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Modelling the impact of climate change on the food systems through integrated assessments

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The fast-ongoing changes in the Earth's climate are today widely scrutinized and well documented (IPCC, 2018). Similarly, evidence now accumulates that agricultural systems and practices have started to cope and adapt in response to the human activities impact on climate (IPCC, 2019). Future climate scenarios let anticipate even more drastic changes in the future, the severity of which will depend on the trajectory chosen by our societies to limit their greenhouse gas emissions (Gidden et al., 2019). The implications of these choices in terms of global warming are relatively clear, and raise serious concerns on food security impacts. However, the regional consequences for food systems are more difficult to predict (IPCC, 2019). For this reason, we would like to highlight in this paper what current approaches are used to answer this question, and the methodological challenges associated to these. We will base this analysis in particular on the experience of the Agricultural Model Inter-comparison and Improvement Project (AgMIP), which was launched ten years ago with the purpose of consolidating the analysis of climate change through better model comparison and integration (Rosenzweig et al., 2013).

The agroeconomic modelling chain of climate impact

Modelling the consequences of climate change on food supply and food security requires several key components. First, we need to know what future climate will look like. This sole question already mobilizes a large scientific community, developing more and more sophisticated models of atmospheric and oceanic circulation (general circulation models, GCMs) to predict future weather patterns (Eyring et al. 2016). These models provide the boundary conditions to simulate typical temperature and precipitation conditions on a day-to-day basis in a given location. The second element of the modelling chain are the crop models (Mueller and Robertson, 2014; Rosenzweig et al. 2014). These models represent the main biological responses of crop growth to climate, environmental and management conditions. Using the predictions of daily temperature and precipitation from GCMs, but also future CO_2 atmospheric concentration, they can estimate what final yield crops will have reached at harvesting time, which allows to project the overall gains or losses of production on planted areas for a given year. Finally, to understand the resulting

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net impact of climate change on food supply, it is necessary to use a third class of models, economic models, that represent how agents respond to the yield shocks and adapt to the shock through management and market responses (von Lampe et al., 2014). These models can in particular be used to infer change in market prices, and study the food security impacts mostly through change in food availability and food accessibility (Nelson et al., 2014a; Valin et al. 2014).

Within AgMIP, such frameworks have been integrated from the climate to the economic component, which allowed to provide some first estimates on the typical magnitude of the changes that the agricultural system could face. Such assessment, broadened in the context of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) fast-track modelling exercise (Warszawski et al., 2014), helped to highlight the channels of propagation of the shock, their compounding or mitigating factors, and provide insights into the different sources of uncertainty. In Nelson et al. (2014b), scenarios produced through the integration of two climate models, five crop models, and nine economic models, provided estimate of the impact of the highest degree of warming at the time horizon 2050 (RCP 8.5), based on temperature and precipitation changes (no CO_2 effects). The assessment concluded that an average 17% average yield loss would impact the agricultural systems, but also lead to a number of adjustments to the biophysical shock, in particular final yield losses reduced at -11% following management and intraregional relocation, and a global production and consumption decrease of only 3% following area increases and adaptation responses through trade.

Adaptation responses to climate change

The adaptation channels highlighted in the ISIMIP fast track assessment are key to the understanding of the final severity of climate change for food security. All economic models displayed adjustment through market responses and agents' behavior in reaction to price signals (Nelson et al., 2014b). A strong climate shock stress would indeed variously affect producers and consumers depending on their adapting capacity. Farmers can shift planting date, adapt their level of inputs, select new crop varieties, alter their crop rotations, or switch to new products. Price increases can accelerate the conversion of land use to produce more food, sometimes at a high cost for the environment, but also in some other areas slow down the pace of farm abandonment and revive rural economies. Well-functioning markets can drive reallocation of food from surplus areas to other regions suffering more important losses, and where markets fail, more targeted policy interventions can help redistribute food where it is most needed. Finally, consumers can also adapt their consumption choices towards food products more abundant on the markets, as more vulnerable supply chains have difficulties to maintain affordable product prices. All these factors together contribute to significantly mitigate and redistribute the impact of climate change for a given pattern of climate shock.

An illustration of these adaptation mechanisms is also given in Leclère et al. (2014) who looked at how these effects would differently unfold for a combination of five different climate models and four different degrees of warming. Some other studies also examined how changing adaptation possibilities could affect model results. For instance, Wiebe et al., (2015), Havlik et al. (2015) or van Meijl et al. (2018) all relied on variation in the background Shared Socioeconomic Pathways

(SSPs, O'Neill et al., 2014) to test the influence of several adaptation factors covered by the SSPs: economic development, technical change, trade openness, diet composition. They consistently found higher price impacts for the low adaptation capacity scenarios (SSP3, "Regional Rivalry" or SSP4, "Poverty") compared to the high adaptation scenario (SSP1, "Sustainability" or SSP5, "Fossil-fueled development"), and more severe consumption impacts in the former case.

From supply shock to food security

Transposing results on food prices and consumption into food insecurity estimates has been achieved in most recent papers, using the FAO methodology to estimate current prevalence of undernourishment as a core approach to derivate future projection of that indicator (Cafiero et al. 2014). The FAO indicator represents how many persons within a population are falling below a minimum dietary energy requirement, calculated based on the demographic structure of the population. Assuming a lognormal profile for food distribution, and projecting the shape of that curve based on economic growth and inequality changes, it is possible to infer how many consumers may be at risk of hunger in the future, and how a climate shock would affect the food security situation. Hasegawa et al. (2018) apply this method on an ensemble of model results for assessing the impact of a moderate level of warming (RCP6.0), and estimated that the population at risk of hunger could increase by 2 to 56 million, depending on the economic model used, under a SSP2 "Middle-of-the-Road" scenario, and by up to 200 million under a SSP3 scenario with decreased adaptation capacity. Hasegawa and colleagues however did not study the impact of higher level of warming (RCP8.5), but the comparison of food availability in their scenario gives an idea of the further implications of stronger warming. For 56 million undernourished, Hasegawa et al. (2018) reports a magnitude of impact of -68 kcal/cap/day (-2%). In comparison, Havlik et al. (2015) estimate that, under RCP 8.5, a decrease of -2.8% of global food availability, and -4.3% without CO_2 fertilization effects are to be anticipated with high adaptive capacity (SSP5). But if adaptation capacity is reduced (SSP4), the respective impacts would be -4.4% with CO_2 effects, and -8.7% without these. Because prevalence of undernourishment is non-linear in response (due to the loglinear profile of the food distribution curve), such magnitude of impact would put several hundreds of millions at risk of hunger. Other health related indicators have also been examined as a result of this food insecurity, such as stunting (Lloyd et al., 2018) or other mortality implications (Hasegawa et al. 2016, Springmann et al., 2016).

Limitations and uncertainties in current assessments

The analyzes above illustrate how integrated frameworks can provide structurally consistent representation of the propagation of climate change impacts along the food supply chain, down to food security metrics. However, the accuracy of these assessments also suffers significant uncertainties and limitation that should be kept in mind and call for future research efforts.

Some uncertainties relate to the characteristics of the tool mobilized. In the case of GCMs, current models provide very different regional predictions for a given level of warming, in particular for future changes in precipitation (Warszawski et al., 2014). Such variable is key for the determination of future crop yields, therefore GCM introduces a first important source of uncertainty from the beginning of the modelling chain (Leclère et al., 2014). Second, for a same climate signal, crop models can also significantly diverge in their prognosis of yield changes. This may relate to different crop management assumptions, but also more fundamentally to some varying representations of key biophysical responses, in particular when it comes to CO_2 effects (Rosenzweig et al., 2014). Furthermore, some important mechanisms of impact are not yet included in global crop models, such as the effect of increased tropospheric ozone, well-known for their detrimental effects on crop yields. The impact of climate change on crop nutrient composition is also an increasing source of attention, but not yet explicitly implemented in these assessments. Finally, economic models also bring their lot of variability (Nelson et al., 2014a,b). Different families of economic models are typically used (for instance, partial versus general equilibrium, aggregated or spatially explicit), and these differ by their structural representation and parameterization. Although these differences have been largely documented, the results variability related to the economic model choices have not to date been satisfactorily reduced.

Other unknowns are more related to the projection of some key variables and the representation of the problem at stake. What typically constitutes the most likely pathway without specific climate action (i.e. the "worst case" scenario) is still debated (Hausfather and Peters, 2020), and the use of RCP 6.0 for many scenario has been somewhat misleading when looking at the time horizon 2050, due to the atypical dynamic of the GHG emission trajectory under that scenario (lower GHG emissions than RCP 2.6 until 2035, and still lower than RCP 4.5 by 2050, see van Vuuren et al., 2011). Additionally, when it comes to food security estimates, future baseline assumption on the state of food distribution is key for the results. Limited attention has been given to the role of future inequality and the potential impacts on such assessment (Rao et al., 2018). Combined assessments bringing together different scales and socioeconomic heterogeneity across households as well as differentiated treatments of urban versus rural areas are also too rare in the context of global analyses (for such applications, see for instance Hallegatte and Rozenberg, 2017; Rozensweig et al., 2018).

Last, the effects represented in these types of analyzes remain based on average impacts, over long time period, and compounding effects of successive or simultaneous extreme events are not well considered (Gaupp et al., 2019), as well as possible biophysical or socioeconomic tipping points (van Ginkel et al., 2020). The potential impacts anticipated by such approaches are for this reason likely to overestimate adaptation responses. This does not question the relevance of such structural integrated modelling, which remains crucial to understand the transmission of climate change impacts through the food system in a consistent manner, but calls for better representation of interannual and intra-annual shocks in these frameworks.

Improving integrated assessment of climate change impact

Significant progresses have been achieved over the past decade to structure the research community on climate change impacts to perform ensemble analyses, bringing together climate, biophysical and economic modelers. This allowed to build much more consistent assessment frameworks for the understanding of food security challenges related to climate change, and these frameworks have continued to be enriched by encompassing more socioeconomic and environmental additional impacts. However, the research agenda to be explored remains considerably vast. Model intercomparison exercises have devoted a lot of energy to broadening the number and ambition of assessments, but have been less successful at sharpening the assessments with thorough model comparisons and improvements (Hertel et al., 2016). This constitutes the first challenge ahead to progress in this research stream.

Second, it is recognized that the role of climate extreme events such as drought, floodings or pests and diseases, will be part of the main challenges for the food system stability (Trnka, 2019, Cooper et al., 2019) and the recent pandemic crisis have illustrated the importance of system resilience. Better representing this dimension in the integrated frameworks described above is key to move forward the research on climate impacts. In particular, the extent to which the food system could adopt through a large array of autonomous or planned adaptation options will need to be better studied.

Last, cross-sectoral impacts also require further attention, in particular when it comes to the link between water stress and agriculture (Schewe et al., 2013; Pastor et al., 2019), the impact of climate on farm labor productivity (Day, 2019), the interdependencies with the energy sector (Diffenbaugh et al., 2012) or international markets (Gouel and Laborde, 2018). Although much topical research has been performed on these topics, systematic integration to modelling chains is still very rare. Some important component of the food systems are also undercovered in typical integrated assessments, such as the impacts on livestock (Rojas-Downing et al., 2017) and fisheries (Barange et al., 2016), which remain key for farm income and/or for food and nutrition security.

References

Barange, M., Bahri, T., Beveridge, M. C. M., Cochrane, K. L., Funge-Smith, S. & Poulain, F. (2018), *Impacts of climate change on fisheries and aquaculture: synthesis of currrent knowledge, adaptation and mitigation options*, FAO.

Cafiero, C., Melgar-Quiconez, H. R., Ballard, T. J. & Kepple, A. W. (2014), 'Validity and reliability of food security measures', *Annals of the New York Academy of Sciences* **1331**(1), 230--248.

Cooper, M. W., Brown, M. E., Hochrainer-Stigler, S., Pflug, G., McCallum, I., Fritz, S., Silva, J. & Zvoleff, A. (2019), 'Mapping the effects of drought on child stunting', *Proceedings of the National Academy of Sciences*, 201905228.

Day, E., Fankhauser, S., Kingsmill, N., Costa, H. & Mavrogianni, A. (2019), 'Upholding labour productivity under climate change: an assessment of adaptation options', *Climate Policy* **19**(3), 367--385.

Diffenbaugh, N. S., Hertel, T. W., Scherer, M. & Verma, M. (2012), 'Response of corn markets to climate volatility under alternative energy futures', *Nature Climate Change* **2**, 514-518.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. & Taylor, K. E. (2016), 'Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization', *Geoscientific Model Development* **9**(5), 1937--1958.

Gaupp, F., Hall, J., Hochrainer-Stigler, S. & Dadson, S. (2019), 'Changing risks of simultaneous global breadbasket failure', *Nature Climate Change* **10**(1), 54--57.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E. & Takahashi, K. (2019), 'Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century', *Geoscientific Model Development* **12**(4), 1443--1475.

van Ginkel, K. C. H., Botzen, W. J. W., Haasnoot, M., Bachner, G., Steininger, K. W., Hinkel, J., Watkiss, P., Boere, E., Jeuken, A., de Murieta, E. S. & Bosello, F. (2020), 'Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research', *Environmental Research Letters* **15**(2), 023001.

Gouel, C. & Laborde, D. (2018), 'The crucial role of international trade in adaptation to climate change', Technical report, National Bureau of Economic Research.

Hallegatte, S. & Rozenberg, J. (2017), 'Climate change through a poverty lens', *Nature Climate Change* **7**(4), 250--256.

Hasegawa, T., Fujimori, S., Havlk, P., Valin, H., Bodirsky, B. L., Doelman, J. C., Fellmann, T., Kyle, P., Koopman, J. F. L., Lotze-Campen, H., Mason-D'Croz, D., Ochi, Y., Domnguez, I. P., Stehfest, E., Sulser, T. B., Tabeau, A., Takahashi, K., Takakura, J., van Meijl, H., van Zeist, W.-J., Wiebe, K. & Witzke, P. (2018), 'Risk of increased food insecurity under stringent global climate change mitigation policy', *Nature Climate Change* **8**(8), 699--703.

Hasegawa, T., Fujimori, S., Takahashi, K., Yokohata, T. & Masui, T. (2016), 'Economic implications of climate change impacts on human health through undernourishment', *Climatic Change* **136**(2), 189--202.

Hausfather, Z. & Peters, G. P. (2020), 'Emissions – the 'business as usual' story is misleading', *Nature* **577**(7792), 618--620.

Havlík, P., Valin, H., Gusti, M., Schmid, E., Leclère, D., Forsell, N., Herrero, M., Khabarov, N., Mosnier, A., Cantele, M. & Obersteiner, M. (2015), 'Climate change impacts and mitigation in the developing world: An integrated assessment of the agriculture and forestry sectors'(7477), Technical report, World Bank.

Hertel, T. W., Baldos, U. L. C. & van der Mensbrugghe, D. (2016), 'Predicting Long-Term Food Demand, Cropland Use, and Prices', *Annual Review of Resource Economics* **8**(1), 417--441.

IPCC (2018), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, IPCC, Switzerland.

IPCC (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.*, IPCC, Switzerland.

von Lampe, M., Willenbockel, D., Ahammad, H., Blanc, E., Cai, Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., Mason D.'Croz, D., Nelson, G. C., Sands, R. D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D. & van Meijl, H. (2014), 'Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison', *Agricultural Economics* **45**(1), 3-20.

Leclère, D., Havlík, P., Fuss, S., Schmid, E., Mosnier, A., Walsh, B., Valin, H., Herrero, M., Khabarov, N. & Obersteiner, M. (2014), 'Climate change induced transformations of agricultural systems: insights from a global model', *Environmental Research Letters* **9**(12), 124018.

Lloyd, S. J., Bangalore, M., Chalabi, Z., Kovats, R. S., Hallegatte, S., Rozenberg, J., Valin, H. & Havlk, P. (2018), 'A Global-Level Model of the Potential Impacts of Climate Change on Child Stunting via Income and Food Price in 2030', *Environmental Health Perspectives* **126**(9), 097007.

van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Domnguez, I. P., Bodirsky, B. L., van Dijk, M., Doelman, J., Fellmann, T., Humpenöder, F., Koopman, J. F. L., Müller, C., Popp, A., Tabeau, A., Valin, H. & van Zeist, W.-J. (2018), 'Comparing impacts of climate change and mitigation on global agriculture by 2050', *Environmental Research Letters* **13**(6), 064021.

Müller, C. & Robertson, R. D. (2014), 'Projecting future crop productivity for global economic modeling', *Agricultural Economics* **45**(1), 37--50.

Nelson, G. C., van der Mensbrugghe, D., Ahammad, H., Blanc, E., Calvin, K., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., von Lampe, M., Mason d'Croz, D., van

Meijl, H., Müller, C., Reilly, J., Robertson, R., Sands, R. D., Schmitz, C., Tabeau, A., Takahashi, K., Valin, H. & Willenbockel, D. (2014), 'Agriculture and climate change in global scenarios: why don't the models agree', *Agricultural Economics* **45**(1), 85--101.

Nelson, G. C., Valin, H., Sands, R. D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E., Kyle, P., von Lampe, M., Lotze-Campen, H., Mason D'Croz, D., van Meijl, H., van der Mensbrugghe, D., Müller, C., Popp, A., Robertson, R., Robinson, S., Schmid, E., Schmitz, C., Tabeau, A. & Willenbockel, D. (2014), 'Climate change effects on agriculture: Economic responses to biophysical shocks', *Proceedings of the National Academy of Sciences* **111**(9), 3274--3279.

O'Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., Mathur, R. & van Vuuren, D. (2014), 'A new scenario framework for climate change research: the concept of shared socioeconomic pathways', *Climatic Change* **122**(3), 387-400.

Pastor, A. V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P. & Ludwig, F. (2019), 'The global nexus of food-trade-water sustaining environmental flows by 2050', *Nature Sustainability*.

Rao, N. D., Sauer, P., Gidden, M. & Riahi, K. (2018), 'Income inequality projections for the Shared Socioeconomic Pathways (SSPs)', *Futures*.

Rojas-Downing, M. M., Nejadhashemi, A. P., Harrigan, T. & Woznicki, S. A. (2017), 'Climate change and livestock: Impacts, adaptation, and mitigation', *Climate Risk Management* **16**, 145--163.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H. & Jones, J. W. (2014), 'Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison', *Proceedings of the National Academy of Sciences* **111**(9), 3268-3273.

Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., Asseng, S., Basso, B., Ewert, F., Wallach, D., Baigorria, G. & Winter, J. M. (2013), 'The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies', *Agricultural and Forest Meteorology* **170**(0), 166-182.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colyn-Gonzбlez, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L. & Kabat, P. (2013), 'Multimodel assessment of water scarcity under climate change', *Proceedings of the National Academy of Sciences* **111**(9), 3245--3250.

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H. C. J., Gollin, D., Rayner, M., Ballon, P. & Scarborough, P. (2016), 'Global and regional health effects of future food production under climate change: a modelling study', *The Lancet* **387**(10031), 1937 - 1946.

Trnka, M., Feng, S., Semenov, M. A., Olesen, J. E., Kersebaum, K. C., Rötter, R. P., Semerádová, D., Klem, K., Huang, W., Ruiz-Ramos, M., Hlavinka, P., Meitner, J., Balek, J., Havlík, P. & Büntgen, U. (2019), 'Mitigation efforts will not fully alleviate the increase in water scarcity occurrence probability in wheat-producing areas', *Science Advances* **5**(9), eaau2406.

Valin, H., Sands, R. D., van der Mensbrugghe, D., Nelson, G. C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T., Havlík, P., Heyhoe, E., Kyle, P., Manson-D'Croz, D., Paltsev, S., Rolinski, S., Tabeau, A., van Meijl, H., von Lampe, M. & Willenbockel, D. (2014), 'The Future of Food Demand: Understanding Differences in Global Economic Models', *Agricultural Economics* **45**(1), 51-67.

Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. & Rose, S. K. (2011), 'The representative concentration pathways: an overview', *Climatic Change* **109**, 5-31.

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D’Croz, D., Müller, C., Popp, A., Robertson, R., Robinson, S., van Meijl, H. & Willenbockel, D. (2015), 'Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios', *Environmental Research Letters* **10**(8), 085010.