Chapter 16
A New Modelling Approach to Adaptation-Mitigation in the Land System

Juliette Maire, Peter Alexander, Peter Anthoni, Chris Huntingford, Thomas A. M. Pugh, Sam Rabin, Mark Rounsevell, and Almut Arneth

Abstract Climate change, growing populations and economic shocks are adding pressure on the global agricultural system's ability to feed the world. In addition to curbing the emissions from fossil fuel use, land-based actions are seen as essential in the effort to mitigate climate change, but these tend to reduce areas available for food production, thereby further increasing this pressure. The actors of the food system have the capacity to respond and adapt to changes in climate, and thereby reduce the negative consequences, while potentially creating additional challenges, including further greenhouse gas emissions. The food system actors may respond autonomously based on economic drivers and other factors to adapt to climate change, whereas policy measures are usually needed for mitigation actions to be implemented. Much research and policy focus has been given to land-based climate change mitigation, but far less emphasis has to date been given to the understanding of adaptation, or the interaction between adaptation and mitigation in the land use and food system. Here, we present an approach to better understand and plan these interactions through modelling. Climate change adaptation and mitigation strategies and the impacts on

J. Maire · P. Alexander (✉) · M. Rounsevell
School of Geosciences, University of Edinburgh, Edinburgh, UK
e-mail: peter.alexander@ed.ac.uk

P. Alexander
Global Academy of Agriculture and Food Security, The Royal (Dick) School of Veterinary Studies, University of Edinburgh, Edinburgh, UK

P. Anthoni · S. Rabin · M. Rounsevell · A. Arneth (✉)
Institute of Meteorology and Climate Research/Atmospheric Environmental Research, Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany
e-mail: almut.arneth@kit.edu

C. Huntingford
UK Centre for Ecology and Hydrology, Wallingford, United Kingdom

T. A. M. Pugh
Birmingham Institute of Forest Research, University of Birmingham, Birmingham, UK

School of Geography, Earth and Environmental Sciences, University of Birmingham, Birmingham, UK

Climate Adaptation Modelling, Springer Climate,
https://doi.org/10.1007/978-3-030-86211-4_16

the global food system and socio-economic development can be simulated over long-term predictions, thanks to the new combination of multiple models into the Land System Modular Model (LandSyMM). LandSyMM takes into account the impacts in changes in climate (i.e. temperature, precipitation, atmospheric greenhouse gas concentrations) and land management on crop yields with its implications for land allocation, food security and trade. This new coupled model integrates, over fine spatial scale, the interactions between commodities consumption, land use management, vegetation and climate into a worldwide dynamic economic system. This study offers an outline description of the LandSyMM as well as the perspectives of uses for climate adaptation assessment.

Keywords Land-use change · Dynamic global vegetation model · Climate change · Food system

Introduction

Food production systems are interlinked with the efforts to tackle climate change impacts. Currently, the food production system accounts for about one-third of the global greenhouse gas emissions, and 50% of the global habitable land (ice- and desert-free) is used for agriculture (IPCC 2019). Land use and land-use change are associated with a quarter of global greenhouse gas emissions from mainly tropical deforestation, methane emissions from livestock and rice cultivation, nitrous oxide emission from fertilized soils and manure management (IPCC 2019). Therefore, land use changes are contributing greatly to climate change as 11% of anthropogenic carbon dioxide (CO_2) emissions are associated with land use change (Friedlingstein et al. 2019), but also they play a key role in adaptation to the impact of climate change on agriculture (Alexander et al. 2018; Agnolucci et al. 2020).

Adaptation to climate change intends to moderate potential damages from climate change along with benefitting from opportunities associated with climate change impacts. The global land use and food system has the capacity to respond and adapt to changes to the climate, and thereby reduce some of the negative consequences of these changes, while potentially creating additional challenges. Adaptive mechanisms are both direct, i.e. as a response to climatic conditions in that location, and indirect, e.g. in response to market movements or policy decision themselves created by environmental changes, including those that may be occurring in other locations. Examples of food production adaptations to climate change include altering agricultural practices, such as choice of crop types or intensity of management, or shifting cultivated areas within and between countries. The wider food system also has capacity to adapt, e.g. through shifts in patterns of consumption. Shifts in consumer perception and preferences (e.g. the rise in vegetarianism and veganism), as well as changes mediated by market prices are both likely to be important for these demand-driven adaptations. And these adaptations may have climate-change mitigation co-benefits through reducing greenhouse gas emissions from land use, as well as reducing fresh-water over-use, water and air pollution, protecting wildlife, restoring lands back to forests or grassland (Rabin et al. 2020).

Modelling approaches are essential to help stakeholders to develop policies toward long-term actions for better food production systems, which are more resilient to climate change impacts and at the same time, contribute to halting climate change. While some of these adaptations may be actively steered by policy, actors throughout the food system will also adjust based on economic and other factors. Part of this autonomous adaptation includes land managers and farmers making decisions that can negatively interact with policymakers' agendas; e.g. intensifying production on existing agricultural land. Land-use modelling offers a unique chance to simulate the impacts of the adoption of land-based climate change mitigation measures, the role of the different actors along the food systems, the effect of the continuing globalization of trade in food products and increasing demand for agricultural goods (Humpenöder et al. 2015). However, currently available land use based models do not focus on adaptation responses to climate change in land use, but more on a top-down mitigation policies neglecting the implementation of the small-scale actors adaptation decisions (Alexander et al. 2018; Robinson et al. 2018). Here, we describe a coupled model system, the Land System Modular Model (LandSyMM) which aims to support future climate research by assessing the interplay between natural system dynamics and socio-economic processes related to supply and demand. The multiple scales represented allow interactions of bottom-up adaptation dynamics and top-down mitigation policies to be represented and explored (Müller et al. 2020).

Modelling Adaptation in the Land Use and Food System

Existing Approaches and Research Gaps

A range of models have attempted to understand how future agricultural and land use systems will affect and be affected by climate changes. These models have highlighted key societal drivers and were applied to a wide range of scenarios (e.g. greenhouse gas emissions and radiative forcing, socio-economic pathways). However, due to computational restrictions, most of the existing models typically use a very low spatial resolution (Robinson et al. 2014). The downside of such an approach is that it cannot well account for physical limitations of productivity and does not relate to location-specific yield response to agricultural changes in inputs (Alexander et al. 2018). Moreover, current model applications tend to focus on the climate change mitigation potential of land use rather than placing adaptation at their core. Adaptation requires information at much finer spatial resolution than can be typically provided in integrated assessment models (IAMs). The resolution of the LandSyMM enables us to explore adaptation measures such as related to crop productivity variations from changes in management practices (e.g. fertilizer and irrigation rates), or management in forests.

LandSyMM Modelling Approach

LandSyMM couples a dynamic global vegetation model (LPJ-GUESS; Smith et al. 2014), a climate system emulator (IMOGEN; Huntingford et al. 2010) and a socio-economic land-use model (PLUMv2; Rounsevell et al. 2014; Engström et al. 2016; Alexander et al., 2018) (Fig. 16.1). LandSyMM is currently being run at 0.5° spatial resolution. The dynamic global vegetation model (DGVM) computes for example changes in crop yields at a given location, in response to climate change, irrigation and fertilizer application which can be adjusted flexibly as part of mitigation strategies. PLUM simulates demand and trade of commodities (e.g. cereals, oil crops, pulses, starchy roots, sugar, fruits and vegetables, wood, dairy and meat products from ruminant livestock and monogastric livestock) based on least-cost optimization principles by adjusting commodity prices instead of assuming market equilibrium, allowing short-term surplus and deficits. This includes also costs for irrigation, fertilizer use and management intensity (e.g. pesticide and machinery use). LPJ-GUESS water runoff outputs are used by PLUM to constrain irrigation use from water availability at the basin level, after adjusting for other uses and environmental limitations. Therefore, changes in water resources as well as plant requirement under future climates can drive adaptation responses in land management. PLUM captures the relationship

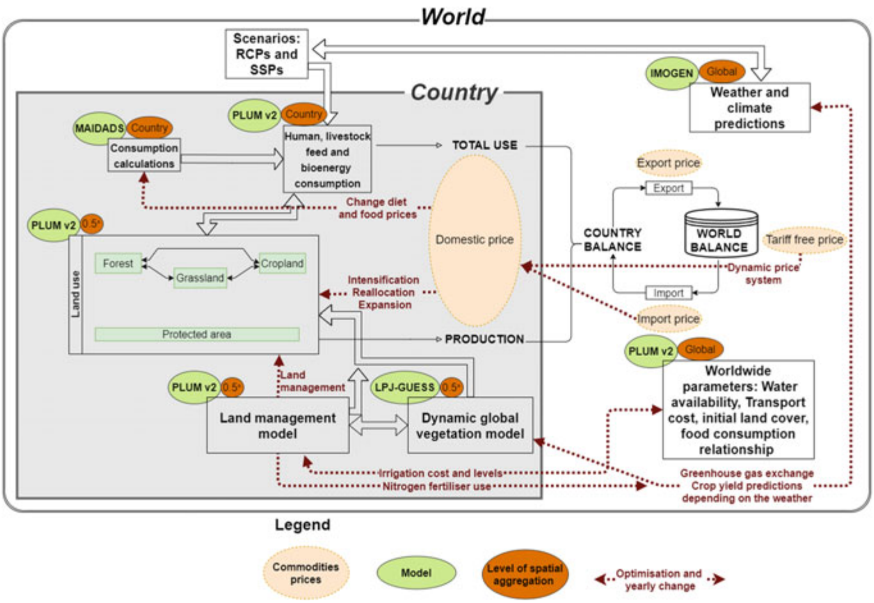

Fig. 16.1 LandSyMM structural overview. The focus of the schematic is on the cross-scale interactions between models (PLUMv2, LPJ-GUESS, IMOGEN, MAIDADS) and the embodied interactions between the country- and world-level calculations for each time step of the model. GDP: Gross Domestic Product; RCPs: representative concentration pathways; SSPs: shared socio-economic pathways

between food demand in each country and income and food prices using a Modified, Implicit, Directly Additive Demand System (MAIDADS) approach (Preckel et al. 2010; Gouel and Guimbard 2018). Prices are endogenous in PLUM and are adjusted through international commodity trade imbalances, while populations and country incomes are exogenously prescription often using SSPs scenarios (O'Neill et al. 2014). The LandSyMM approach offers the unique opportunity to represent trade-offs, responses and cross-scale and international interactions within a dynamic system (Rounsevell et al. 2014). Greenhouse gas emissions from land-use change and land management feedback to simulated climate. Currently in progress is a detailed representation of forestry.

Climate Change Adaptation Applications

From a consumption perspective, LandSyMM captures dietary requirements and preferences at the country level and how consumption changes in response to income levels as well as endogenous country level food commodity prices. In addition to the detailed representation of land management practices (e.g. technical efficiency, fertilizer use, transport, losses during transport, fertilizer cost) at a granular scale, we can assess the effects of autonomous decisions from the food system's actors and their interactions with mitigation policies. For instance, to study the interactions between a country who might have suffered from shocks (e.g. flood, drought, yield shocks, price shocks, pandemic and cyber-attacks) and the rest of the world under growing climate change pressure. The changing risk of some of these shocks, such as drought and flood risk, can be simulated by processes endogenous to LandSyMM (Fig. 16.2). In addition, it is possible to implement policy levers such as international trade tariff barriers and agricultural subsidies into the model to investigate their impacts on the food systems, dietary requirement, land use, climate but also their impacts on the potential benefices of certain climate adaptation measures. The increase in plant productivity under higher climate forcing intensity will change the production patterns at fine scale and creates new opportunities within the food system. The change in production may be related to the adoption of new crop types, the changes in management practices or the shift toward other cultivated areas (Alexander et al. 2018). In some cases, changing agricultural productivity could drive food substitutions in consumer choice leading to changes in a country's imports, exports and production without direct policy implications. Mitigation and adaptation to climate change do not always co-benefit. For instance, the widespread adoption of climate mitigation actions such as bioenergy and reforestation can impact the land and food systems, e.g. through the removal of existing agricultural land and increases in prices for agricultural commodities (Bahar et al. 2020).

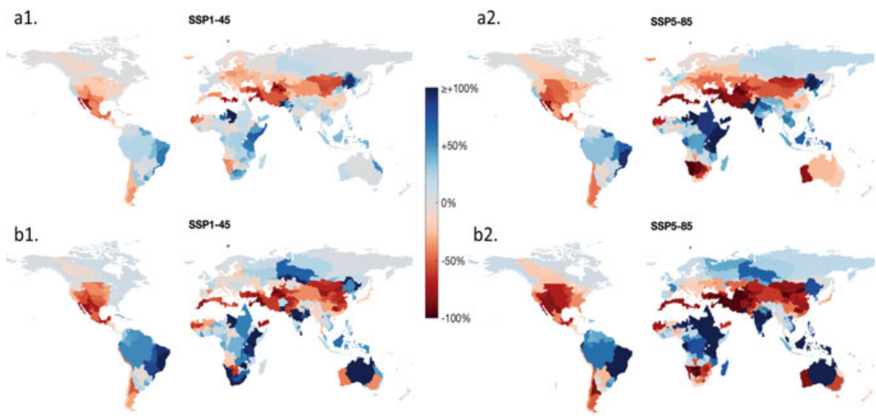

Fig. 16.2 LandSyMM output maps, aggregated to the basin scale, representing **a** the shift in the 5th percentile of annual surface runoff (drought risk), and **b** the shift in the 95th percentile of monthly surface runoff (flood risk) (**b**). The shift was calculated between the predicted values of 2071–2100 and 1971–2000 under (1) SSP 1 (a future in which challenges to both mitigation and adaptation are low) coupled with RCP 4.5 (climate given greenhouse gas emissions consistent with SSP1), and (2) under SSP 5 (a future in which challenges to mitigation are high and for adaptation are low) coupled with RCP 8.5 (climate given greenhouse gas emissions consistent with SSP5)

Conclusions and Recommendations

Agricultural adaptation measures are not necessarily positively synergistic with the environment. Autonomous adaptation in land manager choices is likely to be substantially driven by economic interests. As a result, land manager decisions are likely to minimize impact to market-based outputs, i.e. food and timber production. This means that the outcome for environmental externalities, including greenhouse gas emissions, fresh-water use and biodiversity loss may be detrimental (Fitton et al. 2019; Molotoks et al. 2020). Expansion of agriculture to new areas is expected to lead to carbon losses for soil and vegetation, while increases in food prices are likely to result in increased intensification of agricultural production, with negative environmental consequences. To date, there has been a lack of focus on the, potentially confounding, interactions between climate change mitigation and adaptation in the land system.

LandSyMM is an important new tool with the capacity to address this gap in understanding climate change adaptation-mitigation, and to inform policymakers on the trade-offs between different policy options as well as the impact on various aspects of the food system (e.g. production, international trade and diets). LandSyMM can be used to explore the potential of climate adaptation via the implementation of different scenarios that underpin climate change. These scenarios explore different futures such as different levels of economic growth, population demographics, international trade regimes and dietary preferences. The different scenarios enable the investigation of long-term impacts of policy measures on ecosystem services such as carbon storage, runoff, nitrogen losses, biogenic volatile organic compounds and biodiversity hotspots (Henry et al. 2019; Rabin et al. 2020). Despite the recent improvements, more research is needed to better reflect the reality of our complex world, e.g. integration of non-economic drivers for land manager decisions, and allowing bilateral trade to be represented. However, the current implementation of LandSyMM already provides a platform to better understand the interactions between land-based climate adaptation and mitigation that is currently lacking, and to identify suitable policies and actions.

Acknowledgements We acknowledge the support of the UK's Global Food Security Programme project Resilience of the UK food system to Global Shocks (RUGS, BB/N020707/1) and the Helmholtz Association.

References

Agnolucci P, Rapti C, Alexander P, Lipsis VD, Holland RA, Eigenbrod F, Ekins P (2020) Impacts of rising temperatures and farm management practices on global yields of 18 crops. Nat Food 1:562–571. https://doi.org/10.1038/s43016-020-00148-x

Alexander P, Rabin S, Anthoni P, Henry R, Pugh TAM, Rounsevell MDA, Arneth A (2018) Adaptation of global land use and management intensity to changes in climate and atmospheric carbon dioxide. Glob Chang Biol 24:2791–2809. https://doi.org/10.1111/gcb.14110

Bahar NHA, Lo M, Sanjaya M, Van VJ, Alexander P, Lckowitz A (2020) Meeting the food security challenge for nine billion people in 2050: What impact on forests? Glob Environ Chang 62. https://doi.org/10.1016/j.gloenvcha.2020.102056

Engström K, Olin S, Rounsevell MDAA, Brogaard S, van Vuuren DP, Alexander P, Murray-Rust D, Arneth A (2016) Assessing uncertainties in global cropland futures using a conditional probabilistic modelling framework. Earth Syst Dyn 7:893–915. https://doi.org/10.5194/esd-2016-7

Fitton N et al (2019) The vulnerabilities of agricultural land and food production to future water scarcity. Glob Environ Chang 58:101944. https://doi.org/10.1016/j.gloenvcha.2019.101944

Friedlingstein P et al (2019) Global carbon budget 2019. Earth Syst Sci Data 11:1783–1838. https://doi.org/10.5194/essd-11-1783-2019

Gouel C, Guimbard H (2018) Nutrition transition and the structure of global food demand. Am J Agric Econ 1–21. https://doi.org/10.1093/ajae/aay030

Henry RC, Alexander P, Rabin S, Anthoni P, Rounsevell MDA, Arneth A (2019) The role of global dietary transitions for safeguarding biodiversity. Glob Environ Chang 58:101956. https://doi.org/10.1016/j.gloenvcha.2019.101956

Humpenöder F, Popp A, Stevanovic M, Müller C, Bodirsky BL, Bonsch M, Dietrich JP, Lotze-Campen H, Weindl I, Biewald A, Rolinski S (2015) Land-use and carbon cycle responses to moderate climate change: Implications for land-based mitigation? Environ Sci Technol 49:6731–6739. https://doi.org/10.1021/es506201r

Huntingford C, Booth BBB, Sitch S, Gedney N, Lowe JA, Liddicoat SK, Mercado LM, Best MJ, Weedon GP, Fisher RA, Lomas MR, Good P, Zelazowski P, Everitt AC, Spessa AC, Jones CD (2010) IMOGEN: an intermediate complexity model to evaluate terrestrial impacts of a changing climate. Geosci Model Dev 3:679–687. https://doi.org/10.5194/gmd-3-679-2010

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 terestial ecosystems

Molotoks A, Henry R, Stehfest E, Doelman J, Havlik P, Krisztin T, Alexander P, Dawson TP, Smith P (2020) Comparing the impact of future cropland expansion on global biodiversity and carbon storage across models and scenarios. Philos Trans R Soc B https://doi.org/10.1098/rstb.2019.0189

Müller B et al. (2020) Modelling food security: bridging the gap between the micro and the macro scale. Glob Environ Chang 63

O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, Mathur R, van Vuuren DP (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Clim Change 122:387–400. https://doi.org/10.1007/s10584-013-0905-2

Preckel PV, Cranfield JAL, Hertel TW (2010) A modified, implicit, directly additive demand system. Appl Econ 42:143–155. https://doi.org/10.1080/00036840701591361

Rabin SS, Alexander P, Henry R, Anthoni P, Pugh TAM, Rounsevell M, Arneth A (2020) Impacts of future agricultural change on ecosystem service indicators. Earth Syst Dyn 11:357–376. https://doi.org/10.5194/esd-2019-44

Robinson DT, Di Vittorio A, Alexander P, Arneth A, Barton CM, Brown DG, Kettner A, Lemmen C, Neill BC, Janssen M, Pugh TAM, Rabin SS, Rounsevell M, Syvitski JP, Ullah I, Verburg PH (2018) Modelling feedbacks between human and natural processes in the land system. Earth Syst Dyn 9:895–914. https://doi.org/10.5194/esd-2017-68

Robinson S, van Meijl H, Willenbockel D, Valin H, Fujimori S, Masui T, Sands R, Wise M, Calvin K, Havlik P, Mason d'Croz D, Tabeau A, Kavallari A, Schmitz C, Dietrich JP, von Lampe M (2014) Comparing supply-side specifications in models of global agriculture and the food system. Agric Econ 45:21–35. https://doi.org/10.1111/agec.12087

Rounsevell MDA, Arneth A, Alexander P, Brown DG, de Noblet-Ducoudré N, Ellis E, Finnigan J, Galvin K, Grigg N, Harman I, Lennox J, Magliocca N, Parker D, O'Neill BC, Verburg PH, Young O (2014) Towards decision-based global land use models for improved understanding of the Earth system. Earth Syst. Dyn. 5:117–137. https://doi.org/10.5194/esd-5-117-2014

Smith B, Wärlind D, Arneth A, Hickler T, Leadley P, Siltberg J, Zaehle S (2014) Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. Biogeosciences 11:2027–2054. https://doi.org/10.5194/bg-11-2027-2014