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Modelling climate change impacts on agricultural systems

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Introduction

Climate change is a key threat to agriculture. Its increasing impact requires people working in the agricultural sector to come up with rapid solutions both to adapt to its effects whilst also reducing the sector's contribution to the greenhouse gas (GHG) emissions which cause climate change. Unfortunately, solutions to one problem may compromise solutions to another. Finding the optimum solution requires testing of many alternatives but current projections suggest time is running out to find the best way forward.

Modelling is fundamental to assessing the potential impacts of climate change in a quick and efficient way, at both the field level and on a global scale. Models are available for testing potential mitigation and adaptation measures in a range of scenarios, allowing the agricultural sector to work towards a system transformation that is more climate-adapted and sustainable. This collection summarises the current state of research on improving climate impact models and their use in assessing impacts on different aspects of the agricultural system, on different regions and on specific climate-related problems in agriculture that demand urgent solutions.

The chapters are split into three parts: Part 1 chapters focus on various advances in modelling, such as model integration, improving data flow and integration, the use of crop models to identify new phenotypes adapted to climate change, the development of more integrated approaches in models assessing the impact of climate change and accounting for uncertainties in modelling. Chapters in Part 2 examine modelling climate change impacts on particular aspects of agricultural systems, focusing specifically on crop growth and yield formation, livestock production, low-input smallholder farming systems and agro-ecosystem services. Chapters also discuss modelling climate change impacts on agricultural commodity markets and modelling transition of agricultural systems in response to climate change. Part 3 chapters provide specific examples of modelling climate change impacts on regional agricultural systems, drawing attention to Europe, the United States, Latin America, Australia and Oceania, South and East Asia, North Africa and Southwest Asia and finally, West Africa.

Part 1 Advances in modelling

The first chapter of the book reviews advances in integrating different models that assess the impact of climate change on agriculture. Chapter 1 begins by first reviewing the application of models to problems such as climate change. Based on an 'ideal' modelling archetype, the chapter then goes on to discuss

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different solutions such as a complete and balanced integration of models, coupling sub-models, integrating new knowledge and facilitating inter-operability, integrating behaviours and decision-making to adapt to climate change, incorporating inter- and intra-species diversity into models, from white to black box models and ensemble modelling. The chapter includes examples of all these solutions. The last section explains why these modelling solutions may be insufficient and discusses future trends in modelling.

The subject of Chapter 2 is improving data flow and integration in models assessing the impact of climate change on agriculture. It starts by first describing model-data integration, focusing on multi-criteria calibration of mechanistic agro-ecosystem models. The chapter moves on to review informing spatio-temporal simulations through methods such as remote sensing, proximal sensing and distributed data. A section on the assimilation of data in spatio-temporal simulations is also provided, followed by an analysis of workflows for massive parallel computing. The chapter reviews model-model integration as well as granularity and modular design for model improvement, reuse, exchange and interoperability. A section on the concepts for distributed modelling is also provided.

The next chapter focuses on incorporating genetics into crop models to identify new phenotypes adapted to climate change. Chapter 3 begins by providing an overview of systems analyses and models of crow growth, then goes on to review linking genetics and physiology for phenotypic prediction. The chapter also examines models that predict emergent phenotypes and how crop models can be used to integrate environmental and genomic predictions. A section on the impact of traits and their underpinning genetics on crop performance is also included, followed by an overview of managing genotype x environment interactions to optimise genetic gain in current and future climates. The chapter also discusses how predictive breeding enables iterative impact assessment and adaptation to climate change as well as how crop growth models can enable rethinking of breeding objectives to adapt to and combat climate change.

Chapter 4 draws attention to developing more integrated approaches in models assessing the impact of climate change on agriculture. The chapter identifies four key challenges in regional integrated modelling of agricultural systems: 1) better characterisation of model structural uncertainty and its propagation through the modelled system; 2) improved representation of the importance of non-climate drivers on both the supply and demand sides of agriculture; 3) enabling adaptive capacity to be modified by evolving future socio-economic conditions; and 4) incorporating objective targets or goals for adaptation. The chapter also discusses the IMPRESSIONS Integrated Assessment Platform (IAP) through the form of a case study and identifies four potential areas for future research in improving integrated modelling.

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The final chapter of Part 1 reviews accounting for uncertainties in modelling the impact of climate change on agriculture. Chapter 5 provides in-depth discussions on five different forms of uncertainties and how they can be managed, starting with greenhouse gas emission and climate change scenarios. This is then followed by an overview of uncertainties from crop model input data. The chapter also examines managing uncertainties from model structures, then finally discusses managing uncertainties from adaptations in agricultural practices. A section on reducing model uncertainties is also provided.

Part 2 Modelling climate change impacts on particular aspects of agricultural systems

Part 2 opens with a chapter that focuses on modelling climate change impacts on crop growth and yield formation. Chapter 6 begins by introducing the concept of modelling crop yield in agriculture. It then moves on to review crop modelling responses, focusing on structures of crop growth models, data and soil-crop-climate interactions. The chapter also examines assessing climate change impacts on yield with model ensembles, drawing specific attention to early model comparisons and Agricultural Model Intercomparison and Improvement Project (AgMIP) intercomparisons. The chapter includes examples of AgMIP studies such as wheat, maize, barley, rice, potato, soybean and other comparisons such as sugarcane, livestock and grassland as a more general discussion followed by a review of a pest and disease model.

The next chapter of Part 2 examines modelling climate change impacts on livestock production. Chapter 7 first outlines the crucial role of livestock production systems within global food security, economic growth, employment and society. The chapter then goes on to argue the need for rapid implementation of climate mitigations for livestock production systems, namely ruminant production systems. It also places focus on two of the most crucial mitigation measures available for livestock production systems, enteric methane mitigation (such as breeding and dietary interventions) and carbon sequestration and storage to deliver net zero livestock systems.

Chapter 8 draws attention to modelling climate change impact on low-input smallholder farming systems. The chapter presents the effect of climate change on the different components of the farming systems (crop, livestock, grassland and tree), in the context of low-input systems. After this account, the chapter argues the need for a more integrative approach to assess the effect of climate change on farming systems as a whole. The chapter exposes different approaches: coupling of models and the use of an optimisation model. The chapter also highlights the importance of involving farmers in the process of using models to co-design relevant adaptations to climate change in the context of low input systems.

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The subject of Chapter 9 is modelling climate change impact on agro-ecosystem services. The chapter reviews how multiple ecosystem services may be impacted by climate change and provides an example for modelling benefit-relevant metrics that can assess the potential impacts of future global change on human wellbeing. The chapter also reviews the state of the art of climate impacts on supporting services for agricultural production and co-benefits of agroecosystems, then moves on to emphasise the need for a systemic global approach for modelling food provision as an ecosystem service. The chapter also examines and integrating climate change and societal changes cohesively, with a focus on one approach to modelling nutrition under cohesive climate and societal changes getting to benefit-relevant indicators. The chapter also goes on to discuss benefit-relevant indicators, putting nutrition further in its context by integrating projections of demand.

Chapter 10 focuses on modelling climate change impacts on agricultural commodity markets. The chapter provides some insights on how climate change can affect agricultural commodity markets in the medium to long term. It includes some methodological aspects on how different quantitative tools, ranging from earth system models to farm-level production decisions, can be combined in the analysis of climate change impacts on agricultural markets. The analysis presented in the chapter is supported by several agro-economic studies carried out by the Joint Research Centre of the European Commission.

The final chapter of Part 2 discusses modelling the transition of agricultural systems in response to climate change. Chapter 11 first examines natural responses, then moves on to highlight two forms of man-made responses: incremental short-term and transformative long-term. The chapter also looks at the role of models in informing adaptation responses, followed by ways to capture the transition in modelling approaches and climate change impact studies, such as empirical crop models and mechanistic models. It highlights models of elements of the agricultural system, specifically drawing attention to crop rotation models, ruminant digestion, soil organic matter turnover and nitrate leaching. Sections on agro-economic models, integrated assessment models and suitability models are also provided, followed by an overview of modelling future pathways of agriculture. Overarching limitations of current modelling approaches are discussed, such as uncertainty and uncertainty propagation, interactions and feedbacks and data limitations.

Part 3 Modelling climate change impacts on regional agricultural systems

The first chapter of Part 3 reviews modelling the impact of climate change on agriculture in Europe. Chapter 12 starts by discussing past climate and future projects for Europe, then goes on to highlight agricultural systems currently

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in use across the region. A section on agricultural system modelling is also provided, focusing specifically on models and platforms, which is followed by an overview of modelling and experimental work on impacts of climate change through various case studies. These case studies draw attention to crop yields, changes in soil organic carbon, greenhouse gas emissions, farm economics, animal production systems, grapevine and olives and vegetables. The chapter also emphasises how the development of European agroecosystem models should be seen as being one of the research priorities within the region's agricultural research agenda.

Chapter 13 focuses on modelling the impact of climate change on agriculture in the United States. The chapter begins by providing an overview of the recent past and predicted near future changes in climate at the national and regional scale in the US, then moves on to examine the impacts of this on crop-based agriculture, in particular the direct effect on soil, water and major cash crops. The chapter also provides a case study that uses a crop and soil biogeochemical process-based model to investigate potential responses of corn yield to continued trends in temperature and precipitation for the near future using adapted cultivar. A summary of some of the incentives and payment mechanisms related to carbon markets, especially those that focus on agricultural product supply chains, is also provided.

The subject of Chapter 14 is modelling the impact of climate change on agriculture in Latin America. It focuses first on developments in crop modelling and climate change in Chile and Colombia, assessing model characteristics, strengths and weaknesses and areas for future development. The chapter then includes developments in modelling the impact of climate change on key crops in Brazil: upland and irrigated rice, common beans, soybeans, sugarcane and grass forage production for livestock.

Chapter 15 looks at modelling the impact of climate change on agriculture in Australia and Oceania. The chapter summarises climate change in the recent past and future projections for the Oceanian region. It also reviews how agriculture has responded to past climate changes and how systems modelling has helped to quantify the impact of future climate change, evaluate adaptation strategies and influence policy. Case studies in Australia, New Zealand and Papua New Guinea are presented and future research needs for modelling are discussed.

The next chapter reviews the vulnerability to climate change of the key agricultural sector in South Asian countries. After looking at India as an example of how to assess the specific impact of climate change on agriculture, Chapter 16 summarises the ways climate change affects basic plant processes. It then looks at the range of methods used to analyse climate change impacts and their relative strengths and weaknesses, including mechanistic models derived from historic data, the use of field trials, the role of remote sensing

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data and controlled environment experiments. The chapter also reviews the combined use of different models (e.g. crop, pest, soil and hydrological models) in impact assessments. It reviews the range of current projections for climate change impacts for a wide range of crops across a number of South Asian countries.

Chapter 17 examines modelling the impact of climate change on Agriculture in East Asia. The chapter describes recent research involving climate change impact assessments for the production of primary food crops in the region, focusing specifically on rice, wheat and maize. An overview of the historical impact of climate change on each crop is included, as well as a review of the projected impact of future climate change. The chapter also highlights how modelling extreme climate impact on crop production is becoming more crucial to ensure regional and global food security, as well as how modelling climate change impact on crop disease, weeds and pests should also be developed in order to allow crops to adapt. Sections on modelling climate change impact on crop quality and for diverse and intensified cropping systems are also provided.

The next chapter focuses on modelling the impact of climate change on agriculture in North Africa and Southwest Asia. Chapter 18 begins by examining the geography, economy, climate and agriculture of both regions. It then goes on to describe future climate projections and their effects on regional crop production, followed by an overview of current modelling tools to quantity crop responses to climate change. A section on current climate change impact assessments in North Africa and Southwest Asia is provided. The chapter also examines accounting for the potential of adaptation strategies as well as the limitations of climate change impact assessments.

The final chapter of the book focuses on modelling the impact of climate change on agriculture in West Africa. Chapter 21 begins with an overview of West Africa as a region, followed by an overview of West African climatic conditions. The chapter then provides a meta-analysis of studies investigating the effects of climate change on West Africa. It also highlights challenges in modeling the varied and distinctive characteristics of West African farming systems as well as potential adaptation options. The next section reviews the impact of climate change on livestock production followed by a brief section on integrated climate change impact assessment. The chapter ends with future developments and links to further reading.

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Chapter 1

Advances in integrating different models assessing the impact of climate change on agriculture

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1 Introduction

Climate change has become a major concern, especially for agriculture (Wiebe et al., 2019). The IPCC Sixth Assessment Report (AR6) projects that global surface temperature will continue to increase until 2100 by +1.0°C to +1.8°C under the very low greenhouse gases (GHG) emissions scenario (SSP1-1.9) and up to +3.3°C to +5.7°C under the very high GHG emissions scenario (SSP5-8.5), compared with 1850–1900 (Porter et al., 2014; IPCC, 2021). As global

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temperature rises, the rainfall regime will be significantly altered. Precipitation is likely to become more variable across regions, with an increase in high latitudes and a decrease in parts of the subtropics. Changes in atmospheric circulation and wind speed are also expected (Zeng et al., 2019; Abell et al., 2021). Beyond the changes in mean variables, the intensity, frequency and severity of extreme weather events such as heavy precipitation, flooding, drought and heatwaves are likely to become amplified (IPCC, 2021), but these events are generally difficult to predict (Sillmann et al., 2017).

Although there is uncertainty with regard to the nature, timing and extent of climate change impact, there is a general consensus that the combined effects of increasing temperatures, changing precipitation patterns and elevated carbon dioxide (CO_2) concentrations will affect agricultural and livestock production (Escarcha et al., 2018; Makowski et al., 2020), and that the effects of extreme climate events are likely to exceed those estimated from changes in mean variables (Tubiello et al., 2007). On a biophysical level, increased temperatures accelerate plant growth and development, leading to shifts in plant phenology and growing periods (Gong et al., 2021). Rising temperatures also increase soil evaporation (Abtew and Melesse, 2013), diminish soil moisture (Grillakis, 2019) and increase the water requirement of plants. Changing climatic conditions may also affect the geographical distribution of crops and crop pests (i.e. insects, pathogens and weeds) and outbreak severity (Lamichhane et al., 2015), and facilitate the spread of animal diseases and pests from low to mid-latitudes (Tubiello et al., 2007). The occurrence of climate shocks, such as heat or water stress during critical stages of plant development, could have deleterious effects on yields (Zampieri et al., 2020). A meta-analysis estimated that without implementing adaptation measures, future climate trends and variability are likely to result in higher crop yield variability and aggregated yield losses for the most commonly grown cereals (rice, wheat and maize) (Challinor et al., 2009). It may also impair crop quality, e.g. reduced grain protein and mineral nutrient concentrations and altered lipid composition (DaMatta et al., 2010). Climate change may also be a threat for livestock production because of its impacts on feed crop and forage quantity and quality, animal growth and milk production, animal reproduction, health and mortality (Thornton et al., 2009; Nardone et al., 2010; Rojas-Downing et al., 2017a). Beyond the impact on plant and animal physiology and food quality, climate change may also alter land suitability for crop production (Ramirez-Cabral et al., 2017; Paola, 2018) and changes in hydrological cycles may drive an increased risk of soil erosion (Borrelli et al., 2020).

Climate change is also likely to have socio-economic impacts at farm, local and global levels. Changes in crop productivity could affect farmers' income and threaten food security (Schmidhuber and Tubiello, 2007). In addition, adverse weather shocks can result in an increase in food prices and price volatility (Hertel, 2010; Nelson et al., 2014), which could affect farmers' income and their cropping decisions, and disrupt food supply and the global agricultural market (Porfirio et al., 2018). Studies have also shown that extreme climate events such as drought can alter farmers' risk preferences regarding climate change (Bozzola and Finger, 2021), which may lead to investments in low-risk, low-return activities (Dercon and Christiaensen, 2011).

Climate-smart agriculture (CSA) is promoted as an approach to transform and reorient agricultural development to address the impacts of climate change (Lipper et al., 2014). CSA is defined by the FAO as a set of actions that (FAO, 2010):

1 sustainably increases agricultural productivity;
2 builds resilience to climate change from the farm to national levels (adaptation); and
3 reduces or removes GHG emissions (mitigation) while enhancing the achievement of national food security and development goals.

Mitigation encompasses crop and livestock management strategies, increases soil and biomass carbon storage (e.g. by introducing cover crops and developing pasture-based systems) and reduces energy and fertiliser nitrogen (N) use (e.g. reduced tillage or using legumes; better housing and manure management in livestock systems). Adaptation strategies range from small adjustments to the redesign of entire systems (Willaume et al., 2014) that aim to reduce the vulnerability of agricultural systems to climate change, i.e. 'the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change', which is a function of exposure, sensitivity and adaptive capacity (IPCC, 2022).

For livestock systems, adaptation measures include modifying periods and frequencies of grazing, stocking rates, timing of reproduction, using more heat-tolerant livestock breeds (Rojas-Downing et al., 2017b) and increasing animal and grassland diversity (Martin and Magne, 2015). Adaptation strategies in cropping systems encompass the selection of species and varieties that are better adapted to extreme climate events and resistant to pests and diseases, the use of climate forecasting, adjustment of fertiliser rates, amount and timing of irrigation, the location and timing of cropping activities, diversification of cropping systems (e.g. more diverse rotations) and the use of new technologies and practices that improve water use efficiency, maintain soil moisture and prevent water erosion (e.g. through Conservation Agriculture) (Tubiello et al., 2007; Debaeke et al., 2017).

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