Global Food Security 32 (2022) 100612

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Perspective: The gap between intent and climate action in agriculture

Shalika Vyas [a,e,*], Arun Khatri-Chhetri [a,d], Pramod Aggarwal [a,b], Philip Thornton [a,c], Bruce M. Campbell [a,d]

[a] CGIAR Research Program on Climate Change, Agriculture and Food Security, India
[b] Borlaug Institute for South Asia, International Maize and Wheat Improvement Center, CIMMYT, New Delhi, 110012, India
[c] International Livestock Research Institute, Nairobi, Kenya
[d] International Center for Tropical Agriculture, Cali, Colombia
[e] Alliance of Bioversity International and International Center for Tropical Agriculture (CIAT), Nairobi, Kenya

ARTICLE INFO

Keywords:
Climate change
NDC
Adaptation
Mitigation
Paris agreement
Readiness
Climate hotspots
Agriculture
Climate action

ABSTRACT

Following the UNFCCC Paris Agreement, most nations made commitments within their Nationally Determined Contributions (NDCs) to adaptation and mitigation in agriculture. However, these commitments need to be assessed in relation with ground truth, including bio-physical and socio-economic limits to climate action. We propose a new framework for monitoring climate action by countries/regions, based on four dimensions—intent, need, scope and readiness for implementing adaptation and mitigation in agriculture. While "intent" reflects intended climate action by countries such as those mentioned in NDCs or NAPs (National Adaptation Plans) and NAMAs (Nationally Appropriate Mitigation Actions), "need" highlights vulnerability of a country's agriculture to climate change and historical GHG emissions. The third dimension, "scope", is related to the biophysical opportunities and limits to adapt or to mitigate. Finally, the "readiness" dimension considers a country's current ability to implement various adaptation/mitigation actions and policies. The framework is illustrated with a global analysis, using selected indicators for each of these dimensions. Results indicate that 61 countries globally (including key food producers) should consider corrective action in their adaptation priorities. The framework presented in this paper can serve as a monitoring and evaluation mechanism for NDC implementation and tracking progress.

1. Introduction

Recent studies project a significant impact of climate change on food systems including gradual changes in climate and more frequent extreme weather events (IPCC, 2021). Food production, agriculture, and other land-use activities also account for 23% of anthropogenic emissions (Rivera et al., 2019). Rising to these challenges requires adaptation and mitigation actions at different scales by stakeholders (Bapna et al., 2019; UNFCC, 2017). Nationally Determined Contributions (NDCs), submitted by member nations under "The Paris Agreement" outline individual country pledges to climate action (UNFCC, 2016). Agriculture is one of the critical sectors in prioritizing national mitigation and adaptation plans across the NDCs for 148 and 131 countries respectively (FAO, 2016). This intent is very encouraging, however implementing these actions is highly contingent upon the alignment of critical drivers which affect their feasibility. Globally, very few monitoring and tracking frameworks for climate action are available. Most of them are either multi-sectoral in their focus or do not analyze climate action from a 'food systems' lens, and don't consider the complexities and vulnerabilities of agriculture in a systematic way (Boehm et al., 2021; Hale et al., 2021; OECD, 2021). In addition, the available frameworks miss the interplay between adaptation and mitigation dimensions of agriculture, and a single framework which can monitor both, is missing. In this paper, we propose a new framework for monitoring climate action in agriculture. The framework helps in understanding the alignment of adaptation and mitigation actions planned in the NDCs with ground reality, and countries implementation potential to achieve the goals of the Paris Agreement. The framework is aimed at aligning national policies (NDCs) towards common collective climate goals and enables a global assessment of adaptation and mitigation actions in the agriculture sector. The framework can thus act as a diagnostic tool to identify priority areas for climate action and can be used to monitor and periodically track climate policies for agriculture.

* Corresponding author. CGIAR Research Program on Climate Change, Agriculture and Food Security, India.
E-mail address: s.vyas@cgiar.org (S. Vyas).

https://doi.org/10.1016/j.gfs.2022.100612
Received 16 March 2021; Received in revised form 4 January 2022; Accepted 6 January 2022
Available online 13 January 2022

2. Framework for monitoring climate action in agriculture

The proposed framework examines four inter-related dimensions for climate action in agriculture-the intent, need for action, scope for action and readiness to implement (Fig. 1) at a national scale. Intended climate action should be aligned with a country's need and scope for adaptation and mitigation in agriculture; and its readiness to implement activities, which is influenced by its policy landscape and enabling conditions. We focus on climate action (adaptation and mitigation) required until the 2050s, as this period is critical to keep planetary changes within environmental limits (Rogelj et al., 2016; Steffen et al., 2015) and supporting sustainable development. Each dimension and the potential data and indicators are discussed below:

2.1. Intent

In this framework we frame intent as commitment to do climate action. It is critical to understand a country's intent to undertake action for climate adaptation and mitigation independent of its capacity for implementation. This intent can be judged by the policy actions and/or budgets allocated for this purpose. Inclusion of agricultural adaptation and mitigation actions in NDC documents, National Adaptation Plans (NAPs) and Nationally Appropriate Mitigation Actions (NAMAs) submitted to UNFCCC, along with other domestic policy measures can be used to represent the intent dimension of the monitoring framework (Kuramochi et al., 2020). There are multiple studies available to assess the intent for climate action through NDCs (Richards et al., 2015b) (FAO, 2020), but many are limited to specific regions or sectors.

2.2. Need

We include the need for climate action in this framework, as a set of conditions which necessitates adaptation and mitigation in a country. From a global policy perspective, climate action is needed by many countries to achieve the collective objectives of the Paris agreement, but the specific need for adaptation is also influenced by vulnerability and requirements of the country at national and sub-national scales. This need or requirement for adaptation in agriculture is often influenced by food security situation and climate change outlook for the country, among many other factors. In this analysis, we position the need for adaptation, as the balance between food demand and supply and its exposure to climatic risk—critical to identify potential food insecure regions. For example, if a country is food self-sufficient or produces surplus with high projected climatic impacts, it may be less likely to prioritize an increase in food production but rather focus on maintaining growth and implementing risk management interventions. These countries may still need to implement adaptation options to maintain growth and minimize future risks of climate change. On the other hand, if a country has a food deficit coupled with high projected climatic impacts, it may need to prioritize adaptation actions, even though trade can modify its response.

The need for mitigation, on the other hand can be driven by historical emissions, current and potential future development pathways, food production priorities and land-use changes, among other factors (IPCC, 2021). The need for mitigation and allocation of mitigation targets is highly context-dependent and there are various methods and tools available to estimate mitigation targets in agriculture (Frank et al., 2017; Richards et al., 2018).

2.3. Scope

The scope for climate action as included in the framework, are a set of potential conditions which enables adaptation and mitigation in agriculture. In particular, the scope for adaptation in agriculture can be conceptualized as potential for adaptation, based on a country's bio-physical limits. The growth in crop production seen since the green revolution can be attributed mainly to an increase in productivity (yield gap closure) and crop area expansion (Bren d'Amour et al., 2017). The magnitude of the crop yield gap can be used as an indicator of scope—larger the gap, higher the scope for change. There are some studies and data available to measure crop yield gaps like (Mueller et al., 2012) and (http://www.yieldgap.org/), but these are limited by the number of countries analyzed. Diversification opportunities to expand livestock and fish culture could be additional indicators of scope. Expansion of the arable area for crop cultivation can be another criterion to assess the scope of adaptation through land-use change.

Similarly, scope for mitigation is bio-physical potential for mitigation in agriculture in a country. Scope for mitigation can be assessed by several potential indicators. Emission intensity in terms of food production (CO_2 equivalent emissions from croplands and livestock production per calorie or per unit of production) is a potentially useful criterion to understand the scope for mitigation in agriculture. It is

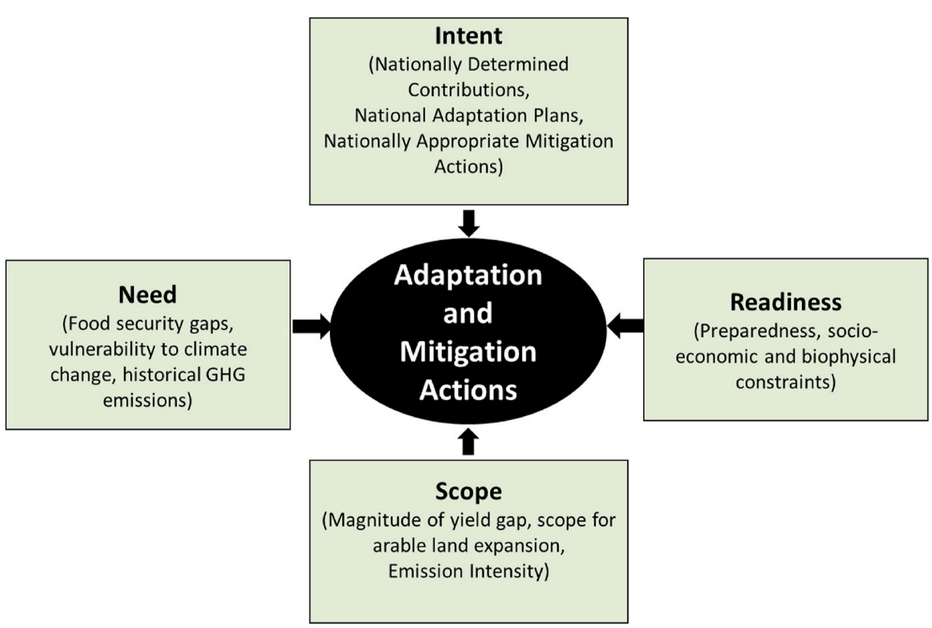


Fig. 1. Framework for analyzing climate action for adaptation and mitigation in agriculture.

better than absolute emissions per ha of land because it reflects both emissions and food production, an important consideration for countries to meet their national food security targets. Emissions reduction potential from the entire food production systems (including transport and other supply chain activties) can be another indicator that can represent the scope for mitigation.

2.4. Readiness

Readiness for climate action, as envisaged in this framework, is the enabling environment and preparedness for scaling out technologies, practices, and services for adaptation and mitigation in agriculture. We conceptualize it as the feasibility of implementing climate action, based on a range of socio-economic and other capacities of the nation. There are many indicators which can be chosen to represent readiness. Ideally, the readiness index should a) combine both biophysical and socio-political dimensions which adequately represent the readiness to implement climate action and b) represent most of the countries and should not be limited in its spatial scale. Available indicators which can be considered are global adaptation index (https://gain.nd.edu/about), change readiness index (https://home.kpmg/xx/en/home/insights/2019/06/2019-change-readiness-index.html) and World Bank's enabling the business of agriculture (https://eba.worldbank.org/).

3. Global analysis to illustrate the framework

To illustrate the framework outlined above, we apply the framework using publicly available indicators and data, to represent the need, scope, readiness and intent for adaptation in agriculture (refer supplementary information for more details). We have chosen global agriculture NDC data (Richards et al., 2015a) to represent the intent for adaptation. Indicator for the need dimension is based on a recent analysis of the gap between national food demand and supply by 2050s, assessed along with projected impacts of climate change on food production in the 2050s (Aggarwal et al., 2019). The scope for adaptation is envisaged as potential for adaptation in agriculture (we have limited the analysis here to crops and not included livestock), based on a country's biophysical limits. It includes increasing crop production by reducing crop yield gaps and increasing cultivated area. To represent this, yield gap as % of attainable yields for cereal crops (maize, wheat and rice) was calculated (Mueller et al., 2012) and arable land as fraction of total agricultural land was estimated using land statistics from FAO (year 2019). Notre Dame-Global Adaptation Index for the year 2019 (ND-GAIN) (Sarkodie and Strezov, 2019) is a generic readiness indicator and includes water, health, food, ecosystems, habitat and infrastructure components, among others. In the absence of another suitable global indicator for agriculture, we have assumed that ND-GAIN also represents the differences in readiness (for implementing climate action) among countries for agriculture sector as well. Although we have chosen indicators that we believe adequately represent the various dimensions of the framework, there could be other suitable indicators that can be used. Future research on developing a specific readiness index for climate action in agriculture would be useful.

Fig. 2 shows results for countries based on the four dimensions of the framework. The scope for adaptation, however, is represented by two variables— cereal yield gap and available arable land. Most of the higher-income countries are in the upper left quadrant of the graph, indicating high scope (due to possibility of expanding arable area despite having low yield gaps) and high readiness despite low to medium need. On the other hand, lower-income countries, especially those of the African continent, are in the right lower quadrant of the graph indicating high scope and low readiness despite high need and intent. Many key food producers (like India, China, Brazil) have medium scope and readiness. The framework illustrated here is dynamic—the indicator for used for readiness is publicly available and updated every year (the ND-GAIN Index is available since 1995), which allows for tracking the progress of each country regularly.

For ease of interpretation and visualization these results are grouped into twelve distinct classes—combinations of three classes of need (high, medium and low), and two classes for each of scope and readiness (high and low) (Fig. 3). Alignment of need with intent, scope and readiness is the key objective of the clustering analysis. Results show that most of the countries need to act urgently on adaptation. Countries (and regions) like Brazil, most of Sub-Saharan Africa and Central Asia, Bangladesh and Indonesia require focus on adaptation actions in agriculture, as their needs are high whereas scope and/or readiness are low. A few higher-income countries of northern and eastern Europe are also hotspots due to projected climate change impacts (Iglesias and Rosenzweig, 2009; Parry et al., 2004), and limited scope for yield gap closure and cropland expansion, despite high readiness. For these countries, food imports from other countries may be an effective adaptation pathway. In comparison, most of the higher-income countries of Western Europe, North

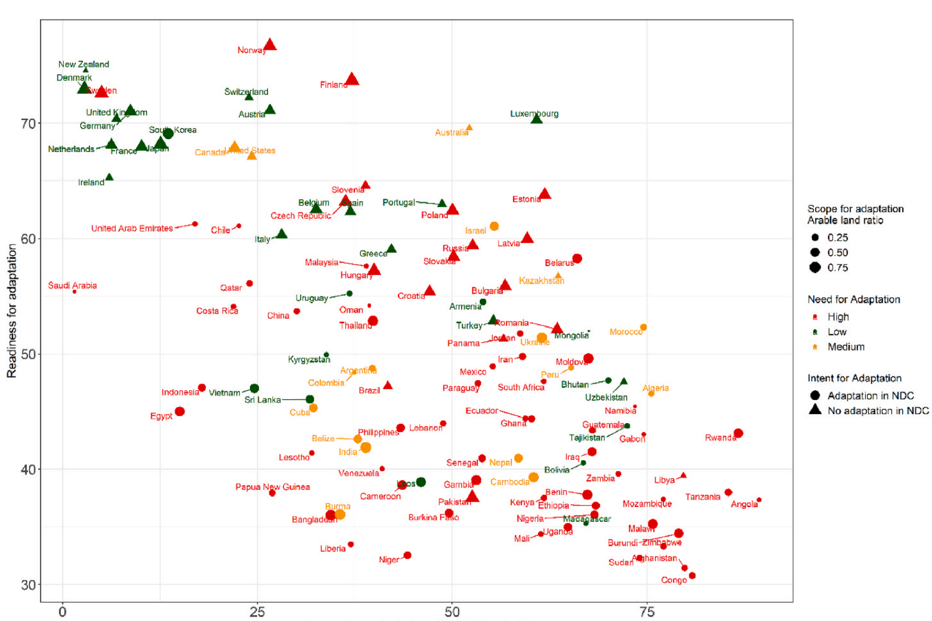
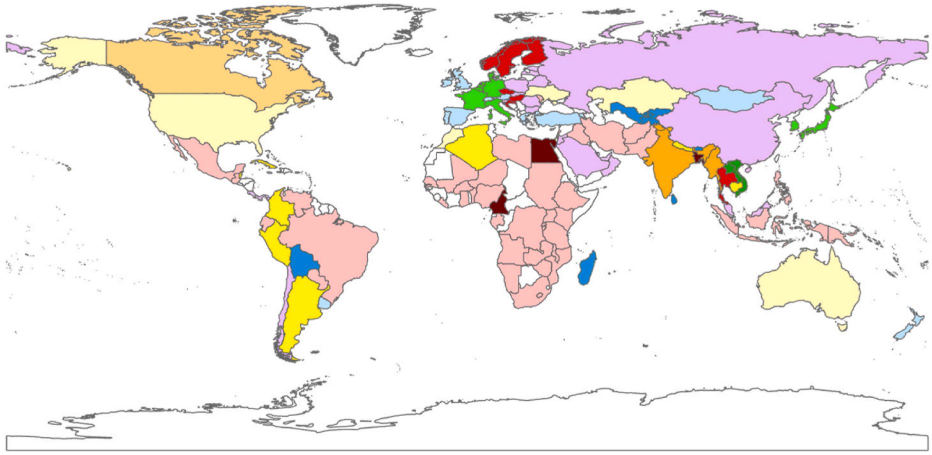


Fig. 2. Illustration of framework with a scatterplot of intent, need, scope and readiness of different countries for adaptation in agriculture. Focus on adaptation (agricultue sector) in the NDCs of countries is taken as an indicator of intent. High need countries are those with a projected future food production deficit and high negative impacts of climate change (more than 10% loss), medium need countries also have similar food production deficit but low negative climate impacts (less than 10%), and low need countries have negligible food production deficit and no negative climate impacts. Scope for adaptation is represented by cereal yield gap (percentage), and by the available arable land as symbol size. Higher the yield gap or available arable land, higher is the scope. Readiness for adaptation is illustrated by the ND Gain Index. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



	Need	Scope	Readiness
	High	Low	Low
	High	Low	High
	High	High	Low
	High	High	High

	Need	Scope	Readiness
	Medium	Low	Low
	Medium	Low	High
	Medium	High	Low
	Medium	High	High

	Need	Scope	Readiness
	Low	Low	Low
	Low	Low	High
	Low	High	Low
	Low	High	High

Fig. 3. Global assessment based on need, scope and readiness in adaptation for agriculture. For details of indicators, please refer to Fig. 2. High scope denotes yield gap more than 50% of the attainable yield and/or current arable land is less than 50% of the total agricultural land. Readiness for climate action of a country is considered high when ND-GAIN Index is greater than 0.5.

America and Australia have high readiness to adapt and variable scope, but their needs are low to medium due to limited food security concerns. Such countries have by and large not committed to adaptation actions in their NDCs. Globally, most of the countries have high to medium need for adaptation, and concerted efforts are required to align adaptation initiatives in agriculture with ground realities.

4. Discussion and conclusion

We highlight crucial takeaways from this study. First, the framework serves as a starting point to develop a comprehensive monitoring mechanism to track NDC progress. Similar mechanisms are already developed for other collective global goals such as the Sustainable Development Goals (https://sdg-tracker.org/). Most indicators which can be used for this framework are reported annually, thus enabling a temporal analysis. Future research integrating synergies and trade-offs between different components of the framework through modelling can further help enhance the current work. Second, results for adaptation show a mismatch between the four dimensions of climate action—particularly amongst developing nations. We found that 61 countries (52% of the total reviewed) have high need for adaptation but a mismatch between scope, intent and/or readiness. On the contrary, 11% of the countries have low needs in adaptation, and a focus on adaptation in the NDC. Adaptation finance today accounts for only 5% of global climate finance, of which only 23% is invested in agriculture, forestry, land-use and natural resource management (CPI, 2018), and is well below what is required (Campbell et al., 2018; Odhong' et al., 2019). For developing countries with limited financial resources, alignment of policy initiatives with need, scope and readiness is essential, so that their fast depleting financial resources are used to support what they need at priority.

The framework presented in this analysis would need periodic updating as its dimensions are likely to change with development and climate change scenarios. For example, the need for adaptation based on projected food supply and climate impacts for the 2050s (and future food security) may change based on demographic changes and actual emissions reduction achieved, respectively. The trajectories countries chose for socio-economic development and adaptation will likely affect their mitigation results and vice-versa (Deng et al., 2017). Dietary changes in future may drive feed expansion at the expense of food production (The Eat-Lancet Commission, 2019), and the current indicator for scope (yield gaps) can only measure one dimension of food production, while leaving out other important issues like nutritional security and sustainable diets (Herrero et al., 2017; Springmann et al., 2021). Further, productivity indicators like crop yield gaps also don't account for other resources like inputs (fertilizer and water), labour and capital resources; and the likely impacts of climate change on resource-use efficiency (Ortiz-Bobea et al., 2018, 2021). Besides, projected land-use changes will influence the area available for farming, and it should also be included in the scope. Arable land expansion when used for intensive farming practices can come in direct conflict with the objectives of Paris agreement. However, it will continue to play an important role in food security policy agenda for many developing countries, and sustainable farming practices like climate-smart agriculture, nature positive solutions (among others) can help in overcoming many of these trade-offs (Delzeit et al., 2017).

In addition, the readiness dimension should not only represent current capacity to implement climate action, but also future food systems innovations and transformational change targeted towards climate action (Jaacks, 2021; Moberg et al., 2021; Steiner et al., 2020; van Delden et al., 2021). Policymakers across the world are also focusing on transforming food systems using sustainable and climate-smart pathways, circular farming principles, and through innovations in technology (Godde et al., 2021; Herrero et al., 2020). Once successful, these innovations would affect all dimensions of the framework. Future research should aim to create global evidence and data for integrating some of these factors in the monitoring framework for climate action and find ways to track systemic changes and innovation capacity of the nations.

To conclude, the Paris Agreement is widely viewed as an important policy and institutional framework for collective global climate action, especially for agriculture (Chand, 2020). The proposed framework provides a holistic way to contextualize and align climate change strategies with existing conditions and to help identify future trajectories. As countries learn to adjust to the new realities of climate change, scaling adaptation and mitigation will play a key role in changing the landscape of climate action across regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The underlying data used in this study are available from open-source datasets. The codes used for analysis and the results of the paper are available from the corresponding author upon request.

Acknowledgements

This work was implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of these organizations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2022.100612.

References

Aggarwal, P., Vyas, S., Thornton, P., Campbell, B.M., 2019. How much does climate change add to the challenge of feeding the planet this century? Environ. Res. Lett. 14, 043001 https://doi.org/10.1088/1748-9326/aafa3e.

Bapna, M., Brandon, C., Chan, C., Patwardhan, A., Dickson, B., 2019. ADAPT NOW: A GLOBAL CALL FOR LEADERSHIP ON CLIMATE RESILIENCE.

Boehm, S., Lebling, K., Levin, K., Fekete, H., Jaeger, J., Nilsson, A., Wilson, R., Geiges, A., Schumer, C., 2021. State of climate action 2021: systems transformations required to limit global warming to 1.5°C. Washington, DC. https://doi.org/10.46830/wrirpt.21.00048.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C., 2017. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. Unit. States Am. 114, 8939–8944. https://doi.org/10.1073/pnas.1606036114.

Campbell, B.M., Hansen, J., Rioux, J., Stirling, C.M., Twomlow, S., Lini, Wollenberg, E., 2018. Urgent action to combat climate change and its impacts (SDG 13): transforming agriculture and food systems. Curr. Opin. Environ. Sustain. 34, 13–20. https://doi.org/10.1016/j.cosust.2018.06.005.

Chand, A., 2020. Paris Agreement needs food system change. Nat. Food 1. https://doi.org/10.1038/s43016-020-00205-5, 772–772.

CPI, 2018. Global climate finance: an updated view. https://doi.org/10.1007/978-3-642-39564-2_4.

Delzeit, R., Zabel, F., Meyer, C., Václavík, T., 2017. Addressing future trade-offs between biodiversity and cropland expansion to improve food security. Reg. Environ. Change 17, 1429–1441. https://doi.org/10.1007/s10113-016-0927-1.

Deng, H.-M., Liang, Q.-M., Liu, L.-J., Anadon, L.D., 2017. Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environ. Res. Lett. 12, 123001. https://doi.org/10.1088/1748-9326/aa98d2.

FAO, 2016. The Agriculture Sectors in the Intended Nationally Determined Contributions: Analysis.

FAO, 2020. A common framework for agriculture and land use in the nationally determined contributions, A common framework for agriculture and land use in the nationally determined contributions. https://doi.org/10.4060/cb1589en.

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., Kleinwechter, U., Fricko, O., Gusti, M., Herrero, M., Smith, P., Hasegawa, T., Kraxner, F., Obersteiner, M., 2017. Reducing greenhouse gas emissions in agriculture without compromising food security? Environ. Res. Lett. 12, 105004. https://doi.org/10.1088/1748-9326/aa8c83.

Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob. Food Sec. 28, 100488. https://doi.org/10.1016/j.gfs.2020.100488.

Hale, T.N., Chan, S., Hsu, A., Clapper, A., Elliott, C., Faria, P., Kuramochi, T., McDaniel, S., Morgado, M., Roelfsema, M., Santaella, M., Singh, N., Tout, I., Weber, C., Weinfurter, A., Widerberg, O., 2021. Sub- and non-state climate action: a framework to assess progress, implementation and impact. Clim. Pol. 21, 406–420. https://doi.org/10.1080/14693062.2020.1828796.

Herrero, M., Thornton, P.K., Power, B., Bogard, J.R., Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, K., Watson, R.A., West, P.C., Samberg, L.H., van de Steeg, J., Stephenson, E., van Wijk, M., Havlík, P., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Heal. 1, e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4.

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., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C., 2020. Innovation can accelerate the transition towards a sustainable food system. Nat. Food 1, 266–272. https://doi.org/10.1038/s43016-020-0074-1.

Iglesias, A., Rosenzweig, C., 2009. Effects of Climate Change on Global Food Production from SRES Emissions and Socioeconomic Scenarios.

IPCC, 2021. Climate change 2021: the physical science basis, IPCC. https://doi.org/10.1080/03736245.2010.480842.

Jaacks, L.M., 2021. Boost public support for food systems innovation. Nat. Food 2, 226–227. https://doi.org/10.1038/s43016-021-00239-3.

Kuramochi, T., Roelfsema, M., Hsu, A., Lui, S., Weinfurter, A., Chan, S., Hale, T., Clapper, A., Chang, A., Höhne, N., 2020. Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions. Clim. Pol. 20, 275–291. https://doi.org/10.1080/14693062.2020.1740150.

Moberg, E., Allison, E.H., Harl, H.K., Arbow, T., Almaraz, M., Dixon, J., Scarborough, C., Skinner, T., Rasmussen, L.V., Salter, A., Lei, X.G., Halpern, B.S., 2021. Combined innovations in public policy, the private sector and culture can drive sustainability transitions in food systems. Nat. Food 2, 282–290. https://doi.org/10.1038/s43016-021-00261-5.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. https://doi.org/10.1038/nature11420.

Odhong', C., Wilkes, A., van Dijk, S., Vorlaufer, M., Ndonga, S., Sing'ora, B., Kenyanito, L., 2019. Financing large-scale mitigation by smallholder farmers: what roles for public climate finance? Front. Sustain. Food Syst. 3, 3. https://doi.org/10.3389/fsufs.2019.00003.

OECD, 2021. The Annual Climate Action Monitor. OECD Publishing, Paris. https://doi.org/10.1787/5bcb405c-en.

Ortiz-Bobea, A., Knippenberg, E., Chambers, R.G., 2018. Growing climatic sensitivity of U.S. agriculture linked to technological change and regional specialization. Sci. Adv. 4, eaat4343. https://doi.org/10.1126/sciadv.aat4343.

Ortiz-Bobea, A., Ault, T.R., Carrillo, C.M., Chambers, R.G., Lobell, D.B., 2021. Anthropogenic climate change has slowed global agricultural productivity growth. Nat. Clim. Change 11, 306–312. https://doi.org/10.1038/s41558-021-01000-1.

Parry, M., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environ. Change 14, 53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008.

Richards, M., Bruun, T.B., Campbell, B.M., Gregersen, L.E., Huyer, S., Kuntze, V., Madsen, S.T.N., Oldvig, M.B., Vasileiou, I., 2015a. How Countries Plan to Address Agricultural Adaptation and Mitigation an Analysis of Intended Nationally Determined Contributions, How Countries Plan to Address Agricultural Adaptation and Mitigation.

Richards, M., Gregersen, L., Kuntze, V., Madsen, S., Oldvig, M., Vasileiou, I., 2015b. Agriculture's Prominence in the INDCs Strategies.

Richards, M.B., Wollenberg, E., van Vuuren, D., 2018. National contributions to climate change mitigation from agriculture: allocating a global target. Clim. Pol. 18, 1271–1285. https://doi.org/10.1080/14693062.2018.1430018.

Rivera, A., Bravo, C., Buob, G., 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In: IPCC. https://doi.org/10.1002/9781118786352.wbieg0538.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631–639. https://doi.org/10.1038/nature18307.

Sarkodie, S.A., Strezov, V., 2019. Economic, social and governance adaptation readiness for mitigation of climate change vulnerability: evidence from 192 countries. Sci. Total Environ. 656, 150–164. https://doi.org/10.1016/j.scitotenv.2018.11.349.

Springmann, M., Clark, M.A., Rayner, M., Scarborough, P., Webb, P., 2021. The global and regional costs of healthy and sustainable dietary patterns: a modelling study. Lancet Planet. Heal. 5, e797–e807. https://doi.org/10.1016/S2542-5196(21)00251-5.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 80 (347). https://doi.org/10.1126/science.1259855, 1259855–1259855.

Steiner, A., Aguilar, G., Bonilla, J.P., Campbell, A., Echeverria, R., Gandhi, R., Hedegaard, C., Holdorf, D., Naoko, I., Quinn, K., Ruter, B., Sunga, I., Sukhdev, P., Verghese, S., Voegele, J., Winters, P., Campbell, B., Dinesh, D., Huyer, S., Jarvis, A., Maria Loboguerrero Rodriguez, A., 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).

The Eat-Lancet Commission, 2019. Healthy diets from planet; food planet health. Lancet 1–32.

UNFCC, 2016. Aggregate Effect of the Intended Nationally Determined Contributions: an Update.

UNFCC, 2017. United nations climate change annual report 2017. https://doi.org/10.1016/j.parkreldis.2015.02.017.

van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J.C., Vialet-Chabrand, S., Woltering, E.J., van de Zedde, R., Zhang, Y., Marcelis, L.F.M., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2, 944–956. https://doi.org/10.1038/s43016-021-00402-w.