BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Climate change and agriculture

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Introduction

It has been suggested that agriculture may account for up to 24% of the greenhouse gas emissions (GHGs) contributing to climate change. Agricultural production accounts for over 80% of food system emissions, and nearly 60% of global non-CO_2 GHGs. At the same time climate change is threatening to disrupt agricultural production. This collection reviews key research addressing this challenge. Part 1 of the book reviews current research on the impacts of climate change on agriculture, such as the effects of increased temperatures, as well as the ways these impacts can be modelled. Part 2 assesses what we know about the contribution of agriculture to climate change, including the impacts of both crop and livestock production as well as land use. Part 3 surveys mitigation strategies to achieve a more 'climate-smart' agriculture such as the role of integrated crop-livestock and agroforestry systems.

Part 1 Impacts of climate change on agriculture

Atmospheric changes, including high carbon dioxide (CO_2) concentrations, air temperature and tropospheric ozone concentrations , are challenging our crop cultivation systems, with potential negative implications for global food production. Chapter 1 investigates how these atmospheric changes directly affect different physiological processes, and further modify agro-ecosystem functioning through complex interactions with other environmental factors, including nutrient or water availability. The chapter reviews current research on the impact of elevated CO_2 concentrations, higher temperatures and high ozone concentrations on crop growth and yields. This research shows, for example, that elevated CO_2 levels may have a fertilizing and positive impact on crop yield and water use in some cases, whereas heat stress and increased ozone concentrations may reduce crop yields.

As Chapter 2 indicates, the high atmospheric concentrations of GHGs such as CO_2, nitrous oxide (N_2O) and methane (CH_4) have had significant negative impacts on soil processes. The impacts range from a decline in carbon sequestration and soil health to increased soil temperatures, decomposition of soil organic matter, release and leaching of nutrients, increased microbial activity, salinization, alkalization and moisture stress. The chapter highlights current knowledge on the effects of climate change on soil properties and processes, and a set of climate-smart technologies for climate change mitigation. Climate-smart technologies include conservation agriculture, precision agriculture, integrated nutrient management, residue retention, soil and water conservation, agroforestry, controlled grazing and stocking rates, crop rotations, cover crops, biochar and improved plant varieties.

Crop models are powerful tools to explore climate change impacts on crop productivity and the effect of different agricultural management practices. Chapter 3 reviews how crop models take into consideration the effects of biotic factors such as climate variables, soils and crop genetics, and how they are used in climate change impact assessments. The chapter emphasizes how the wide use of crop models raises challenges that need to be addressed in future research, highlighting the need for model improvements to consider extreme weather events and stresses related to low input agricultural systems.

Part 2 The contribution of agriculture to climate change

Despite gains in productivity often accompanied by reduced emissions, the livestock sector remains the largest anthropogenic emitter of CH_4 and has significantly reduced global carbon storage and photosynthetic capacities as well as releasing nitrogen and phosphorus to air, water and/or soil. Chapter 4 explores some of the many facets of livestock's contributions to climate change and the difficulties involved in quantifying them. It provides a closer look into the contribution of livestock CH_4 emissions to changing atmospheric CH_4 concentrations over the last few decades. The chapter discusses the production of livestock CH_4, global atmospheric concentrations and the global CH_4 cycle, ways of quantifying enteric fermentation and emissions from manure. It includes a case study to show measurement issues in practice.

While gains in agricultural productivity have enabled rising levels of food security, they have also made the food system a major contributor to global climate change. Chapter 5 reviews the contribution to climate change of various GHGs from global crop cultivation. Topics include fertilizer management, the effect of land use changes on peatlands, crop residue management, cropland soil organic matter changes and bioenergy production. In each case the chapter reviews the current state of knowledge and data availability as well as the outstanding uncertainties in current estimates. The chapter also considers cropland GHG emissions in the context of food security and other sustainable development goals. Finally, the chapter provides an overview of how future scenarios of agricultural development can be used to project local and regional GHG emissions within integrated assessment frameworks.

Building on the previous chapter, Chapter 6 discusses the role of agricultural expansion and the effects of land cover and land-use change in contributing to climate change. It begins by reviewing the impacts of land-use change on climate, specifically focusing on carbon emission, surface energy fluxes – such as reflection of solar radiation and evapotranspiration and hydrological impacts – and the emission of reactive gases from vegetation. It assesses current techniques to estimate the impacts of land-use change on climate. It also reviews the role of the land sector in climate change mitigation, highlighting how the reduction of deforestation, the increase of reforestation, restoration and afforestation programmes and the growth of bioenergy crops have the potential help to mitigate and adapt to climate change. Finally, the chapter reviews future land-use trajectories and their use in assessing future potential climate change as a result of different levels of GHGs emissions. It concludes by providing future research trends and resources for further information.

Chapter 7 explores how the accurate assessment of agricultural GHGs emissions for accounting and mitigation options is still a key concern. While an extensive body of data is available, limitations of the different measuring approaches have often been ignored. Despite some constraints, chamber-based approaches have dominated annual assessments of GHGs to provide information on spatial and temporal variations. The Eddy Covariance (EC) technique has become the approach of choice and the basis of international monitoring networks. However, as the chapter points, the method has limitations such as footprint constraints, poor replicability, complexity and high cost. In the case of measuring enteric CH_4 emissions from livestock systems, respiratory chamber, tracer or GreenfeedTM techniques also have limitations for confined animals and requiring significant technical expertise can be used. An overview of other livestock-associated approaches is given in this chapter, arguing for further investment in alternative methods for routine on-farm measurements and the identification of mitigation options.

Part 3 Adaptation and mitigation strategies

Climate-smart cropping options aim to simultaneously improve crop productivity, adapt to climate change and reduce GHGs emissions. Echoing themes in Chapter 2, Chapter 8 provides a concise overview of a wide range of climate-smart cropping options and investigates in detail the potential of conservation agriculture and soil fertility management practices to contribute to the three pillars of climate-smart agriculture (CSA), taking in the issues of possible trade-offs and constraints to adoption. The chapter shows that gaps in understanding and assessing impacts may lead to an overestimation of the potential of CSA. Two contrasting case studies from intensive and low-input agriculture illustrate that reliable contextualized and quantitative information can be obtained with participatory, integrated and cross-scale assessments. Such information is key to support decision and policy making towards holistic solutions that can enable a successful transformation to CSA.

Chapter 9 illustrates through a contrasting set of examples how current crop–livestock systems contribute to the food and nutrition security of smallholder livelihoods. It highlights how farmers use these systems to cope with a variable climate. The chapter provides an overview of recent research on climate change and mixed crop–livestock systems. It also assesses ways of quantifying how crop–livestock systems contribute to food supply, dietary diversity and income of smallholder farmers. The chapter then reviews analyses of short-term climate variability coping strategies that farmers currently apply in mixed crop–livestock systems, highlighting most effective adaptation options to climate change in mixed farming systems. It concludes by consolidating these findings to provide a review of the resilience of mixed crop–livestock systems in the face of existing and future climate variability.

With appropriate management, agroforestry contributes to the provision of food, fiber and wood products and helps maintain ecosystem services such as nutrient cycling and biodiversity. Chapter 10 reviews recent research on the role of trees in integrating climate mitigation and adaptation goals, including the development of novel bioenergy solutions based on intercropping trees and shrubs in croplands. Many perennial staple crops are native to the African continent, and expanded production of these species could make a notable contribution to supply the future food and nutrition needs of vulnerable communities. The chapter discusses how agroforestry can be seen as an effective ecosystem-based adaptation strategy and an efficient carbon sink. The chapter discusses examples such as the semi-arid Sahel region in Africa, where community-driven tree regeneration has helped increase carbon sequestration in agricultural lands.

Chapter 1

The effects on crop cultivation of increased CO_2, temperature and ozone levels due to climate change

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1 Introduction

Making our world food secure is a challenge today but nothing less in the future. A 60–100% increase in food supply is required towards 2050 to accommodate nutritional needs of the expected 9 billion people and their changing consumption pattern (Alexandratos and Bruinsma, 2012; FAO et al., 2018; Godfray et al., 2010; Ingram and Porter, 2015). Moreover, agricultural productivity has to increase sustainably, knowing its resources like water, land and fertilizers are scarce and are increasingly to be shared with other sectors (i.e. industry and households) (Keating et al., 2014). The challenge is intensified by atmospheric changes and air pollution, which are already present today and will further affect crop yield in the future (Bindi et al., 2015; Elbehri, 2015; Gornall et al., 2010; Ingram and Porter, 2015; Field et al., 2014; Tai et al., 2014; Wheeler and Braun, 2013). Weather variability is responsible for over 30–50% of yield variability of major crops (Frieler et al., 2017; Ray et al., 2015; Zampieri et al., 2017) and further atmospheric changes can have a large impact.

In this chapter, I present observed and projected future effects on crop cultivation for food production caused by three evident changes of the

http://dx.doi.org/10.19103/AS.2020.0064.01

atmosphere, that is atmospheric CO_2 concentration ([CO_2]), air temperature and tropospheric ozone concentration ([O_3]). They went through a notable development since the Industrial Revolution, and all three are projected to further increase. Each atmospheric phenomenon is here covered by:

1 a presentation of the current status and future projections of its physical conditions,
2 a concise description of observed physiological and agronomic consequences in experiments, and
3 an impact assessment at the global scale.

Thereafter, interactive effects of several (atmospheric) changes are discussed and one local-scale case study is presented. The chapter finishes with an outlook on potential future contributions of research to sustainable crop production under altered atmospheric conditions. Ultimately, recommended reading is presented for those who are hungry for more information.

2 The effects of elevated CO_2 concentration on crop cultivation

2.1 The physical phenomenon

Atmospheric [CO_2] has steadily increased since the Industrial Revolution from 280 ppm to above 400 ppm today, and is expected to continue to rise for decades by approximately 2 ppm per year, even with stringent emission reductions (Stocker et al., 2013). Projected end-of-the-century [CO_2] depends on the assumed representative concentration pathway (RCP) that denotes the approximate radiative forcing (W/m^2) in 2100 relative to 1750 (van Vuuren et al., 2011). By the year 2100, [CO_2] is projected to reach 421 ppm after an earlier peak following the low RCP 2.6; a stable 538 to 670 ppm following the stabilization RCPs 4.5 and 6.0, respectively; or an intermediate 936 ppm following the high RCP 8.5 (Stocker et al., 2013). Since plants assimilate CO_2 to build biomass, these changes affect crop production.

2.2 Physiological and agronomic consequences

Major effects of elevated atmospheric [CO_2] ([CO_2]e) on plants include improved photosynthetic efficiency and reduced stomatal conductance (Ainsworth and Long, 2005; Drake et al., 1997), resulting in improved crop water productivity, that is the ratio of crop yield over evapotranspiration (Vanuytrecht et al., 2012). In C3 plants, [CO_2]e increases the carboxylation rate of photosynthesis and improves its efficiency by suppressing photorespiration (Ainsworth and Rogers, 2007). Within the C3 category, tubers and nitrogen-fixers respond more vigorously to CO_2 fertilization (e.g. McGrath and Lobell, 2013a; Vanuytrecht et al., 2012). C4 plants on the other hand are saturated at ambient [CO_2] and avoid photorespiration, hence little direct CO_2 stimulation is expected for those plants (Leakey, 2009). Even though Rubsico activity and content decrease at [CO_2]e (Ainsworth et al., 2002; Ainsworth and Rogers, 2007; Wang et al., 2013), improved photosynthesis translates generally in boosted biomass production of both vegetative and reproductive plant parts (Ainsworth, 2008; Ainsworth et al., 2002; Jablonski et al., 2002; Vanuytrecht et al., 2012; Wang et al., 2013). Leaf stomata respond to (inter-cellular) [CO_2]e by decreasing conductance (Ainsworth, 2008; Ainsworth and Rogers, 2007; Wang et al., 2013). Indirectly, this effect additionally benefits crop production, also for C4s, and more so in dry than in wet conditions (Bishop et al., 2014; van der Kooi et al., 2016).

Other effects include reduced overall plant water use (Kimball, 2016; Shimono et al., 2013; Vanuytrecht et al., 2012), increased leaf area but reduced specific leaf area hence thicker leaves (Ainsworth et al., 2002; Burkart et al., 2011; Kimball et al., 2002), changed carbon allocation (Vanuytrecht et al., 2012; Wang et al., 2014b) and altered elemental composition. Concentrations of nitrogen, proteins and nutrients decrease in general (Broberg et al., 2017; Dong et al., 2018; Myers et al., 2014; Taub et al., 2008; Walker et al., 2017; Wang et al., 2013; Zhu et al., 2018), while starch and sugar concentrations increase (Dong et al., 2018). Reduced nutrient concentrations result from an interplay of mechanisms (including dilution by additional carbon uptake, reduced stomata-mediated nutrient uptake and within-plant transport), which is yet to be fully understood (Broberg et al., 2017; McGrath and Lobell, 2013b; Taub and Wang, 2008). Notwithstanding the stimulatory effect of [CO_2]e on quantitative biomass and yield production, altered nutrient concentrations have a serious impact on food nutrition and security. The responses at individual plant level induce changes in plant communities and ecosystems (Ziska and Bunce, 2006).

Crop responses to [CO_2]e are being studied in fully controlled growth chambers (e.g. Leisner et al., 2018; Reddy and Zhao, 2005), as well as in the field in open-top chambers (OTC, e.g. Saha et al., 2015; Wang et al., 2018) or free air CO_2 enrichment (FACE) experiments (e.g. Bourgault et al., 2018; Gray et al., 2016; Manderscheid et al., 2018; Zhu et al., 2018). The latter mimic natural conditions more closely by ensuring free root grow, minimizing boundary effects and allowing to assess ecosystem effects (Hendrey et al., 1993). Meta-analyses summarizing the wealth of observational data contribute to our general understanding of crop responses to [CO_2]e. For a variety of (C3) crops, meta-analysis of FACE observations confirmed biomass and yield gains by +18–19% for a typical increase in [CO_2] to 550 ppm. Evapotranspiration decreased for both C3 and C4 by −5–10% on average, resulting from the reduction in stomatal conductance but increase in leaf area (Kimball, 2016; Vanuytrecht et al., 2012). Studies for soybean (Ainsworth et al., 2002), rice (Ainsworth, 2008) and wheat revealed +23–24% yield increase for an average increase in [CO_2] to 620–700 ppm. Associated increases in pod number but unaltered seed mass for soybean (Ainsworth et al., 2002) were reported, as well as increases in grain mass, grain and panicle/ear number for rice and wheat (Ainsworth, 2008; Wang et al., 2013). Interestingly, Ainsworth (2008) and Wang et al. (2013) found roughly half the CO_2 stimulation in free-air experiments compared to more enclosed (or pot-rooted) systems. Environmental conditions including drought and nitrogen limitation affected the response magnitude with magnified versus suppressed responses, respectively (Wang et al., 2013).

When focusing on plant nitrogen dynamics at [CO_2]e (~ 666 ppm), Lam et al. (2012) found increased nitrogen uptake (+17%), but reduced yield nitrogen concentration (−8 to 10%) except in legumes. An equivalent effect was found for protein concentration of barley, rice and wheat grains (−10 to 15%) and potato tubers (−14%), and a smaller but nevertheless significant effect for soybean (−1.4%) (Taub et al., 2008). Also the concentration of other essential nutrients tended to change with, for example, strong negative effects for important elements including Fe, S, Zn and Mg in wheat (Broberg et al., 2017). Table 1 summarizes general impacts of [CO_2]e on yield quantity, yield quality and water use. Note that responses depend on the magnitude of change in [CO_2] and on the interaction with other stresses determined by the environmental setting.

2.3 Global assessment of CO_2 induced impact

The global impact of [CO_2]e, and climatic changes in general, on crop cultivation has now been studied for over 20 years, by biophysical process-based crop or ecosystem models or by statistical relations. Those assessments can be made with an ensemble of impact models driven by future climate projections from multiple climate models (Challinor et al., 2013, 2014a, 2018; Rosenzweig et al., 2013; Wallach et al., 2018). An in-depth discussion of modelling methodologies for climate impact assessment on crop production can be found in Chapter 6 of this book. In this first chapter, I mainly present the large-scale projected impacts of the atmospheric changes by these studies.

Many global assessments evaluate the CO_2 effect in combination with associated climatic changes to present a realistic future scenario (e.g. Asseng et al., 2013; Challinor et al., 2014b; Rosenzweig et al., 2014). For research purposes, though, isolating the CO_2 effect in modelling exercises can nevertheless be informative. Global yield benefits of CO_2 (hence, when isolated from the integrated whole of climatic changes) were simulated for 2080 for maize (+13%), rice (+24%), wheat (+26%) and particularly soybean (+35%) under RCP 8.5 by a model ensemble of six global gridded crop models driven

Table 1 Summary of crop responses to atmospheric changes as observed in field-scale experiments (FACE, OTC and open air in general)

Atmospheric change	Impact level		Response (relative to ambient conditions)
Increased [CO_2]			
	Yield		
	quantity	▲▲	for C3 due to photosynthesis stimulus
		yet: △	for nitrogen deficient conditions
		△△△	for drought conditions
		▲	for C4 in drought conditions due to water savings
	quality	▼	in nitrogen, protein and nutrient concentration
	Water use	▼	in canopy-scale transpiration
		yet: ▷	for drought conditions
		▽▽▽	in stomatal conductance
Increased temperature (T)			
	Yield		
	quantity	▼▼	for T rise close to crop's optimal temperature range due to a distorted balance between photosynthesis and respiration
		yet: △	for moderate T increases in cooler climates
		△	for alternative cultivars with longer growing season
		△	for new crops in previously uncultivated regions
		▼▼▼	for extreme heat
	quality	▼	due to adverse effects on yield traits (e.g. milling quality or grain chalkiness) and due to visual damage (especially horticultural crops)
	Water use	▲	in evapotranspiration due to higher evaporative demand
		yet: ▽	in stomatal closure for drought conditions
Increased [O_3]			
	Yield		
	quantity	▼▼	due to molecular, biochemical and metabolic responses
	quality	▲	in nitrogen, protein and nutrient concentration
		▼	due to adverse effects on yield traits (e.g. starch concentration or grain chalkiness) and visual injury
	Water use	▼▼	in stomatal conductance as initial defence strategy
		yet: ▷ - △	due to subsequent lower stomatal sensitivity

▼ decrease; ▲ increase; ▶ status-quo.
number of ◀◀◀ indicates strength of the response: ◀ moderate; ◀◀ strong; ◀◀◀ very strong.
This table summarizes general responses. In reality, responses highly depend on the magnitude of change (in [CO_2], [O_3] or T) and on the interaction with other stresses determined by the environmental setting.

by data from five global climate models (GCMs) (Deryng et al., 2016). Note that these projected CO_2 fertilization effects could not counterbalance the negative impacts of associated climatic changes for maize and rice but contributed to a break-even for soybean and a slight improvement in wheat yield. CO_2-induced yield gains and associated reductions in crop evapotranspiration further

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