 $GtCO_2e$ globally, the largest contributors were agriculture, land use, land-use change activities (~70%) and the remaining emissions coming from other downstream and upstream activities (i.e., retail, transport, consumption, fuel production, waste management, industrial processes and packaging) (Crippa et al., 2021). Since global food production is estimated to increase by 15% in coming decades (FAO, 2018), FS emissions might increase by up to 80% from 2010 to 2050 (Tilman et al., 2014; Bajželj et al., 2014; Springmann et al., 2018; Clark et al., 2020). In addition, there are still almost 700 million people undernourished and living under severe food insecurity (FAO-Stat, 2021) who must be considered in FS planning. Therefore, the Paris Agreement and Sustainable Development Goals can only be achieved with significant contributions from FS, including supply-side measures in agriculture production and demandside measures related to diet changes and reduced food waste (Roe et al., 2019; 2021), while strengthening food security and safety (Steiner et al., 2020).

Substantial GHG emissions reductions in FSs are attainable by implementing low-emission interventions to improve efficiency and nature-based carbon sequestration (Cusack et al., 2021; Roe et al., 2021). Low-emission interventions could result in ~40-70% less GHG intensive production systems compared to today's average levels (Poore & Nemecek, 2018). Additionally, a carbon sequestration potential, of approximately 10 $GtCO_2$ y^{-1}, is associated with FS production under the expansion of agroforestry systems, improved pasture and crop management and application of biochar to soils (Roe et al., 2021).

Nevertheless, the mitigation benefits of improved systems could be offset under food production's current growth trajectory, especially for livestock production (Springmann et al., 2018). Even with higher efficiency, greater production needed to meet growing demand might increase net GHG emissions. This condition suggests that dietary changes, including a reduction in consumption of livestock products and replacement by plant-based foods, is also important to help transition to low-carbon and net-zero food systems (Cusack et al., 2021; Roe et al., 2019; 2021). Furthermore, several technologies developed or under development might help further reduce emissions in the medium and long run, such as feed additives for livestock, novel perennials, soil additives, nanoproducts and intelligent food packaging (Herrero et al., 2020).

Therefore, a combination of actions (e.g., implementation of low-emissions interventions for improving production systems efficiency, promotion of carbon sequestration; reduction in livestock-based protein consumption and deployment of new-horizon technologies) is likely necessary to reduce net GHG emissions of FSs aligned with net-zero emissions strategies (Cusack et al., 2021; Springmann et al., 2018). However, only a few studies have put these actions into perspective to evaluate options for achieving net-zero emissions in global FSs. This work provides a vision global FSs could use as guidance for achieving net-zero emissions by 2050.

Methods

To estimate current and future FS emissions and design strategies to achieve net-zero emissions by 2050, we evaluated emissions from 19 major crop and livestock value chains using production projections provided by FAO (2018) and FS emissions intensities (10^{th}, 20^{th}, 30^{th}, 40^{th} and average) provided by Poore & Nemecek (2018). The business-as-usual food system production assumes that GHG emissions per unit of food produced remain constant at current levels. For livestock value-chain emissions, we deducted emissions from feed production (Poore & Nemecek, 2018) to avoid double-counting the emissions from the production of feed ingredients (e.g., grains).

We estimated changes in FS emissions starting in 2020 through 2050 for multiple scenarios:

- Implementation of low-emissions interventions to shift production to the 40^{th}, 30^{th}, 20^{th} and 10^{th} pctl of least emission-intensive systems (Poore & Nemecek, 2018).This shift fosters more efficient production systems and promotes reductions in deforestation and food loss and waste linked to FS.

- We considered that this shift would promote carbon sequestration in cropland and grassland soils (through best management practices), above and below-ground agroforestry systems and the application of biochar to soils, according to potentials provided in Roe et al. (2021). We tested the realization of those potentials at 50, 75 and 100%. We did not consider the carbon sequestration potential from afforestation and reforestation (A/R) and other natural ecosystem restoration (e.g., mangroves and peatlands) to FS (Roe et al., 2021). We also assumed the eventual spared area used for feed production would be directed to expansion of other crops for human consumption.
- Reduce global production, driven by lower consumption, of livestock-based protein (meat and milk) by 10, 25 and 50%, calculated using the 2050-projected levels as reference (FAO, 2018). We assumed that reducing consumption of livestock products lowers milk and meat production. This process should slow demand growth, and eventually reduce the number of livestock heads – the major GHG source in the agricultural sector.
- Adoption of new-horizon technologies across the food value-chains. These technologies include those that are not yet present on farms but could increase mitigation from GHG–efficient food production practices, land-use change, and carbon sinks (Ahmed et al, 2020), as well as make affordable current not cost-effective practices and technologies (Roe et al., 2021).

We built a pathway towards 2050 by assuming these strategies would be implemented at a rate of 20, 50 and 100% by 2030, 2040 and 2050, respectively. For livestock and rice production, we adjusted Poore & Nemecek (2018) data to reflect the contribution of CH_4 emissions to warming potential using the GWP* concept (Alen et al., 2018; Cain et al., 2019). Under GWP*, stable CH_4 emission rates contribute a relatively small CO_2e emission. Increasing CH_4 emission rates are reflected as a large CO_2e emission and can exceed the GWP_{-100} of CH_4 if rates increase at more than approximately 1% per year. Declining CH_4 emission rates are reported as a negative CO_2e emission and can reach zero CO_2e if emission rates decline by 0.35% per year over 20 years. For that, we consider 2020 as the base year where the GWP* concept was applied. We must also consider that approximately 70% of the emissions from livestock and rice production are in the form of CH_4 (FAO-Stat; 2021) and that approximately 70% of these emissions come from farm level (Poore & Nemecek, 2018).

Results

Food system emissions snapshot

We estimate that global FSs emitted 18.7-21.4 Gt CO_2e/y from 2010 to 2020 (Figure 1). This estimate is consistent with the emissions range of recent estimates covering the same period (9-22 $GtCO_2$e/y) (Vermeulen et al., 2012; Poore & Nemecek, 2018; Rosenzweig et al., 2020; Clark et al., 2020; Crippa et al., 2021; Tubiello et al., 2021). Four value-chains–beef, milk, rice and maize–are responsible for nearly 65% (13.9 $GtCO_2$e) of total FS emissions, and seven value-chains (+ wheat, pig and poultry) are responsible for almost 80% of emissions (17.2 $GtCO_2$e). Livestock production (meat and milk) alone accounts for

60% of total FS emissions (12.6 $GtCO_2e$) (Figure 1). Close to 70% of FS emissions come from land-use change and farming activities (Poore & Nemecek, 2018).

The production of major grains, meat and milk is projected to increase 29-81% by 2050 compared to today's levels (FAO, 2018). Under current average production practices, meeting the 2050 projected food production (FAO, 2018) would increase FS emissions by 38% (~8 $GtCO_2e/y$) and 58% (~11 $GtCO_2e/y$) compared to 2020 and 2010 levels, respectively (Figure 1). These findings are also consistent with previous analyses that have suggested that global FS emissions might increase by up to 80% from 2010 to 2050 (Tilman et al., 2014; Bajželj et al., 2014; Springmann et al., 2018; Clark et al., 2020).

Mitigation potential of low-emission and carbon sequestration food production practices

We find that the adoption of low-emission practices could shift global FS production from the average to the 40th, 30th, 20th and 10th-percentile (pctl) of least emission-intensive systems (Poore & Nemecek, 2018) and could mitigate 9.1-13.2 $GtCO_2e/y$ in 2050 compared to the 2020 base year level (21.4 $GtCO_2e$) (Figure 2). Major contributions would come from livestock and rice value-chains (Figure 2).

Although these FS value-chains are the most emission-intensive, they also have the largest mitigation potential across FSs (Figure 2). For example, improving production practices with existing technologies could reduce emissions by 40%-70% compared to average values: beef from 7.3 to ~2.5 $GtCO_2e/y$, rice from 2.4 to ~1.0 $GtCO_2e/y$ and milk from 2.4 to ~1.0 $GtCO_2e/y$ (Figure 2). Most of this mitigation potential is related to reductions in land-use change (e.g., deforestation for agricultural land expansion), improvements in animal feeding and breeding and manure management, nutrient management (with focus on nitrogen fertilizers), water management in rice paddies and energy efficiency (e.g., renewables) across the value-chain as well as measures to reduce food loss and waste (i.e., improved packaging and storage) (Reisinger et al., 2021; Roe et al., 2021; Poore & Nemecek, 2018; Herrero et al., 2016; Gerber et al., 2013). Also, using a global warming potential accounting for short-lived GHGs (GWP*), like CH_4, means that relatively small annual reductions in CH_4 emissions (~0.3%) can lead to CH_4 warming neutrality in 20 year-time (Costa Jr et al., 2021; Lynch et al., 2020; Allen et al., 2018).

Harnessing the carbon sequestration potential associated with low-emissions agricultural practices could contribute to an additional emission abatement of 10.5 $GtCO_2e/y$ (Roe et al., 2021). Most of this potential is related to the below- and above-ground carbon accumulation with the expansion of agroforestry systems (5.6 $GtCO_2e/y$) and soil carbon sequestration with improvements of pasture and crop management (2.5 $GtCO_2e/y$), such as the adoption of reduced and no-tillage and grass-legume mixtures in pastures, and the application of biochar to soils (2.4 $GtCO_2e/y$) (Roe et al., 2021). Furthermore, it is worth noting that these mitigation actions also have synergies with food productivity, climate adaptation, and other environmental aspects (e.g., water and soil conservation) (Herrero et al., 2016; Griscom et al., 2017; Bossio et al., 2020).

Reduction in livestock-based protein consumption

Reducing livestock-based protein consumption is often pointed out as another option to reduce GHG emissions from food systems (Clark et al., 2020; Tilman, et al., 2014). Nevertheless, under current average livestock production practices, a reduction of livestock-based protein consumption would only decrease livestock emissions in 2050, compared to the 2020 levels, if projected production is cut over 25% (Table 1). At or below this level, livestock emissions would rise or be kept constant considering today's average production system emissions and projected increases in meat (+37%) and milk (+29%) productions by 2050 (FAO, 2018; Table 2). On the other hand, if accompanied by the implementation of low emission practices, reducing the consumption of livestock-based protein by 10% and 25%, for example, could promote emission reductions of 0.5-2.5 $GtCO_2e$/y by 2050 (Table 1). Therefore, scaling the implementation of low emissions practices to improve livestock production is a feasible precondition to drive significant changes in emissions towards net-zero FSs.

New-horizon technologies

New technologies to reduce GHG emissions from FSs include those that are still costly (Roe et al., 2021) and primarily not yet present in food value-chains but could increase mitigation from GHG–efficient food production practices, land-use change, and carbon sinks (Ahmed et al, 2020). This diverse pipeline, including consumer-ready artificial meat, methane inhibitors, intelligent packaging, vertical agriculture, nano-drones and 3-D printing, presents real opportunities for systemic change (Herrero et al., 2020). Also, if these technologies are developed to reduce costs of existing agricultural-related practices that are not cost-effective today (e.g., >100 USD/tCO_2e), it could unlock emissions reductions and carbon sequestration of approximately 8.5 $GtCO_2e$/y, representing close to 40% of today's FS emissions and 50% of agricultural-related mitigation potential (Roe et al., 2021). For example, the implementation of agroforestry has the technical potential to sequester approximately 11.2 $GtCO_2e$/y but only 20% of this potential is considered cost-effective today (Roe et al, 2021).

Food system mitigation potential

By randomly combining the implementation of major FS mitigation actions to target net-zero emissions by 2050 in 64 scenarios, we found that only eight would lead to net-zero FSs through the implementation of existing low emission and carbon sequestration production practices (Figure 3), another eight scenarios would need to further rely on diets shifts and the remaining 48 would need additional emission reduction with the implementation of new-horizon technologies reducing up to 5 $GtCO_2e$/y (Figure 3).

Through the implementation of existing low-emission and carbon sequestration practices only (i.e., excluding the reduction in livestock-based protein consumption and new-horizon technologies), we estimate that FS emissions could shift from 21.4 to ~ -2.0 $GtCO_2e$/y by 2050 (i.e., 110% reduction compared to 2020 level by moving FS to the 10^{th} pctl of least emission-intensive practices and harnessing 100% of the carbon sequestration potential) (Figure 3).

The higher the implementation of low-emissions practices (i.e., towards the 10th pctl of leasts emission-intensive systems), the lower the dependance on carbon sequestration, reduction of livestock-based protein consumption and new-horizon technologies. Therefore, scaling low-emissions practices to improve FS production is fundamental to feasibly driving significant changes in emissions towards net-zero FSs (Figure 3).

The conditions for harnessing the full FS mitigation potential in the next three decades are ambitious given the cost-effectiveness of practices, differences in regional contexts (e.g., cost of implementation, institutional and technical capacity, and food access and demands), historical trends and uncertainties related to carbon sequestration (Roe et al., 2021; FAO-Stat, 2021; Dynarski et al., 2020; Steiner et al., 2020; Kim et al., 2008). For example, over the last 30 years (1988-2017), global productivity of cereals, rice, beef and dairy increased 9-40% while emission intensity (at farm level - major emission source; Figure 2) was reduced by 7-40%, respectively (FAO-Stat, 2021). These numbers are far behind the emission reduction potential of ~65% (i.e., 10th pctl least emission-intensive systems) and more compatible with the 40th pctl least emission-intensive systems (Figure 2). Only about 50% of the technical mitigation potential of existing agricultural-related practices and technologies are cost-effective today (e.g., up to 100 USD/tCO_2e), and close to 75% of that is in developing (~65%) and least developed (~10%) countries (Roe et al., 2021). This may add extra financial, technical and policy constraints for implementing FS net-zero emissions plans, as developing and least developed nations likely have lower institutional capacity for implementing more effective climate policies (World Bank, 2021).

There are still concerns regarding carbon sequestration permanence, which encompasses issues related to the time and vulnerability of the carbon sequestered in soils and biomass, such as (i) differential sequestration rates over time and long run decline to a near-zero rate, and (ii) release of sequestered carbon back into the atmosphere after discontinued carbon sequestering practices (Dynarski et al., 2020; Kim et al., 2008; Herzog et al., 2003). These aspects suggest that bolder actions to mitigate GHG from FSs are necessary to increase chances to achieve net-zero FS emissions by 2050; according to the strategies and assumptions evaluated in this work, there is no silver bullet, and a combination of actions should therefore be targeted to increase the feasibility of achieving net-zero emission FSs by 2050 (Figure 3).

The roadmap for net-zero food systems

Without relying on carbon offsets (e.g., related to REED+ or afforestation and reforestation), FSs have the potential to reach net-zero emissions by 2050 (Figure 3), but countries' contextual constraints are likely to limit the potential reach of implementation. However, recent engagement of global FS actors, along with advances in the plant-based protein industry and disruptive technologies (UNFSS, 2021; Statista, 2020; Herrero et al., 2020), has created momentum for action that may speed the implementation of low-emission and carbon sequestration practices, as well as the dissemination of diet shifts, to move FS emissions away from current trends. In this context, a vision for a net-zero FS encompasses:

- Large-scale adoption of low-emission practices to shift the production to the 30th pctl of least emission-intensive systems (~45% emissions reduction across FSs), which could mitigate 10.6 $GtCO_2e$/y, or ~50% of the mitigation needed by 2050 compared to the 2020 base year.
- Realizing 50% of the carbon sequestration potential associated with low-emission practices (i.e., soil carbon, agroforestry and biochar) could contribute another ~38% (5.2 $GtCO_2e$/y) emission reduction.
- Reducing the remaining FS emissions (5.6 $GtCO_2e$/y) by decreasing 2050 projected livestock production, especially in high- and middle-income countries, in 25% (1.2$GtCO_2e$/y) and by deploying new-horizon technologies (4.4 $GtCO_2e$/y) (Figure 3).

Major actions to implement this vision over the next three decades could be summarized as follows:

- By 2030, implement cost-effective actions to reduce CO_2 emissions from land-use change (e.g., deforestation and other land conversion) for food production along with using existing technologies to improve (i) beef, milk and rice production and (ii) nutrient management (focusing on nitrogen fertilizer) across major grain production systems (e.g., maize and wheat). By 2040, low-emissions agricultural practices should be implemented to harness the remaining cost-effective mitigation potential. Of this mitigation potential, 55% to 87% could be achieved with practices costing up to 100 US$/$tCO_2$ (Figure 4; Table 2).
- Implement cost-effective technologies and practices to sequester 1.7, 3.5 and 5.2 $GtCO_2$ annually by 2030, 2040 and 2050, respectively. This can be achieved by adopting agroforestry, applying biochar to soils and improving crop (e.g., tillage and cover crops) and pasture management (e.g., rotational grazing and fertilization) practices. Close to 45% of the carbon sequestration potential (4.8 $GtCO_2$ y^{-1}) would cost up to 100 US$/$tCO_2$ (Figure 4; Table 2).
- By 2040, scale the use of renewable energy (e.g., wind and solar), enhance fuel efficiency, expand the electric transportation fleet, improve fertilizer production, expand the circular economy and peri-urban agriculture, and promote diet shifts in high- and middle-income countries (Figure 4; Table 2).
- From 2040 to 2050, develop and produce affordable new-horizon technologies for negative emissions, with focus on livestock production systems (e.g., methane capture, feed additives and new breeds), novel plants and perennials for carbon sequestration and enhanced energy efficiency for storing, processing, transporting, packaging and retailing. Approximately 5.6 $GtCO_2e$/y (2.6 and 5.7 $GtCO_2e$ emissions reduction and carbon sequestration, respectively) - or ~25% of the mitigation needed for net-zero FS - could be unleashed with the reduction of implementation costs (today above 100 US$/$tCO_2$) (Figure 4; Table 2).

Making net-zero food systems realistic

Our results show that the implementation of major mitigation actions for intensifying FSs based on existing low emission and carbon sequestration practices have the potential to reduce FS emissions beyond net-zero by 2050 while increasing food production. Our analysis also demonstrates that an intensification strategy with a more diverse portfolio of practices, most notably diet shifts and new-horizon technologies, will be more effective for reaching net-zero emissions by 2050 without relying on carbon offsets (e.g., from REED+ or afforestation and reforestation), considering historical trends and differences in regional contexts.

Even so, this scenario may not be realistic under today's trends considering that net-zero FSs require reducing emissions by 3.3% or ~700 $MtCO_2e$ annually between 2020 and 2050. In 2020, global fossil fuel emissions dropped 5.4% as a consequence of the COVID-19 pandemic, which is an unprecedented emissions reduction (at least since 1970) (UNEP, 2021). However, as the global economy is rebuilt, a rebound of 4.8% is expected in 2021 (UNEP, 2021), leaving a net emissions reduction of just 0.6%. These numbers illustrate how difficult and massive the challenge to change current production patterns and reduce emissions is.

This scenario could be different for FSs given the recent engagement of global FS actors with the climate agenda and climate commitments (e.g., UNFSSS, Global Methane Pledge, and SBTi) (McIntyre et al., 2020). Along with significant advances in the plant-based protein industry and disruptive technologies, this engagement has created a momentum for action that may speed up the implementation of steps to move FS emissions away from business-as-usual trends.

Against this backdrop, implementing cost-effective measures and making affordable practices and new-horizon technologies in the coming decades seems to be a reasonable mitigation pathway for increasing the chances of food systems achieving net zero emissions by 2050. Making this implementation realistic is essential to overcoming barriers related to regional contexts (e.g., cost of implementation, institutional and technical capacity, and food access and demands), historical trends, and uncertainties related to carbon sequestration. To realize ambitious emissions reductions, FS actors must also coordinate and promote improvements on several other fronts, including institutional capacity (i.e., governance), finance, research, and technical assistance, especially in developing and least developed countries.

To make net-zero FSs realistic, FS actors should plan major emission reductions in the short run using current cost-effective practices within their respective food value-chains. This would improve the feasibility of net-zero commitments and make FSs less dependent on the success and affordability of new-horizon technologies for large-scale negative emissions (which are uncertain at the moment) and cause carbon-intensive industries to stop growth and move to less intensive options.

The mitigation potential of FS interventions must be validated against efficacy and cost-effectiveness across regions to avoid unintended consequences and minimize trade-offs (Hijbeek et al., 2019; Corbeels et al., 2016), which safeguards the effectiveness of practices in reducing emissions and enhancing food production and security. To support this process, research could be directed to tailor practices for different contexts, while making affordable new-horizon technologies in the medium- and long-term. This process must be done in close coordination with technical assistance for effective adaptation and implementation of mitigation and carbon sequestration practices on the ground along with farmer, in conjunction with assistance to meet monitoring, reporting and verification (MRV) of emissions requirements (Smith et al., 2019). Science-based targets (FLAG) could be a reference as well as carbon market standards (e.g., VERRA and Gold Standard). Global benchmarks (e.g., FAO-Stat) must also be kept up to date to track the implementation of food system actions and commitments.

Critically, the reorientation of both public and private sector sources of capital is needed to achieve net-zero emissions in global food systems by 2050. Financial mechanisms to support adoption of practices to realizing net zero could be created by orienting traditional bank loans for positive climate impact, and scaling other approaches, such as blended finance (Apampa, 2021) and carbon markets (Crossman et al., 2011).

Traditional bank loans offer a pathway to scale validated cost-effective technologies given the position of the lender to incentivize technology adoption. However, following the experience in the sector of renewable energy and energy efficiency, this requires access to patient capital and technical assistance for building the capacity of financial intermediaries, especially in developing and least developed countries, to construct loan portfolios and design incentive mechanisms that are explicitly linked to climate outcomes (e.g., Global Climate Partnership Fund - GCPF). The public sector can support in developing institutional frameworks such as cost-effective assessment and monitoring frameworks to enable the growth of such portfolios.

Secondly, innovate financial mechanisms are needed to demonstrate the viability of investments in the adoption of low emission interventions and carbon sequestration practices in developing and least developed countries, as well as absorb some of the early risk and up-front cost associated with a shift away from business as usual. Strategically allocating public sector capital to de-risk some of the private sector challenges (i.e. blended finance mechanisms etc.) and incentivizing the private sector to create new investment opportunities (i.e. carbon markets etc.,) are critical transition tools to build a diversified portfolio of cost-effective technologies. Furthermore, overlaying and co-designing such mechanisms with large corporations through, for example, implementing customized and collaborative corporate insetting programs within shared supply chains can ensure buy-in while contributing to the net zero transition.

Lastly, new funding models are required to sustain inflows of high-risk capital to incubate and accelerate new horizon technologies, especially to move technologies from the investment readiness phase to the implementation phase. Public sector can support in creating an enabling environment for such programs, especially in developing and least developing countries where models are less developed.

Evidence shows that countries with better governance have more effective climate policies and could help maintain the integrity of the net-zero target while avoiding unintended consequences due to policy changes (Brutschin, 2021; Reay, 2021). Investing in education, especially in regard to gender, is a key predictor of higher levels of governance. Increasing societal awareness of the need to support changes in food systems and consumption patterns is also fundamental for driving transformational change (Steiner et al., 2020).

To foster this scenario at a global level, FS net-zero plans could put more emphasis in the short run on a strong coalition of developing and developed nations, which are likely to have a higher capacity, while build capacity in developing and least developed countries, where international cooperation may also help.

It is important to note that since our analysis is limited to a global overview, the implications of FS intensification may have different consequences at regional scales. Further analysis will shed more light on the possibility to mix different intensification strategies to optimally meet economic and environmental targets.

Although net-zero FSs are achievable, bolder implementation of more efficient production practices is fundamental to feasibly meet both global food production and climate goals. This work provides an overview of this challenge along with a vision that could guide FS actors towards these objectives.

Declarations

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to privacy restrictions but are available from the corresponding author on reasonable request.

References

1. Ahmed, J., Almeida, E., Aminetzah, D., Denis, N., Henderson, K., Katz, J., Kitchel, H., Mannion, P. 2020. Agriculture and climate change. Reducing emissions through improved farming practices. https://www.mckinsey.com/industries/agriculture/our-insights/reducing-agriculture-emissions-through-improved-farming-practices
2. Allen, M.R., Shine, K.P., Fuglestvedt, J.S., Millar, R.J., Cain, M., Frame, D.J., Macey, A.H. 2018. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *NPJ Clim. Atmos. Sci.,* 1, 16. https://dx.doi.org/10.1038/s41612-018-0026-8
3. Bajželj, B., Richards, K. S., Allwood, J. M., Smith, P., Dennis, J. S., Curmi, E., Gilligan, C. A. 2014., Importance of food-demand management for climate mitigation. *Nat. Clim. Chang.* 4, 924–929. https://doi.org/10.1038/nclimate2353
4. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargioni, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M.,Griscom, B. W. 2020. The role of soil carbon in natural climate solutions.*Nat Sustain* **3,**391–398.https://doi.org/10.1038/s41893-020-0491-z
5. Brutschin, E. 2021. A new framework assesses the feasibility of climate scenarios, pointing out stumbling blocks and how to surmount them. IIASA – Policy Brief. https://iiasa.ac.at/policy-briefs/oct-2021/finding-feasible-path

6. Clark,M. A.,Domingo,N.G.G., Colgan,K., Thakrar,S.K., Tilman,D., Lynch,J., Azevedo,I., Hill, J.D. 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science*,**370**, 705-708. doi:10.1126/science.aba7357
7. Costa Jr C, Wironen M, Racette K, Wollenberg E. 2021. Global Warming Potential* (GWP*): Understanding the implications for mitigating methane emissions in agriculture. CCAFS Info Note. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).https://hdl.handle.net/10568/114632
8. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A. 2021 Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food*, **2**, 198–209.https://doi.org/10.6084/m9.figshare.13476666
9. Crossman, N.D., Bryan, B.A., Summers, D.M.2011. Carbon payments and low-cost conservation. *Conserv Biol*. **25**: 835–845.
10. Cusack, D., Kazanski, A.H., Chow, K., Cordeiro, A. L., Karpman, J., Ryals, R. 2021. Reducing climate impacts of beef production: A synthesis of life cycle assessments across management systems and global regions. *Glob Change Biol.,* **27**,1721–1736.https://doi.org/10.1111/gcb.15509
11. Dynarski, K.A., Bossio, D. A., Scow, K. M. 2020. Dynamic Stability of Soil Carbon: Reassessing the "Permanence" of Soil Carbon Sequestration. Frontiers in Environmental Science 8. https://doi.org/10.3389/fenvs.2020.514701
12. FAO-Stat. 2021. Food and Agriculture Data (2021). Food and Agriculture organization of the United Nations (FAO). www.fao.org/faostat/en/#data.
13. FAO. 2018. Global Perspective Studies – Food and agriculture projections to 2050. Food and Agriculture organization of the United Nations (FAOhttp://www.fao.org/global-perspectives-studies/food-agriculture-projections-to-2050/en/
14. Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio G. 2013 Tackling climate change through livestock—a global assessment of emissions and mitigation opportunities. 139.https://www.fao.org/3/i3437e/i3437e.pdf
15. Griscom, B., Adams, J., Ellis, P., Houghton, R., Lomax, G., Miteva, D., Schlesinger, W., Shoch, D., Siikamäki, J., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M., Fargione, J. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences*. 114. 10.1073/pnas.1710465114.
16. Hasegawa, T., Fujimori, S., Frank, S., Humpenoder, F., Bertram, C., Després, J., Drouet, L., Emmerling, J., Gusti, M., Harmsen, M., Keramidas, K., Ochi,. Y., Oshiro, K., Rochedo, P., van Ruijven, B., Cabardos, A., Deppermann, A., Fosse, F., Haylik, P., Krey, V., Popp, A., Schaeffer, R., van Vuuren, D., Riahi, K. 2021. Land-based implications of early climate actions without global net-negative emissions. *Nat Sustain,* 4, 1052–1059.https://doi.org/10.1038/s41893-021-00772-w
17. Herrero, M., Henderson, B., Havlík, P.,Thornton, P., Conant, R., Smith, P., Wirsenius, S., Hristov, A., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., Stehfest, E.Greenhouse gas mitigation potentials in the livestock sector.*Nature Clim Change* 6, 452–461 (2016).https://doi.org/10.1038/nclimate2925

18. Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde. C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., Wijk, M. van, Zanten, H.H.E. van, Vermeulen, S., Vervoort, J., &West, P.C. 2020. Innovation can accelerate the transition towards a sustainable food system. Nature Food **1**:266–272.
19. Corbeels, M., Marchão, R., Neto, M., Ferreira, E.G., Madari, B.E., Scopel, E., Brito, O.R. 2016.Evidence of limited carbon sequestration in soils under no-tillage systems in the Cerrado of Brazil.*Sci Rep* 6, 21450 (2016).https://doi.org/10.1038/srep21450
20. Herzog, H., Caldeira, K. & Reilly, J. An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage.*Climatic Change* 59, 293–310 (2003).https://doi.org/10.1023/A:1024801618900
21. Hijbeek, R., van Loon, M.P., van Ittersum, M.K. 2019. Fertiliser use and soil carbon sequestration: opportunities and trade-offs. CCAFS Working Paper no. 264. Wageningen, the Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available online at: www.ccafs.cgiar.org
22. IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R. K. Pachauri, L. A. Meyer, Eds. Intergovernmental Panel on Climate Change (IPCC).
23. Kim, M., McCarl, B. A., Murray, B. 2008.Permanence discounting for land-based carbon sequestration. *Ecol. Econ.*, **64(4)**, 763-769. htpps://doi.org/10.1016/j.ecolecon.2007.04.013
24. Lynch, J., Cain, M., Pierrehumbert, R., Allen, M. 2020. Demonstrating GWP*: A means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long- lived climate pollutants. Environ. Res. Lett. 15, 044023.https://doi.org/10.1088/1748-9326/ab6d7e
25. McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., Wijk, M. van, Zanten, H.H.E. van, Vermeulen, S., Vervoort, J., West, P.C. 2020. Innovation can accelerate the transition towards a sustainable food system. *Nature Food* 1:266–272.
26. Poore, J., Nemecek T. 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992 (2018). https://doi.org.10.1126/science.aaq0216
27. Reay, D. 2021. Land Use and Agriculture: Pitfalls and Precautions on the Road to Net Zero. *Front. Clim.*https://doi.org/10.3389/fclim.2020.00004
28. Reisinger, A., Clark, H., Cowie, A.L., Emmet-Booth, J., Gonzalez Fischer, C., Herrero, M., Howden, M., Leahy, S. 2021. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? *Phil. Trans. R. Soc. A***379**: 20200452. https://doi.org/10.1098/rsta.2020.0452

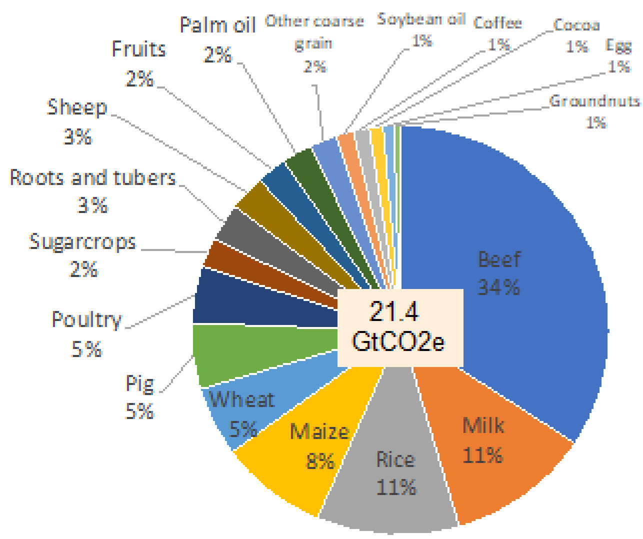
29. Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk,J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., Lomax, G., Lehmann, J., Mesnildrey, L., Nabuurs, G., Popp, A., Rivard, C., Sanderman, J., Sohngen, B., Smith, P., Stehfest, E., Woolf, D., Lawrence, D. 2021. Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*. https://doi.org/10.1111/gcb.15873
30. Roe, S., Streck, C., Obersteiner, M., Frank, S., Griscom, B., Drouet, L., Fricko, O., Gusti, M., Harris, N., Hasegawa, T., Hausfather, Z., Havlík, P., House, J., Nabuurs G.-J., Popp, A., Sánchez, M. J. S., Sanderman, J., Smith, P., Stehfest, E., Lawrence D. 2019. Contribution of the land sector to a 1.5°C world. *Nat. Clim.Chang.* **9**, 817–828.https://doi.org/10.1038/s41558-019-0591-9
31. Rosenzweig, C., Mbow, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E. T., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., Xu, Y., Mencos Contreras, E., Portugal-Pereira, J. 2020.Climate change responses benefit from a global food system approach. *Nat. Food*, **1**, 94–97. doi:10.1038/s43016-020-0031-z
32. Smith, P., Soussana, J., Angers, D., Schipper, L., Chenu, C., Rasse, D., Batjes, N., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., Klumpp, K. 2019. How to measure, report and verify soil carbon change to realise the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology* 26. https://doi10.1111/gcb.14815
33. Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M., Scarborough, P. 2018. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: A global modelling analysis with country-level detail. *Lancet Planet. Health*, **2**, e451–e461. doi:10.1016/S2542-5196(18)30206-7
34. Statista (2020).https://www.statista.com/forecasts/877369/global-meat-substitutes-market-value
35. Steiner, A., Aguilar, G., Bomba, K., Bonilla, J.P., Campbell, A., Echeverria, R., Gandhi, R., Hedegaard, C., Holdorf, D., Ishii, N., Quinn, K., Ruter, B., Sunga, I., Sukhdev, P.,Verghese, S., Voegele, J., Winters, P., Campbell, B., Dinesh, D., Huyer, S., Jarvis, A., Loboguerrero, A.M., Millan, A., Thornton, P., Wollenberg, L., Zebiak, S. 2020. Actions to transform food systems under climate change. Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). https://ccafs.cgiar.org/resources/publications/actions-transform-food-systems-under-climate-change
36. Tilman, D., Clark, M. Global diets link environmental sustainability and human health.*Nature* **515,**518–522 (2014). https://doi.org/10.1038/nature13959
37. Tubiello, F. N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S. Y., De Barros, J., Flammini, A., Mencos-Contreras, E., Souza, L., Quadrelli, R., Heiðarsdóttir, H. H., Benoit, P., Hayek, M., Sandalow, D. 2021.Greenhouse gas emissions from food systems: building the evidence base. *Environ. Res. Lett.*, **16**, 065007

38. UNEP. 2021. Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered – Executive Summary. Nairobi, Kenya: United Nations Environment Programme (UNEP).https://www.unep.org/resources/emissions-gap-report-2021
39. UNFSS. 2021. United Nations Food Systems Summit -https://www.un.org/en/food-systems-summit
40. Vermeulen, S., Campbell, B. M., Ingram, J. S. I. 2012. Climate change and food systems. *Annu. Rev. Environ. Resour.* **37**, 195–222. doi:10.1146/annurev-environ-020411-130608
41. World Bank. 2021. Worldwide Governance Indicators (WGI). The World Bank Group.https://info.worldbank.org/governance/wgi/Home/Reports

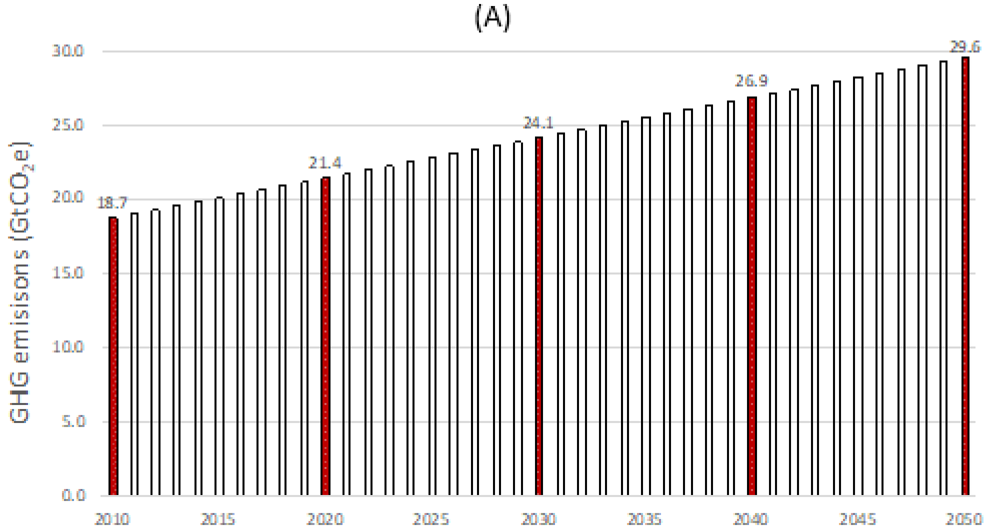
Tables

Tables 1 to 2 are available in the Supplementary Files section

Figures



(A)



(B)

Figure 1

Global food systems emissions in 2020 (A) and estimated global food systems emissions 2010-2050 (B).

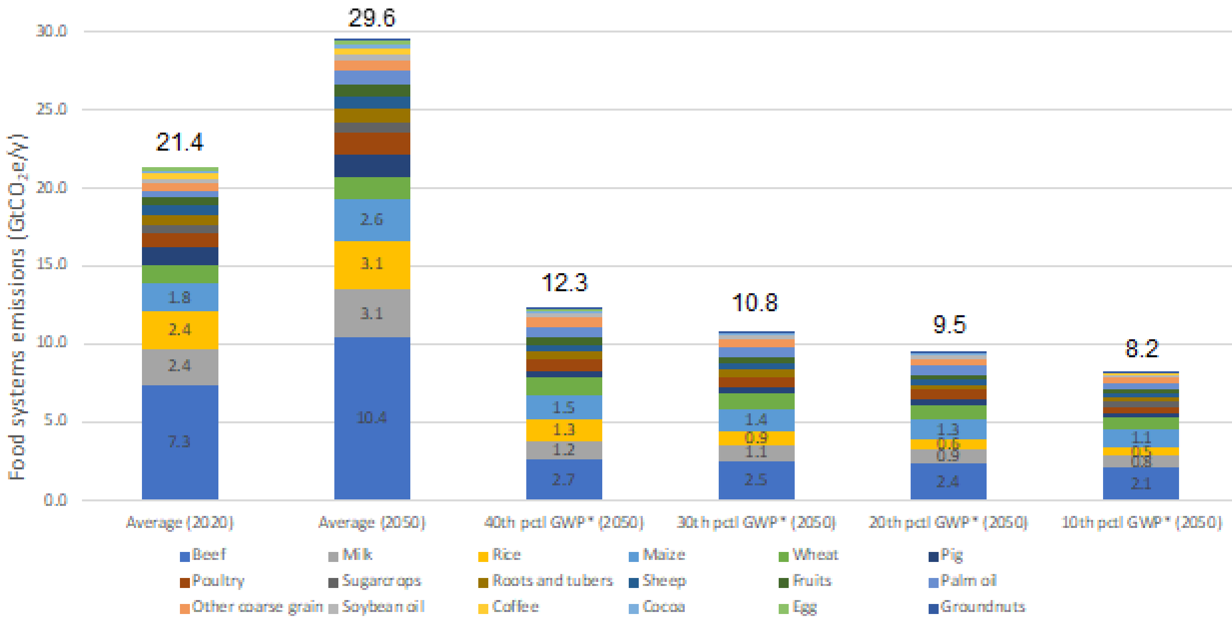


Figure 2

Food systems emissions by shifting global food production to the 40th, 30th, 20th and 10th pctl least emission-intensive systems in 2050

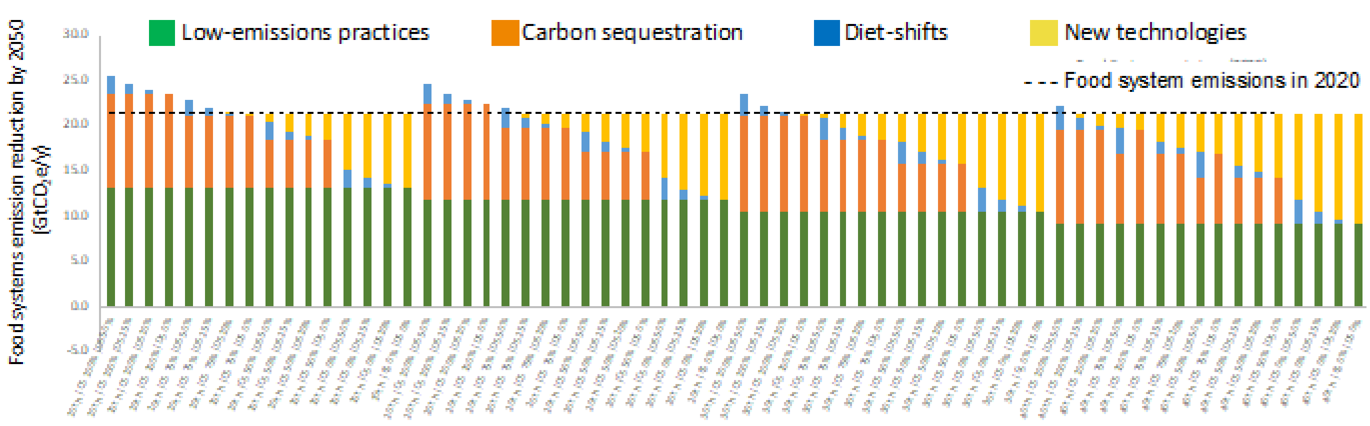


Figure 3

Food systems emissions reduction (green bar) with the implementation of low-emission practices (to move production systems to the least 10th, 20th, 30th and 40th pctl emissions intensive*), realization of potential carbon sequestration (CS) in agriculture in soils, agroforestry and biochar application (CS; at 0, 50, 75 and 100% level of implementation**), diet shift (DS) to reduce livestock-based protein consumption (SD; at 0, 10, 25 and 50% of projected 2050 values***) and adoption of new-horizon technologies (orange bar). *(Poore & Nemeck, 2018); **(Roe et al., 2021; 10 $GtCO_2e$); ***(Based on 2050 projected meat and milk projections – FAO, 2018)

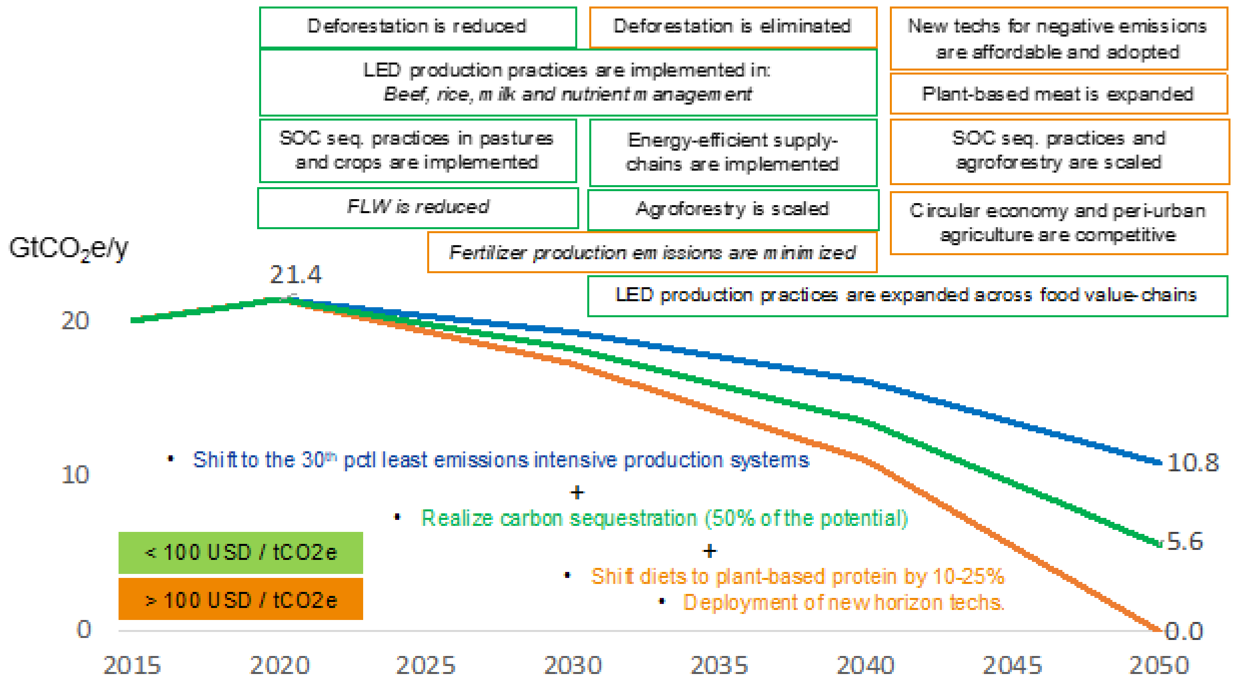


Figure 4

Roadmap for food systems net zero emissions by 2050.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- CostaJretalRoadmapnetzerofoodsystemstable1.docx
- CostaJretalRoadmapnetzerofoodsystemstable2.docx