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Review

Food and Earth Systems: Priorities for Climate Change Adaptation and Mitigation for Agriculture and Food Systems

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Abstract: Human activities and their relation with land, through agriculture and forestry, are significantly impacting Earth system functioning. Specifically, agriculture has increasingly become a key sector for adaptation and mitigation initiatives that address climate change and help ensure food security for a growing global population. Climate change and agricultural outcomes influence our ability to reach targets for at least seven of the 17 Sustainable Development Goals. By 2015, 103 nations had committed themselves to reduce greenhouse gas emissions from agriculture, while 102 countries had prioritized agriculture in their adaptation agenda. Adaptation and mitigation actions within agriculture still receive insufficient support across scales, from local to international level. This paper reviews a series of climate change adaptation and mitigation options that can support increased production, production efficiency and greater food security for 9 billion people by 2050. Climate-smart agriculture can help foster synergies between productivity, adaptation, and mitigation, although trade-offs may be equally apparent. This study highlights the importance of identifying and exploiting those synergies in the context of Nationally Determined Contributions. Finally, the paper points out that keeping global warming to 2 °C above pre-industrial levels by 2100 requires going beyond the agriculture sector and exploring possibilities with respect to reduced emissions from deforestation, food loss, and waste, as well as from rethinking human diets.

Keywords: food systems; adaptation; mitigation; greenhouse gas emissions; climate change; climate-smart agriculture; small farms; family farms

1. Introduction

During the 20th century, global populations rose from approximately 1.6 to 6.0 billion. During this same period, substantial increases in crop yields were achieved in many countries by adopting improved crop cultivars. In many instances, enhanced soil, crop, water, and nutrient management accompanied this, though environmental problems have also emerged. However, as we shall discuss later, adoption rates of more intensive and higher yielding agricultural practices have been substantially greater in developed nations compared to developing ones, where a range of constraints still limit

widespread uptake of such practices. In spite of successes, by 2017 it was estimated that globally over 820 million of people were undernourished [1].

In the 21st century the challenges to achieve global food security will be immense. According to Alexandratos and Brunisma [2], by 2050 the world will need to respond to an increased demand due to population and income growth. Therefore, agricultural production will have to increase at least by 60% considering both food and nonfood products compared to 2005–2007. This challenge will be exacerbated by the fact that such ongoing population growth is inevitably and directly linked with growing constraints on land and water availability for crops and livestock and declining wild fishery stocks [3].

In addition, the latest report from the Intergovernmental Panel on Climate Change (IPCC) concludes that agriculture, and consequently food security, is already being affected by climate change [4]. At the same time, agriculture and food value chains, as significant emitters of CO₂ and non-CO₂ greenhouse gases (GHGs), are also very important in fueling climate change. With an estimated 2.5 billion people globally dependent on small-scale agriculture who are vulnerable to climate change, and with food systems contributing 19–29% of GHGs global emissions [5], the challenge related to agriculture and climate change in the 21st century is both urgent and multifaceted and is reflected in seven out of 17 of the Sustainable Development Goals (SDGs), namely, SDG1: no poverty; SDG2: zero hunger; SDG5: gender equality; SDG12: responsible consumption and production; SDG13: climate action; SDG14: life below water; and SDG15: life on land. As an imperative, it will require not only a major initiative to meet rapidly increasing food demands, but also a substantial investment in both adaptation and mitigation initiatives, within global agriculture itself and in the context of wider food systems (Figure 1) [6–8].

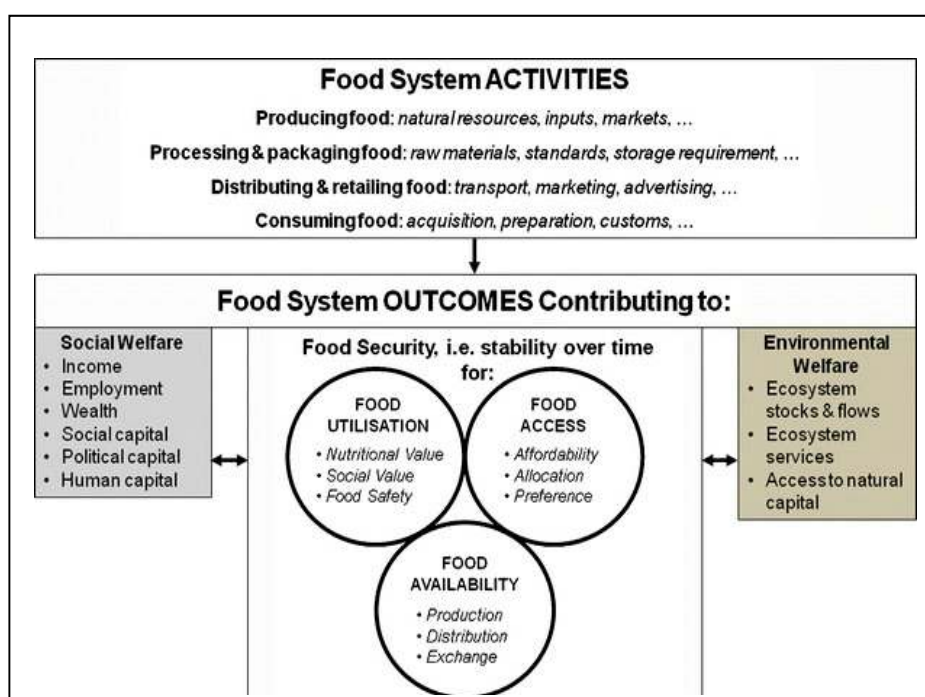


Figure 1. The food system concept [6–8].

The Purpose of This Paper

This paper reviews the literature on priorities for adaptation and mitigation. While many of the adaptation and mitigation options are relevant globally, our focus is on small and family farms in developing countries, for it is that sector that will face the greatest challenges with respect to climate change. Some of the key mitigation options, e.g., reducing loss at the demand end of the supply chain and changes in consumption, are more relevant to developed countries, but will become global

priorities as countries develop. In this paper, we use the terms small and family farms as used by Lowder et al. [9]. According to Lowder et al., “small farms (less than 2 ha) operate about 12% and family farms about 75% of the world’s agricultural land.” This paper used two sources of information to select the priorities for action on adaptation and mitigation: (i) the work implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security and (ii) a set of review papers that include priority setting analyses [10–14].

The paper starts by describing the evolving importance of agriculture and climate change within the United Nations Framework Convention on Climate Change (UNFCCC) and discusses some of the concerns that still remain to be addressed with regard to adaptation and mitigation actions by small and family farms. We then provide an overview of some potentially promising and more prevalent adaptation and mitigation options that can be adopted by such farmers but indicate where barriers to widescale uptake still need to be addressed.

In the case of mitigation, we show that such actions will need to go beyond agriculture alone and must be addressed across the whole global food system if the near-term goal for 2030 of 1 GtCO₂ e yr⁻¹ emission reduction is to be achieved. We then discuss the importance of identifying where potential synergies exist between improved food production, greater livelihood resilience (to climate change and other stresses), and mitigation. Finally, we distil important adaptation and mitigation messages that have emerged from the literature.

2. The Evolving Importance of Agriculture Within the UNFCCC

Within the UNFCCC, agriculture was first mentioned in Article 2 of the Earth summit in 1992 through a reference to food security [15] and, since then, has received an increasing amount of attention. However, it was not until the 17th Conference of Parties (COP 17) in Durban in 2011 that the conference requested that the Subsidiary Body for Scientific and Technological Advice (SBSTA) consider issues related to agriculture. However, actions agreed in Durban were in the mitigation track of UNFCCC negotiations, which are separate from adaptation discussions. This potentially obscured opportunities for agriculture which can deliver benefits for both, and has led to a concern that the focus on agricultural adaptation, a priority for developing countries, will be insufficient [16,17]. In addition, there are more specific concerns regarding agricultural mitigation that have emerged (see Box 1).

Box 1. Ref [16] Note the following concerns raised regarding agricultural mitigation being included in SBSTA text.

- *The inclusion of agriculture under the mitigation track could lead to mandatory commitments.*
- *Possible mechanisms (e.g., carbon trading) will not benefit small-holder and family farmers.*
- *Some countries do not welcome potential restrictions on conversion of land to agricultural use.*
- *Export-focused producers worry that mitigation measures for agriculture could restrict trade from “high-emission” agriculture.*
- *Some negotiators are concerned that technical challenges (e.g., carbon monitoring by millions of farmers and pastoralists) are too great to develop agriculture agreements.*

Nevertheless, in 2015, in the lead up to the Paris Agreement, 160 states submitted Intended Nationally Determined Contributions (INDCs) for climate actions for the near term 2025–2030 [18] and, of these, 103 countries included agriculture as one of the sectors in which they intended to make emissions reductions towards their targets and 102 countries listed agriculture as a priority for adaptation. The implementation of INDCs in developing countries will be supported by, amongst others, the Green Climate Fund (GCF), to which industrialized nations have pledged \$100 billion annually to support adaptation, GHG emissions abatements, climate-informed development, technology transfer, and capacity building. However, the GCF has not provided a specific funding window dedicated to the links between poverty, adaptation and mitigation [19]. Questions remain in relation to adaptation actions tending to be underrepresented in the current GCF portfolio of projects

and to how to establish longer term emission targets post 2020 and how to enforce the Common but Differentiated Responsibility (CBDR) principle in executing INDCs [20].

However, in 2017, COP 23 addressed several of such concerns and marked a milestone for action in that during the closing plenary session, both the SBSTA and the Subsidiary Body for Implementation (SBI) were requested to jointly address issues related to agriculture which covered adaptation, mitigation, resilience, synergies and potential constraints to adoption [21]. Specific issues to be addressed include (i) methods and approaches for assessing adaptation, adaptation cobenefits, and resilience; (ii) improved soil carbon, soil health, and soil fertility under grassland and cropland as well as integrated systems, including water management; (iii) improved nutrient use and manure management towards sustainable and resilient agricultural systems; (iv) improved livestock management systems; and (v) socioeconomic and food security dimensions of climate change in the agricultural sector.

3. Adaptation Actions

There is growing recognition that adapting smallholder and family agriculture to climate change requires developing resilience to the risks associated with natural climate variability [22–26]. Because anthropogenic forcing interacts with natural climate variability, smallholder and family farmers experience climate change largely as shifts in the frequency and severity of extreme events. Increasing risk from extreme events, such as drought, flooding from extreme precipitation and coastal storm surge, and heat waves, is projected across much of the developing world [26,27]. Climate variability—through loss of productive assets and human capital resulting from extreme events [28–31], and the adverse effect that the resulting uncertainty has on investment in agricultural inputs and innovation [32–36]—frustrates the efforts of smallholder and family farmers in risk-prone environments to escape poverty and build a better life [37–39].

The actions required for adaptation to climate change within agriculture are wide-ranging. They span the continuum from incremental adaptation to transformative adaptation, where incremental adaptation is defined as actions where the central aim is to maintain the essence and integrity of a system or process at a given scale, whereas transformative adaptation involves changes in the fundamental attributes of a system in response to climate and its effects (pp. 15–58 [27]). It is important to mention that under some circumstances gradual changes and incremental steps can add up to a transformative change [40]. Both incremental and transformative adaptation can occur across scales from farm households to national agencies [41] (Figure 2). For example, with infrequent and/or minor climatic impacts, households can decide to change varieties and breeds, while with more frequent and/or more severe events they may need to shift to other crops or other livestock species. With even more extreme conditions, the only solution may be to transit out of agriculture, with migration being a valid, if sometimes risky, adaptation action. Examples of adaptation actions which span that continuum are shown in Figure 2. Equally important is to acknowledge the transition that has already taken place as people have shifted from agriculture to other sectors and the consequences that these transitions can have on adequate adaptation options.

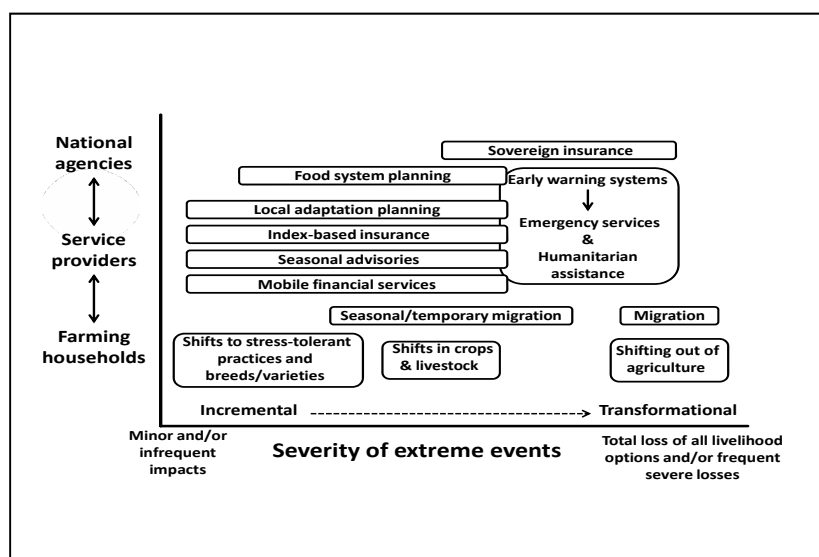


Figure 2. Climate adaptation requires a diversity of actions [41].

3.1. New Stress Tolerant Crop/Livestock Varieties/Breeds

Climate change is already changing the frequency and severity of stresses such as high temperature, tropical storms, drought, and saline intrusion; the incidence and intensity of climate-sensitive pests and diseases of both crops and livestock is already occurring [42]. Initiatives to develop and promote new varieties, breeds, and populations that are adapted to such abiotic and biotic stresses are underway around the world [43–45]. In the context of the improvement of crop varieties, crop–climate models can be used as a tool to accelerate the development of crop germplasm adapted to future climates [46,47].

However, in spite of initiatives to promote the adoption of new crop varieties and animal breeds throughout the developing world, long recognized constraints to widespread adoption faced by resource poor farmers still remain in place and, in many instances, adoption rates are disappointingly low. Parallel initiatives that address easy and timely access to improved germplasm, information on complementary production inputs, more capable and better resourced extension services and the provision of climate information and rural financial services are all essential [48]. This was again confirmed by a recent study in Africa. Nine years after the Programme for Drought Tolerant Maize for Africa (DTMA) was launched, studies for adoption rates across six East and Southern African countries (Ethiopia, Tanzania, Uganda, Malawi, Zambia, and Zimbabwe) were made [45]. The results revealed considerable intercountry variation in farmer uptake of drought tolerant maize, from 9% of maize plots in Zimbabwe to 61% in Malawi and again identified lack of timely access to germplasm and lack of awareness as key constraints. However, whilst confirming the constraints identified by many previous studies, the results illustrate that where the right supportive measures are in place (as in Malawi), adoption rates can be considerably improved.

3.2. Climate Information Services

Climate Information Services (CIS) involve the production, translation (e.g., advisories, decision support), and communication and use of climate information. Information about past climate variability and trends and predictions at a range of lead times support the targeting and implementation of a range of adaptation actions. Appropriate information enables farmers to understand the role of climate vs. other drivers in perceived productivity changes [49,50], and to manage climate-related risks throughout the agricultural calendar. CIS supports incremental adaptation to climate change by allowing farmers to understand the trends, variability, and seasonality of their recent climate and anticipate and plan for the upcoming growing season.

Increasing interest and investment, supported in part by creation of the UN Global Framework for Climate Services, are expanding opportunities for CIS to contribute to agricultural adaptation. However, to be effective and adopted widely, such services must address the challenges of (i) ensuring that climate information and advisory services are relevant to the decisions of small-holder and family farmers (salience); (ii) providing timely climate services access to remote rural communities with marginal infrastructure (access); (iii) ensuring that farmers own climate services and shape their design and delivery (legitimacy); and (iv) ensuring that climate services are accessible by and useful to women and other socially and economically marginalized groups (equity). In addition, in order to enable effective management of climate-related agricultural risk, CIS should be integrated with other development interventions [51,52].

A recent Africa-focused review of published evidence on CIS for farmers found considerable variability in rates of access, but in most cases (with exceptions that include women farmers in Mali, and pastoralists) the majority of farmers who access CIS use it in their decision-making [53]. It highlighted challenges to reliably estimate how the use of CIS translates into agricultural productivity and livelihood benefits. Econometric studies highlight CIS as one of the most important factors influencing adaptation and transformation of farming systems. For example, an analysis across more than 5000 households in East and West Africa, South Asia, and Central America found access to CIS is a positive determinant of adaptation through agricultural diversification, and of agricultural intensification in Bangladesh and India [54]. The literature also highlights widespread gaps between farmers' information needs and the information and services that are routinely available [51,55]. Good practice in CIS design and communication can reduce this gap, resulting in high rates of use and perceived benefits for farm decision-making, e.g. Clarkson et al., [56], but evaluation evidence is lagging for adoption of improved practice.

3.3. Index-Based Agricultural Insurance

Index insurance builds resilience and contributes to adaptation both by protecting farmers' assets in the face of major climate shocks, by promoting access to credit, and adoption of improved farm technologies and practices [10,57–59]. Index insurance triggers payouts based on an index (e.g., rainfall, remote sensing) that is correlated with losses, rather than actual losses, eliminating costly farm visits to verify losses, reducing administration costs, lowering premiums, and providing more timely payments. "Basis risk"—farmers experiencing losses when a payout is not triggered or receiving a payout when losses are not experienced—is a particular challenge to adoption of index-based insurance [60,61]. The failure of many index insurance programs for farmers in the developing world has raised concerns about demand and variability [62,63]. However, evidence shows that demand for insurance is not fixed but can be enhanced by designing indexes that reduce basis risk [64] and that invest in farmers' understanding and trust in insurance [65–68]. Index insurance is not a solution to all climate-related risk but appears to be scaling most successfully (without heavy premium subsidy) where it targets risk-related barriers to accessing improved production technologies and markets [69–71]. Developing the capacity of private insurers to address farmers' insurance needs at scale may continue to depend on public support including: creating an enabling regulatory environment, investing in meteorological and agricultural data systems, educating farmers about the value of insurance, and facilitating international reinsurance. In some contexts, publicly subsidized index insurance is treated as an adaptive social protection intervention to address agricultural development or rural poverty reduction goals.

3.4. Productive Social Safety Nets (PSSN)

There is growing interest in protecting the livelihoods of chronically vulnerable and food-insecure populations from the increasing frequency and intensity of extreme climate events through PSSN, including cash and in-kind transfers [72,73]. PSSN have spread rapidly from their early prominence in the middle-income nations and, by 2015, over 130 developing countries made PSSN an important pillar of their development policies [74].

Well-designed PPSN programs have proven potential to reduce costly household coping strategies [75,76] and migration [77] in the face of climate shocks; and stimulate agricultural production by alleviating capital constraints [75,78–81]. Motivated in part by climate change, adaptive social protection extends social safety nets to promote improved livelihoods through, e.g., credit, production inputs, agricultural extension, and risk finance [82–85]; and introduces financial mechanisms to increase the responsiveness of PSSN programs to climate shocks [83,86–88]. For example, Ethiopia’s Livelihoods Early Assessment and Protection (LEAP) program adds a layer of contingent finance, triggering additional funds to scale up its Productive Safety Net Program when a climate index indicates emerging drought [88,89]. In cases where agricultural production may not offer a realistic near-term pathway out of poverty, PSSN may allow poor smallholder and family farmers to build up sufficient assets to move out of poverty through improvements to their farming, or provide a level of security until growth in other sectors expands off-farm employment opportunities [10]. Whilst the primary purpose of such PSSN is to protect the food security and livelihood resilience of chronically vulnerable households against severe climate shocks, it has been shown that Ethiopia’s PSSN, covering approximate 600,000 ha, has also resulted in a total reduction in net GHG emissions of 3.4 million Mg CO₂ e y⁻¹, which is approximately 1.5% of the emissions reductions in Ethiopia’s NDC for the Paris Agreement, even though it did not form an integral part of that NDC [90]. In order to maximize the potential of all such PSSN, the authors recommend that to enhance food security whilst at the same time maximizing mitigation, climate projections, and mitigation and adaptation responses should be mainstreamed into the future planning and implementation at all levels.

3.5. Agricultural Transformation and Migration

With progressive climate change, climatic suitability of cultivable areas will decline to a greater or lesser extent for most staple foods [91]. This means that farmers will need to adapt, either through access to improved crop germplasm with enhanced tolerance to the new climatic conditions (incremental adaptation) or by switching crops or even activities (transformative adaptation). For example, in areas of sub-Saharan Africa already marginal for crop production, Jones et al. [92] suggest that farmers may be forced to switch to livestock as the primary source of livelihood. In Nicaragua, Bunn et al. [93] suggest that climate pressure might soon lead farmers to shift from coffee to other crops such as cocoa.

However, although there is an increasing recognition of the potential limitations of incremental adaptation, the literature available on transformational adaptation remains relatively scarce [94]. Nevertheless, from a recent review of 93 peer-reviewed papers which discussed transformational literature, it was noted that the literature on this topic has steadily increased from six articles in 2011 to 24 in 2016–2017 [95], and notes that transformative adaptation actions that are discussed can be broadly grouped in five types:

1. Adaptation actions adopted at a larger scale. For example, large scaling of rainwater harvesting in sub-Saharan Africa [96].
2. Shifting crops and changing agricultural systems. For example, shifting from rice to sugarcane production due to water scarcity and market access [97].
3. Changing business scale, structure, and location. For example, the change of Australian agricultural industries in structure and function [98].
4. Creating new croplands/irrigation. For example, large-scale development of irrigation schemes [99].
5. Forced farm abandonment and migration. For example, forced farm abandonment due to impacts of climate change in Central America [100].

However, through a study of irrigated agriculture in Canada [101], there are suggestions that there is a nuanced interplay between incremental and transformation adaptation and further developed the related concept of ‘transitional adaptation’, first defined as “... an intermediary form or adaptation.

It can indicate an extension or resilient adaptation to include a greater focus on governance or an incomplete form of transformational adaptation that falls short of aiming for or triggering cultural or political regime change" [102]. Indications show that there are interactions between these three types of adaptation strategies in that (i) there are interdependencies between and among actions and actors across various scales and (ii) one type of adaptation can set boundaries for the other [101]. They also show that transitional adaptation, in their case study the development of water markets during a severe drought, was reversible to 'incremental' in that it has only occurred once in 2001 but is anticipated to become more frequent in the future in which case it would become 'transformational' [103].

In spite of the increasing attention being given to the complexities of transformational adaptation, some authors conclude that due to the current challenges facing agriculture in the developing world, coupled with the existing uncertainties of climate change projections, there seems to be little appetite for such approaches at the level of development practice [94]. We believe that this, as a priority, needs to change, especially with regard to climate-induced migration. Climate change impact on migration can happen through increases in the frequency and intensity of weather and climate risks. Such climate-related risks can be the actual or anticipated sudden onset events such as drought, floods, or tropical storms, but in the longer term is projected to become more associated with projected slow onset events such as sea-level rise, salinization, and desertification. Safe, orderly, and planned migration can contribute, through remittances, to agriculture development, economic growth, food security, and rural livelihoods. In contrast, poorly managed migration can increase vulnerability to climate risks, heighten pressure on scarce natural resources, and exacerbate tensions between migrants and host communities [104].

The fact remains however that, due to progressive climate change, farming is likely to become a nonviable enterprise in many areas, especially for coastal communities where sea-level rise will increasingly bring adverse impacts such as submergence, coastal flooding, and erosion [105]. In such cases, the only solution available to farmers might be transitioning out of agriculture and seeking alternative livelihoods through migration. Today the total number of international migrants, including those displaced by climate-related natural disasters, is 40% higher than in 2000, with numbers expected to exceed 400 million by 2050 [104].

The Sendai Framework for Disaster Risk Reduction [106], the Paris Agreement, and the 2030 Agenda for Sustainable Development [107] have all highlighted the need for urgent action to respond to climate change, and to address its role as a driver of migration. Given the complexity and projected scale of such a dramatic transformative adaptation action, we suggest that research for development needs to move from 'recognition' to 'action' and give urgent priority to identifying where such large-scale migration is likely to occur with the development of preplanned practical policy measures that will need to be put in place to support the future livelihoods of such migrants.

4. Actions Toward the Mitigation of GHG Emissions

With agriculture's significant contribution to global emissions, the additional emissions in supply chains, the need for reductions in agriculture to meet global policy targets and the opportunity for reducing emissions across the food system (Table 1), reducing food system emissions, and sequestering carbon in the soil and biomass have received increasing attention [108]. Developing countries' NDCs show they are ready to rise to the challenge, conditional on funding [18].

Table 1. Estimates of the relative contributions of different stages of the food system to global greenhouse gas (GHG) emissions (Adapted from [6]).

Stage of Food System		Emissions (MtCO ₂ e)
Preproduction	Fertilizer manufacture	282–575
	Energy use in animal feed production	60
	Pesticide production	3–140
Production	Direct emissions from agriculture	5.120–6.116
	Indirect emissions from agriculture	2.198–6.567
Postproduction	Primary and secondary processing	192
	Storage, packaging, and transport	396
	Refrigeration	490
	Retail activities	224
	Catering and domestic food management	160
	Waste disposal	72

4.1. Direct Emission Targets

Reaching the reduction target for emissions from agriculture required to limit warming in 2100 to 2 °C above pre-industrial levels will be challenging. Indeed, achieving global food security in the light of projected increases in human populations without drastic increases in GHG emissions will necessitate policy measures to move from a business-as-usual (BAU) path and initiate a global transition to low-emission development (LED). From an analysis of 134 crop and livestock systems in 15 countries, it was reported that the adoption of improved management practices and technologies by small-holder farmers, notably alternate wetting and drying in paddy rice and agroforestry systems, would significantly reduce the GHG emission intensity of agricultural production, while either decreasing or only moderately increasing net GHG emissions per area [109]. However the authors concluded that whilst improvements in small-holder systems effectively reduce future GHG emissions compared to BAU development, these contributions are insufficient to significantly reduce net GHG emission in agriculture beyond current levels, particularly if future agricultural production grows at projected rates. Indeed, with a near-term goal for 2030 of 1 GtCO₂e yr⁻¹ for non-CO₂ emissions reduction compared to the BAU scenario, and using optimistic assumptions with regard to the dissemination and adoption of currently available improved production practices, currently available mitigation practices in agriculture will only deliver 21–40% of the mitigation required, suggesting that more transformative technical options will be needed in the longer term [110].

Agricultural emissions (methane and nitrous oxide) vary significantly among countries, with only four countries contributing 39% of emissions: China, India, Brazil, and the USA [111]. The availability and suitability of mitigation measures varies both across countries and within. For example, additives to cattle feed and slow release fertilizer are still unaffordable in most low-income countries. Assessing the suitability of water management in paddy rice in Southeast Asia showed the areas that are biophysically eligible for this practice were more limited than previously thought [112].

Developing policies to achieve mitigation goals in the agricultural sector effectively is as important as developing technologies to deliver these reductions in emissions. This is reflected in the case of Costa Rica and its Coffee NAMA (Nationally Appropriate Mitigation Action). This national policy aims at improving resource use efficiency in the coffee sector and is part of a wider Costa Rican effort to attain carbon neutrality by 2021. The policy includes capacity building and awareness-raising to increase technical knowledge of low-carbon production, financial support and incentives, and market studies to promote access to markets for differentiated coffees [113].

Mitigation of non-CO₂ gases emissions will be necessary given their significant contribution to global emissions and the opportunity for rapid reduction of these shorter lived GHGs in the atmosphere. Considering possible changes in technical options, changes in farming systems, and consumer responses to changes in food availability and price, Frank et al. [114] show that increasing the

carbon price from \$25/tCO₂ eq to \$100/tCO₂ eq would provide non-CO₂ reductions in agriculture of 2.6 GtCO₂ eq/year by 2050. However, they stress that for such an optimistic target to be reached, several adoption barriers, such as lack of education and infrastructure and poor access to markets or land tenure insecurity, would have to be overcome. However, looking to the future mitigation potentials, promising transformative technical options for methane and nitrous oxide emission reductions are in the pipeline. Future options include (i) recently developed methane inhibitors that reduce dairy cow emissions by 30% while increasing body weight without affecting milk yields or composition [115], (ii) cattle breeds that produce less methane [116], and (iii) wheat and maize varieties that inhibit nitrous oxide production [117]. In addition, evidence suggests it may be possible to manage soil–plant microbial processes to increase the stability of soil organic matter and retain carbon longer [118].

Bioenergy crops play a potentially important role in the transition to renewable energy and can contribute to the mitigation of emissions from fossil fuels in fertilizer production, farm mechanization, and the food supply chain. However, issues related to competition with food crops, the role of bioenergy crops as a driver of land use change, the life cycle emissions and efficiency of biofuels, site-specific outcomes, differential impacts on the poor, and sustainable cultivation practices have made bioenergy controversial as a mitigation measure [119].

Additional mitigation in the food system is possible from land use change and food supply chains [120]. An integrated approach to addressing mitigation at all three scales—farm, landscape, and supply chain—will enable progress on multiple fronts to meet the 2030 target.

4.2. Reducing Deforestation and GHG Emission Whilst Enhancing Food Security through Agricultural Intensification

Despite growing awareness about their impacts, deforestation and forest degradation globally remain high with clearance of forests and trees for oil palm, cattle production, rubber, coffee and timber plantations, and for low-yielding agriculture. For example, in Africa, notably in West and East Africa, approximately 3.4 million ha^{−1} year^{−1} was lost between 2000 and 2010. In South America, almost 4 million ha^{−1} year^{−1} was lost during the same period. Independent global satellite imagery studies and ground-based inventories from 2000–2005 by several authors, show that emissions from gross deforestation in tropical regions reached 3.0 Gt CO₂ yr^{−1} [121,122]. However, this value excludes emissions from the cultivation of mineral soils, peatland degradation, and forest degradation activities that could account for another 2.3 Gt CO₂ yr^{−1}. Therefore, deforestation and forest degradation accounted for approximately 15% of total global GHG emissions per year for that period. It has been demonstrated that just 20 tropical countries with high emissions from agriculture-driven deforestation and with potential for forest-sparing interventions, have the potential to mitigate 1.3 Gt CO₂ e yr^{−1} [123]. Given the urgency to cut these emissions, sustainable agricultural intensification (productivity increases per unit of land and other resources) and governance mechanisms for protecting the boundaries of high carbon stock areas are widely recognized as essential in making an important contribution to preserving forested land, grasslands, and wetlands and, consequently, reducing and capturing emissions whilst at the same time enhancing the food security of both current and future population [124–126].

Nevertheless, it is important to consider that having a more efficient agriculture could lead to higher profits, which could incentivize an expansion of the cultivated area. In the short-term, the magnitude of this direct rebound effect depends on the price elasticity and effective governance [127]. Also, it is important to highlight that in achieving the potential benefits of agricultural intensification on land preservation, food security, and GHG emission, it must be ensured that the required changes in land management practices are achieved without degrading soils and causing wider environmental damage [128]. For example, some authors have shown that once such soil degradation occurs, small-scale and family farmers in Africa are no longer able to benefit from key elements of intensification such as improved crop varieties and low level fertilizer inputs [129].

Earlier in this paper we referred to the disappointingly low adoption rates of many of the possible crop, soil, and water management innovations that can lead to successful agricultural intensification and have cited many authors who have stressed the need for a wide range of improved strategies and policies to provide an enabling environment for small-scale and family farmers in the developing world. Hence, investment in Agriculture Research for Development (AR4D) targeting improved farmer innovation, improving productivity, and enforcing forest boundaries, remains one way to reduce the pressure of deforestation by nearby farmers [130], although efforts to apply this approach widely have to deal with market price issues, unclear land rights, and frontier governance conditions. Some policy options include reducing overall agricultural rent and promoting economic development that can contribute to raise the opportunity cost of labor and, therefore, that can reduce agricultural rent and targeting intensive agriculture (where intensive means intensive in productive inputs other than land) [131].

4.3. Food Waste and Loss

It is estimated that globally one-third of human food produced annually—approximately 1.3 billion tones—gets lost or wasted [132]. To put this number in perspective, if just one-fourth of this waste could be saved, it would be enough to feed 870 million hungry people yearly. This is a major squandering of resources—water, land, energy, labor, and capital—and a source of needless GHG emissions. It is estimated that each year global food loss and waste generate 4.4 GtCO₂ eq., or ~8%, of total anthropogenic GHG emissions [133], and that “if food wastage were a country, it would be the third largest GHG emitting country in the world behind only the USA and China.” The highest carbon footprint of wastage occurs at the consumption phase (37% of total) (Table 2).

Table 2. Percent relative food wastage by volume per region ¹ and by phase of food supply chain (Source: Abstracted from FAO [134]) and contribution of each phase of the food supply chain to food wastage and carbon footprint (Source: Abstracted from FAO [133]).

Stage of Food Supply Chain	% by Volume	% of C-footprint	EU	NAM	iAS	SSA	NA	SA	LAM
Agricultural production	32	17	37	32	26	35	30	32	40
Postharvest handling and storage	23	17	10	10	20	35	24	36	21
Processing	11	14	13	11	10	13	18	11	16
Distribution	13	15	6	9	14	13	14	10	12
Consumption	22	37	34	38	30	4	14	11	11
	100%	100%							
Per capita food wastage footprint (kg CO₂ eq./year)			680	860	810	210	350	350	540

¹ EU = Europe; NAM = N. America & Oceania; iAS = Industrialized Asia; SSA = sub-Saharan Africa; NA = N. Africa + W. & C. Asia; AS = S & SE. Asia; LAM = L. America.

Differentiating by regions (Table 2), it is clear that on a per capita basis annual food wastage (kg CO₂ eq./year) is substantially greater in high income regions and that food volume wastage at the consumption stage is also greatest in these regions, largely due to factors such as aesthetic preferences and arbitrary ‘sell-by date’ labeling. Food wastage at the consumption stage is lower in low-income regions still experiencing food insecurity, but nevertheless, food wastage constitutes a resource for energy generation in these regions. In low-income regions, food losses tend to be more of a concern due to the lack of handling, storage, and transport infrastructure. This can often be exacerbated by unfavorable weather conditions which can accelerate food spoilage during storage [135]. A review of food waste and loss opportunities in USAID projects across 20 value chains in 12 countries and review of the literature suggests that food waste and loss opportunities vary more by specific localities than by region. One exception is dairy, where loss reductions have similar opportunities among regions because of the initial high emissions compared to other agricultural sectors [136]. One study of three

value chains in sub-Saharan Africa showed food loss reductions ranging from 4.5% to 36%, with proportional GHG reductions [137].

The United Nations Sustainable Development Goal 12 (SDG 12) on “Ensuring sustainable consumption and production patterns” includes a specific food waste reduction target: “by 2030, to halve per capita global food waste at the retail and consumer levels.” Decreasing food waste is essential in any strategy for achieving global food security by 2050 whilst at the same time delivering the required GHG emission target [133].

There are many policy initiatives, especially in developed economies that are trying to address the issue of food waste and loss. Some of these include the United Kingdom campaign: Love Food Hate Waste under The Waste and Resources Action Programme (WRAP) launched in 2007 and that is currently running in Australia, New Zealand, and Canada; the May 2017 Resolution from the European Parliament to reduce food waste by setting binding reduction targets, updating the list of food exempt from “best before” labeling and establishing tax exemptions on food donations; and Japan’s regulatory efforts to reduce food waste by promoting recycling food waste into animal feed and fertilizers [138].

4.4. Changes in Food Consumption Patterns

Over the past 50 years, there has been an approximately 1.5-fold increase in the global numbers of cattle, sheep, and goats, with equivalent increases of 2.5- and 4.5-fold for pigs and chickens, respectively, largely due to human population growth and dietary changes associated with increased wealth (Table 3). The global average per capita meat consumption has increased approximately 15 kg/capita/year since 1973 with the average person consuming around 43 kg of meat/year in 2013, but with marked differences across regions.

Table 3. Trends in per capita meat consumption for the period 1973–2013 [139] and projected human population increases for the period 2013–2050 [140].

Regions & Selected Countries	Meat Consumption kg/Capita/Year			Meat Consumption Increase kg/Capita/Year		Projected Human Population Increase (Millions)
	1973	1993	2013	1973–1993	1993–2013	2013–2050
Americas						
Northern America	100.3	114.0	112.7	13.7	−1.3	84
Central America	22.5	35.8	54.9	13.3	19.1	64
South America	37.4	52.8	81.5	15.4	28.7	92
Europe						
Northern Europe	65.2	70.4	80.2	5.2	9.8	16
Western Europe	82.4	90.4	85.3	8.0	−3.2	8
Eastern Europe	58.8	61.8	68.8	3.0	7.0	−35
Southern Europe	54.3	82.3	81.9	28.0	−0.4	−13
Africa						
Northern Africa	12.3	17.4	28.9	5.1	11.5	143
Middle Africa	13.0	16.7	23.9	3.7	7.2	240
Eastern Africa	12.8	10.2	10.8	−2.6	0.6	510
Western Africa	9.4	10.5	12.8	1.1	2.3	476
Southern Africa	34.5	37.7	60.0	3.2	22.3	24
Asia						
Western Asia	17.0	24.0	39.7	7.0	15.7	149
Eastern Asia	11.9	31.5	60.2	19.6	28.7	−30
South East Asia	9.4	16.6	29.4	7.2	12.8	180
Southern Asia	4.6	6.1	6.8	1.5	0.7	600
Central Asia	n/a	36.5	45.2	n/a	8.7	42.1
Oceania						
	104.9	104.6	108.5	−0.3	4.1	28.8

Meat consumption is highest in regions dominated by high income countries such as North America (113 kg/capita/year), Europe (78 kg/capita/year), and Oceania (109 kg/capita/year). However, changes in consumption in high income countries have been much slower—with most stagnating or even decreasing over the period 1993–2013. Growth in per capita meat consumption since 1973 has been most marked in regions in which strong economic transition and associated changes in dietary preferences and aspirations have occurred such as Central and South America, Southern

Europe, Southern Africa, and Eastern Asia. Notable examples of country level increases between 1973 and 2013, associated with economic transition, include Brazil, where consumption has increased from 32 to 98 kg/capita/year, and China, where it has increased from 10 to 61 kg/capita/year. The major exception to this pattern has been in India, where dominant lacto-vegetarian preferences mean that per capita meat consumption in 2013 was almost exactly the same as in 1973 at less than 4 kg per person. However, in the context of livestock related GHG emissions, this statistic masks the fact that cattle and buffalo numbers in India have increased from 240 million in 1973 to 298 million in 2013.

Projected human population increase (Table 3) across industrialized regions, as well as those in economic transition, will continue, which strongly suggests that GHG emissions from the livestock sector will remain a concern. As of 2000, the global livestock sector—including land use and land use change—is estimated to have contributed 18% of total anthropogenic GHG emissions, a figure projected to rise by approximately 40% by 2050 if current livestock production trends in response to changes in dietary preferences and human population projections continue. Given that the conversion efficiency of plant to animal matter is approximately 10%, and that about one-third of global cereal production is fed to animals, there is a strong case for a transition to lower meat diets, also for health reasons as recommended by several authors, especially in the developed world [125,141]. It is estimated that such dietary changes could free up to 2700 Mha of pasture and 100 Mha of cropland and reduce mitigation costs to achieve a 450 ppm CO₂-eq. stabilization target in 2050 by about 50% [13]. However, given the robust projections of human population increases, especially in regions of emerging economic growth (Table 3) where such growth associates dietary changes to higher meat per capita consumption, such a potential is unlikely to be realized, unless meat and protein substitutes are found. Some reductions in GHG emissions will be possible in industrialized regions where per capita meat consumption is at its highest, but has leveled off or even decreased. However, such reductions in these regions will have to be substantial enough to offset projected human population increase for any net reduction in GHG emissions to have any significance.

Policy can play an important role in promoting the changes required in food consumption patterns. One interesting example is the New Nordic Diet, which has developed 24 Nordic policy solutions to change food consumption. These include meal initiatives, an agreement on facts for the Nordic Nutrition Recommendations, and capitalizing on new Nordic food culture, among others. Each solution represents a tangible step to address a specific issue, constituting a new and holistic approach to food policy [142,143].

5. Climate-Smart Agriculture: An Attempt to Achieve the Necessary Synergies among Productivity, Adaptation, and Mitigation

According to the 2017 Sourcebook on CSA [144] “Climate-smart agriculture (CSA) is an approach for developing actions needed to transform and reorient agricultural systems to effectively support development and ensure food security under climate change. CSA aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible.”

CSA provides one framework to operationalize actions aimed at understanding synergies among productivity, adaptation and mitigation. Significant amount of evidence supports the potential for CSA technologies to produce such triple wins as are the examples of conservation agriculture in Tanzania and silvopastoral systems in Nicaragua (Table 4). Nevertheless, trade-offs amongst outcomes may be equally apparent. Some examples include (i) Rwanda’s “Girinka” program (One Cow per Poor Family), which sought to address malnutrition by increasing rural milk consumption. According to Paul et al. [145], with this program, food availability increased at the cost of increasing GHG emissions. (ii) Bellarby et al. [146] describe how Kenya and Ethiopia have increased maize yields while at the same time augmenting GHG emissions due to a rise in the use of fertilizers. (iii) Kurgat et al. [147] analyzed productivity and economic and climate trade-offs in soil fertility management strategies for smallholder farmers in Kiambu county, Kenya. According to this study, farmers are more likely to

choose options with higher economic benefits when selecting soil management practices that improve productivity, but these are not necessarily the best options considering lower environmental impacts in terms of GHG emissions.

Table 4. Select examples of synergies among productivity, resilience, and mitigation in agriculture.

Management Practice	Location	Product	Productivity		Resilience		Mitigation		Source
			% Change	Indicator	% Change	Indicator	% change	Indicator	
Mixed inorganic-organic fertilizer	Kenya	Vegetables	159	Benefit-Cost Ratio	-	-	-75	N ₂ O _i	Kurgat et al., [147]
Intercropped leguminous agroforestry	Zambia	Maize	102	Yield	23	Yield stability			Sileshi et al., [148]
Alternate wetting and drying	China	Rice	0	Yield	43	Water prod.	-59	CH ₄	Liang et al., [149]
Conservation agriculture	Tanzania	Maize	40	Yield	21	Rainfall use intensity	-32	GHG _i	Kimaro et al., [150]
Improved feeding	Kenya	Meat	13	Live weight gain	5	Feed efficiency	-	-	Kariuki et al., [151]
Silvopastoral systems ¹	Nicaragua	Milk	82	Yield	-	-	-36	CH ₄	Gaitán et al., [152]

¹ Based on models estimates of GHGs.

Although existing trade-offs can sometimes seem to outshine synergies, some global studies show otherwise. For example, a global study by Tilman et al. [153] suggests that agricultural intensification through technology adaptation and transfer and enhancement of soil fertility in the poorest countries could help reduce yield gaps, thus achieving a more equitable global food supply and contributing at the same time to decrease GHG emissions, amongst other benefits.

The orientation of CSA toward achieving outcomes versus just developing a technology and the diversity of potential solutions under the CSA umbrella provides farmers, project managers, program developers, and policy-makers significant opportunities to select the right intervention for the right place [154]. However, without (i) broad political will, such as expressed by the Global Alliance for Climate-Smart Agriculture (GACSA), aiming to help 500 million farmers practice CSA; (ii) good implementation capacity, as major global NGOs set up to be frontline workers; and (iii) emerging investment and commitments by the private sector and GCF, significant hurdles stand in the way of using CSA as a tool to promote the necessary changes to promote an adapted and sustainable agriculture.

Concerns have been raised about the fundamentals of CSA. Some authors suggest that although the bulk of discussion has focused on developing countries, there is a paucity of useful information on the policy and practical experienced gained in developed nations [155]. Despite the ability for CSA to provide holistic approaches to development, implementation is often constrained to market-oriented technical fixes, and thus does not live up to its stated aims [156]. These critiques and others suggest a disconnection between principles and practice. The way some have suggested to remedy this is thorough clearer definition of what is and what is not CSA [144]. That however goes against the fundamental definition of resilience, time, and location specificity which is core to CSA and the UNFCCC agenda which promotes continuous improvements. Therefore, what is CSA today may not be CSA tomorrow. Drawing boundaries would seemingly contradict part of what makes CSA attractive: its flexibility for different stakeholders with their own values to contribute to the same goals.

Whilst such discussion is likely to continue, the fact remains that CSA provides a framework within which synergies between adaptation, mitigation and improved food security for small-scale and family farmers can be identified, developed, and disseminated. Given that the majority of developing countries have identified adaptation to climate change as a priority for achieving future food security in their NDCs, but that many also have reservations with regard to mitigation commitments (see Box 1), identifying such synergies is essential. However, if CSA is to gain greater ability to achieve such transformative change it will need to tackle important issues including the generation of evidence

in relation to progress towards increasing productivity and resilience and reducing GHG; and also demonstrating its added value as a development initiative.

6. One World, but Differentiated Challenges and Solutions

Priorities with respect to adaptation and mitigation are and should be varied by country specific conditions and by different types of farmers. Solutions need to be context specific. By combining production gaps with the severity of impacts of climate change on maize, wheat, and rice, Aggarwal et al. [157] demonstrate that different countries have different adaptation needs. Figure 3 illustrates the difference between countries such as Ethiopia and South Africa compared to India, Peru, and Pakistan. For the first set of countries, wheat shows moderate production gaps combined with small effects of climate change on production. The latter could imply a focus on incentivizing incremental adaptation actions at local scale and at the same time strengthening their food supply through trade. The story is different for India, Peru, and Pakistan where, most probably, technology growth will have to be bundled with transformative adaptation in relation to land use and the use of varieties that are tolerant to climate stress and high yielding. In these countries, the consumption of wheat is very large and important negative impacts of climate change are expected, implying the need to adapt to large production gaps.

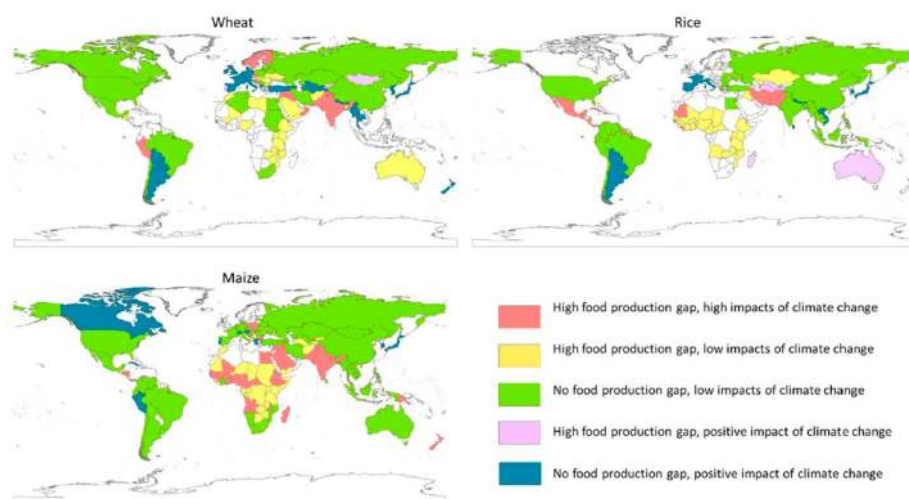


Figure 3. Hotspots of climate change based on assessments of impacts after adaptation on crop yield at country scale for the 2050s and the production gap (the difference between estimated cereal demand in 2050 and current cereal supply). Countries with a large cereal gap and high impacts of climate change are most vulnerable. Countries included only if the cropped area >10,000 ha [157].

A similar story can be told with respect to mitigation options. Just to give an example, Table 2 highlights the differentiated mitigation opportunities when considering reducing emission through reduction of food loss and waste. It is even emphasized that for this particular matter, opportunities vary more by local context than region. Figure 4 taken from IPCC's Fourth Report, presents an overview of the differences between countries and regions when considering mitigation options [158]. As can be observed for all soil carbon options, mitigation potential goes all the way from 900 Mt CO₂ eq/yr in China to around 50 Mt CO₂ eq/yr in Central Asia.

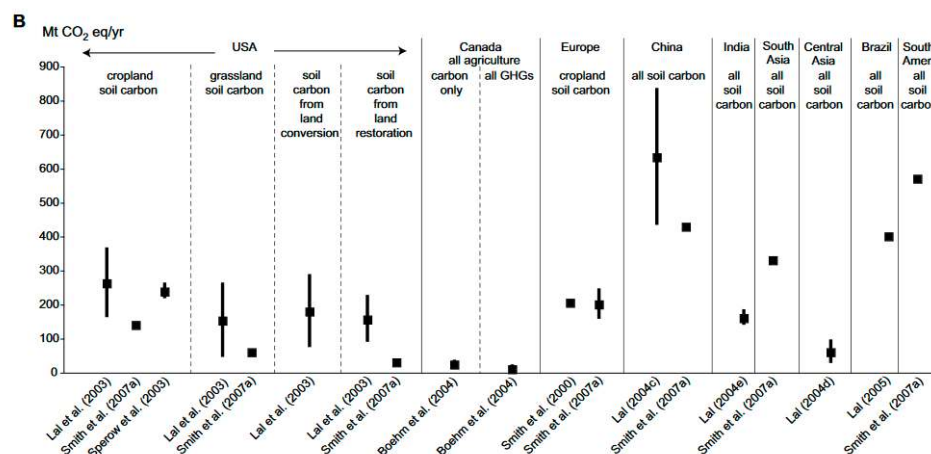


Figure 4. Regional estimates of technical mitigation potential by 2030 [158].

7. Summary and Conclusions

In the coming decades leading up to 2050, the world faces an unprecedented challenge of having to raise food production by 60% in order to feed a projected global population of 9 billion people. Such a challenge, already daunting, is exacerbated by growing constraints on land and water availability for crops, pasture, and livestock production and the current and projected negative impacts of climate change. Recognition of the scale of the challenge is reflected in the increasing attention being given to food security, agriculture and climate change within the UNFCCC since the first Earth Summit in 1992. Most recently, in 2017, during the closing plenary session of COP 23, both the SBSTA and the SBI were requested to jointly address issues related to agriculture and climate change which covered adaptation, mitigation, resilience, opportunities for synergies, and potential constraints to adoption that are evident. Initiatives are needed to create a conducive enabling environment which encourages innovation, investment, and action. The right policies and incentives need to be in place so that the challenges imposed by climate change on food systems can be addressed. Based on the adaptation and mitigation literature we have discussed, the following important points have emerged.

7.1. Adaptation Actions

- Potential adaptation actions are wide ranging and span the continuum from incremental to transformative, depending on the frequency and severity of extreme weather and climatic impacts. Both incremental and transformative adaptation can occur across scales from farm households to national agencies.
- Breeding will play a crucial role in the development of crop varieties that are tolerant or resistant to both biotic and abiotic climate change impacts. Whilst the adoption of improved varieties has been disappointingly slow in some regions, evidence shows that where enabling dissemination and policy environments are in place, this is not the case.
- Evidence is emerging that when CIS are constructed with farmer input and are targeted in a timely and inclusive manner they are a positive determinant of adaptation through the adoption of more and/or different farm level practices. However, currently assessments of the economic impact of CIS are scarce; hence increased frequency of such studies is needed.
- Index insurance schemes are often heavily subsidized. In addition, the failure of many index insurance programs for farmers in the developing world has raised concerns about demand. To overcome such constraints, there is a need to develop the capacity of private insurers to address farmers' needs. For wide scale impact, creating an enabling regulatory environment, investing in meteorological and agricultural data systems, educating farmers about the value of insurance, and facilitating international reinsurance will all be essential.

- PSSN have spread rapidly and are now in place in 130 developing countries. They have proven potential to reduce economic loss and migration in the face of climate shocks, especially when integrated with credit schemes, production inputs, extension, and risk finance. A recent analysis has shown that such schemes can result in substantial reductions of GHG emissions. More analyses on such mitigation potential are required.
- Planned temporary or seasonal migration (incremental adaptation) can enhance household resilience and food security through remittances. However, longer term and large-scale migration out of agriculture due to the slow onset of projected climate change-induced events such as sea-level rise, salinization, and desertification (transformative adaptation) could prove catastrophic for hundreds of millions unless properly anticipated and planned. Urgent priority should be given to identifying where such large-scale migration is likely to occur with the development of practical policy measures that will need to be put in place to support the future livelihoods of such migrants.

7.2. Mitigation Actions

- Analyses has shown that with a near term goal for 2030 of 1 Gt CO₂ e yr⁻¹ emission reduction compared to the BAU scenario, and using optimistic assumptions with regard to the dissemination and adoption of currently available improved production practices, direct emissions from agriculture will only deliver 21–40% of the mitigation required. Given the ongoing constraints that are associated with the implementation of LED pathways, additional mitigation will also be required from a more holistic approach which includes indirect emissions and which spans the entire food system (Table 1).
- Reducing GHG emissions from forest clearance and degradation associated with agricultural expansion through agricultural intensification has enormous potential to reduce GHG emissions, with estimates of up to 1.3 Gt CO₂ e yr⁻¹ being possible. Investment in AR4D targeting improved adoption rates of intensification innovations remains one of the best ways to reduce pressure on increasingly scarce land resources.
- Global food loss and waste amounts to 1.3 billion tones/year. Each year such loss and waste generate 4.4 Gt CO₂ eq., or ~8% of total anthropogenic GHG emissions. Thirty-seven percent of this occurs at the consumption stage (Table 2). On a per capita basis food wastage (kg CO₂ eq./year) is substantially greater in high income regions. In contrast, in low income regions, postharvest losses are highest due to the lack of infrastructure and of knowledge on proper storage and handling. Hence, actions to increase food security and reduce GHG emissions should target loss during the consumption stage in high income countries and postharvest handling and storage in low income countries.
- As of 2000, the global livestock sector—including land use and land use change—is estimated to have contributed 18% of total anthropogenic GHG emissions, a figure projected to rise by approximately 40% by 2050 if current trends in per capita meat consumption and population growth continue. A transition to lower meat diets could reduce mitigation costs to achieve a 450 ppm CO₂-eq. stabilization target in 2050 by ~50%. However, given the projections of human population increases, especially in regions of emerging economies where increased meat consumption is also occurring (Table 3), such potential reductions are unlikely to be realized. Reductions in GHG emissions should target industrialized regions where per capita consumption is highest but has leveled off or decreased in recent years.

7.3. Seeking Synergies

The Global Alliance for Climate-Smart Agriculture provides a framework within which synergies between adaptation, mitigation and improved food security for small-scale and family farmers can be identified, developed, and disseminated. Given that the majority of developing countries have identified adaptation to climate change as a priority for achieving future food security in their INDCs,

but that many also have reservations with regard to mitigation commitments (Box 1), identifying such synergies is essential. Recent analyses of case studies have shown that synergies among productivity, resilience, and mitigation occur in many CSA innovations (Table 4). Where such opportunities exist and also meet the local aspirations of small-scale and family farmers, their successful scaling up is a priority, but will require transformative changes in current policies, institutional arrangements, and funding mechanisms. Such synergies are also important in large-scale agriculture where their realization will face fewer constraints.

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