Crop and pasture response to climate change

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We review recent research of importance to understanding crop and pasture plant species response to climate change. Topics include plant response to elevated CO_2 concentration, interactions with climate change variables and air pollutants, impacts of increased climate variability and frequency of extreme events, the role of weeds and pests, disease and animal health, issues in biodiversity, and vulnerability of soil carbon pools. We critically analyze the links between fundamental knowledge at the plant and plot level and the additional socio-economic variables that determine actual production and trade of food at regional to global scales. We conclude by making recommendations for current and future research needs, with a focus on continued and improved integration of experimental and modeling efforts.

agriculture | impacts

Land management for food production is a fundamental human activity, supporting the livelihood of everyone on this planet. Of the ≈14 billion hectares of ice-free land on Earth, ≈10% are used for crop cultivation, while an additional 25% of land is used for pasture. Over 2 billion tons of grains are produced yearly for food and feed, providing roughly two-thirds of total direct and indirect protein intake; a mere 10% of this total, or 200 million tons, is traded internationally. Resource management is key to achieve current production levels; for instance, although irrigated land is only 17% of total arable land, irrigated crops supply a significant portion of total production (≈40% in the case of cereals) consuming >2,500 billion m^3 water, or 75% of the total fresh water resources consumed annually. Finally, agriculture is a significant contributor to land degradation and anthropogenic global greenhouse gas emissions, being responsible for 25% of carbon (largely from deforestation), 50% of methane, and >75% of N_2O emitted annually by human activities (1). Perhaps the most important challenge that agriculture will face in coming decades is represented by the need to feed increasing numbers of people while conserving soil and water resources (2). Existing projections indicate that future population and economic growth will require a doubling of current food production, including an increase from 2 billion to >4 billion tons of grains annually. Providing that current growth trends in crop yields continue into the future, increased supply may, in fact, be achieved without significantly increasing current arable land (3, 4). Specifically, in the course of this century slower population growth and increasing gross domestic product per capita is projected to lead to a decrease in the growth of global food demand, with continued shifts in global food consumption patterns from crop-based to livestock-based diets (5). This trend, in turn, may have consequences for land demand for cereal and pasture. Some land expansion will take place in developing countries, most of it in sub-Saharan Africa and Latin America (2, 4), while crop yields will continue to rise; for instance, cereal yields in developing countries are projected to increase from 2.7 tons/hectare today to 3.8 tons/hectare in 2050 (6). Importantly, without considering climate change, the number of undernourished people is expected to decline significantly toward the end of this century, although not fast enough to meet the millennium development goals (4), from >800 million at present to ≈100 million to 300 million people by 2080 (4, 6, 7). Notwithstanding these overall improvements, areas in sub-Saharan Africa, Asia, and Latin America with projected high population growth rates and high rates of natural resource degradation are likely to continue to have high rates of poverty and food insecurity (3, 8).

Any assessment of climate change impacts on agro-ecological conditions of agriculture must therefore be undertaken against the relevant background of changing socio-economic environment (7); in particular, it is this background that may critically determine how rural populations cope with, and respond to, climate impacts, including, in some instances, their ability to feed themselves. Yet there is significant uncertainty about the exact magnitude and in some cases even the direction of the associated impacts. Furthermore, important regional discrepancies between developed and developing countries may be exacerbated by climate change, because of combinations of different agro-climatic and socio-economic conditions (4, 9–11).

Another important consideration is that experimentally observed crop and pasture physiological responses to climate-change variables at plot and field levels are too simplified in current models. As a consequence, the potential for negative surprises is not fully explored, thus reducing the level of confidence in regional and global projections. Key interactions that are currently poorly described by crop and pasture models include: (*i*) nonlinearity and threshold effects in response to increases in the frequency of extreme events under climate change; (*ii*) modification of weed pest and disease incidence; (*iii*) field response of crops to elevated CO_2 concentration; and (*iv*) interactions of climate and management variables with elevated CO_2. It is thus imperative to continue to advance the fundamental knowledge of crop and pasture species responses to climate change, reduce uncertainties in impact projections, and assess future risks.

The recent Intergovernmental Panel on Climate Change report (12) provides a number of important conclusions to this end. At the plot level, and without considering changes in the frequency of extreme events, moderate warming (i.e., in the first half of this century) may benefit crop and pasture yields in temperate regions, while it would decrease yields in semiarid and tropical regions. Modeling studies indicate small beneficial effects on crop yields in temperate regions corresponding to local mean temperature increases of 1–3°C and associated CO_2 increase and rainfall changes. By contrast in tropical regions, models indicate negative yield impacts for the major cereals even with moderate temperature increases (1–2°C). Further warming

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Abbreviation: FACE, free-air carbon dioxide enrichment.

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projected for the end of the 21st century has increasingly negative impacts in all regions. At the same time, farm-level adaptation responses may be effective at low to medium temperature increases, allowing coping with up to 1–2°C local temperature increases, an effect that can be seen as "buying time" (13).

Increased frequency of heat stress, droughts, and floods negatively affect crop yields and livestock beyond the impacts of mean climate change, creating the possibility for surprises, with impacts that are larger, and occurring earlier, than predicted using changes in mean variables alone.

Climate Change Effects on Plant Growth and Yield

Plant development, growth, yield, and ultimately production of crop and pasture species will respond to increases in atmospheric CO_2 concentration, higher temperatures, altered precipitation and transpiration regimes, increased frequency of extreme temperature and precipitation events, and weed, pest and pathogen pressure (12, 14). Recent research has helped to better quantify the potential outcome of these key interactions.

Effects of Elevated CO_2. Hundreds of studies conducted over the last 30 years have confirmed that plant biomass and yield tend to increase significantly as CO_2 concentrations increase above current levels. Such results are found to be robust across a variety of experimental settings, such as controlled environment closed chambers, greenhouses, open and closed field top chambers, and free-air carbon dioxide enrichment (FACE) experiments. Elevated CO_2 concentrations stimulate photosynthesis, leading to increased plant productivity and modified water and nutrient cycles (e.g., refs. 15 and 16). Experiments under optimal conditions show that doubling the atmospheric CO_2 concentration increases leaf photosynthesis by 30%–50% in C_3 plant species and 10%–25% in C_4 species, despite some down-regulation of leaf photosynthesis by elevated atmospheric CO_2 concentrations (e.g., ref. 17).

Crop yield increase is lower than the photosynthetic response. On average across several species and under unstressed conditions, compared with current atmospheric CO_2 concentrations of $\approx$380 ppm, crop yields increase at 550 ppm CO_2 in the range of 10–20% for C_3 crops and 0–10% for C_4 crops (17–19). Increases in above-ground biomass at 550 ppm CO_2 for trees are in the range 0–30%, with the higher values observed in young trees and little to no response observed in the few experiments conducted to date in mature natural forests (16, 20, 21). Observed increases of above-ground production in C_3 pasture grasses and legumes are $\approx$+10 and +20%, respectively (16, 17).

Some authors have recently argued that crop response to elevated CO_2 may be lower than previously thought, with consequences for crop modeling and projections of food supply (22, 23). Results of these new analyses have, however, been disputed, showing in fact consistency between previous findings from a variety of experimental settings and new FACE results (7). In addition, simulations of unstressed plant growth and yield response to elevated CO_2 within the main crop simulation models have been shown to be in line with experimental data, e.g., projecting crop yield increases of $\approx$5–20% at 550 ppm CO_2 (7, 24). Claims that current impact assessment simulation results are too optimistic because they assume too high a CO_2 response with respect to experimental data are therefore, in general, incorrect (7).

Plant physiologists and modelers alike recognize that the effects of elevated CO_2, as measured in experimental settings and subsequently implemented in models, may nonetheless overestimate actual field and farm-level responses, because of many limiting factors such as pests, weeds, nutrients, competition for resources, soil water and air quality, etc. (7, 17, 18, 25–28)., which are neither well understood at large scales, nor well implemented in leading models. Future crop model development should therefore strive to include these additional factors to allow for more realistic climate-change simulations. In the meantime, studies projecting future yield and production under climate change should do so by incorporating sensitivity ranges for crop response to elevated CO_2 to better convey the associated uncertainty range (12).

Interactions of Elevated CO_2 with Temperature and Precipitation. Climate changes projected for future decades will modify, and may often limit, the direct CO_2 effects on crop and pasture plant species that were discussed above. For instance, high temperature during the critical flowering period of a crop may lower otherwise positive CO_2 effects on yield by reducing grain number, size, and quality (29–31). Increased temperatures during the growing period may also reduce CO_2 effects indirectly, by increasing water demand. For example, yield of rain-fed wheat grown at 450 ppm CO_2 was found to increase up to 0.8°C warming, then declined beyond 1.5°C warming; additional irrigation was needed to counterbalance these negative effects (32). In pastures, elevated CO_2 together with increases in temperature, precipitation, and N deposition resulted in increased primary production, with changes in species distribution and litter composition (33–36). Future CO_2 levels may favor C_3 plants over C_4; yet the opposite is expected under associated temperature increases; the net effects remain uncertain.

Because of the key role of water in plant growth, climate impacts on crops significantly depend on the precipitation scenario considered. Because >80% of total agricultural land, and close to 100% pastureland is rain fed, general circulation model-projected changes in precipitation will often shape both the direction and magnitude of the overall impacts (37–39). In general, changes in precipitation, and more specifically in evapotranspiration-to-precipitation ratios, modify ecosystem productivity and function, particularly in marginal areas; higher water-use efficiency caused by stomatal closure and greater root densities under elevated CO_2 may in some cases alleviate or even counterbalance drought pressures (40). Although the latter dynamics are fairly well understood at the single-plant level, large-scale implications for whole ecosystems are not well understood (41–43).

Interactions of Elevated CO_2 with Soil Nutrients. FACE experiments confirm that high N soil contents increase the relative response to elevated atmospheric CO_2 concentrations (16). The yield response of a C_3 grass to elevated atmospheric CO_2 concentration was not significant under low N supply, but increased over 10 years under high applications of N fertilizer in a FACE experiment (44). This increase was caused by removing N limitation to plant growth through the application of N fertilizer. A decline in N availability may be prevented by an increase in biological N_2 fixation under elevated atmospheric CO_2 concentrations. In fertile grasslands, legumes benefit more from elevated atmospheric CO_2 concentrations than nonfixing species (45- 47). Nevertheless, other nutrients, such as phosphorus, may act as the main limiting factor restricting legume growth response to atmospheric CO_2 concentrations (48).

Increased Frequency of Extreme Events. The impacts of increased climate variability on plant production under climate change are likely to increase production losses beyond those estimated from changes in mean variables alone (49). Yield damaging climate thresholds spanning periods of just a few days for cereals and fruit trees include absolute temperature levels linked to particular developmental stages that condition the formation of reproductive organs, such as seeds and fruits (50, 51). This means that models of yield damage need to include detailed phenology and above-optimal temperature effects on crops (49). Short-term natural extremes such as storms and floods, interannual and decadal climate variations as well as large-scale circulation changes such as the El Nino Southern Oscillation all have important effects on crop, pasture, and forest production. For example, El Nino-like conditions increase the probability of farm incomes falling below their long-term median by 75% across most of Australia's cropping regions, with impacts on gross domestic product ranging from 0.75% to 1.6% (52). Europe experienced a particularly extreme climate event during the summer of 2003, with temperatures up to 6°C above long-term means and precipitation deficits up to 300 mm. A record crop yield drop of 36% occurred in Italy for corn grown in the Po valley where extremely high temperatures prevailed (53). The uninsured economic losses for the agriculture sector in the European Union were estimated at 13 billion Euros (ref. 54 and www.senat.fr/rap/r03–195/r03–195.html). In dry regions, severe soil and vegetation degradation may lead to significant loss of pastoral areas and farmlands.

Understanding links between increased frequency of extreme climate events and ecosystem disturbance (fires, pest outbreaks, etc.) is particularly important to better quantify impacts (55–57). Only a few analyses have started to incorporate effects of increased climate variability on plant production.

Impacts on Weed and Insect Pests, Diseases, and Animal Production and Health. The importance of weeds and insect pests and disease interactions with climate change, including increasing CO_2 concentrations, is understood qualitatively, but quantitative knowledge is lacking, in comparison to data from experiments that manipulate easily controllable climate and management variables. Recent research has highlighted the key role of competition between C_3 crop and C_4 weed species under different climate and CO_2 concentrations (27). CO_2–temperature interactions are recognized as a key factor determining plant damage from pests in future decades; CO_2/precipitation interactions will be likewise important (58, 59). Most studies continue to investigate pest damage as a separate function of either CO_2 (60–63) or climate, mostly temperature (64–66). For instance, recent warming trends in the United States and Canada have led to earlier insect activity in the spring and proliferation of some species, such as the mountain pine beetle.

Importantly, increased climate extremes may promote plant disease and pest outbreaks (67, 68). Studies focusing on the spread of animal diseases and pests from low to mid-latitudes due to warming have shown that change is already under way. For instance, models project that bluetongue, a disease affecting mostly sheep, and occasionally goat and deer, would spread from the tropics to mid-latitudes (12). Likewise, simulated climate change increased vulnerability of the Australian beef industry to the cattle tick (*Boophilus microplus*). Most assessment studies do not explicitly consider either pest–plant dynamics or impacts on livestock health as a function of CO_2 and climate combined.

Lack of prior conditioning to weather events most often results in catastrophic losses in confined cattle feedlots (69). In Africa, impacts of droughts (1981–1999) have been shown to induce mortality rates of 20–60% of national herds (12). New models of animal energetics and nutrition (70) have shown that high temperatures put a ceiling on dairy milk yield from feed intake. In the tropics, this ceiling occurs between one-third and one-half of the potential of the modern (Friesians) cow breeds. The energy deficit of this genotype will exceed that normally associated with the start of lactation and decrease cow fertility, fitness, and longevity (ref. 71 and www.bsas.org.uk/downloads/BSAS_prog_text.pdf). Increases in air temperature and/or humidity have the potential to affect conception rates of domestic animals not adapted to those conditions. This is particularly the case for cattle, in which the primary breeding season occurs in the spring and summer months (12).

Interactions with Air Pollutants. Tropospheric ozone has significant adverse effects on crop yields, pasture and forest growth, and species composition (12). While emissions of ozone precursors, chiefly NOx compounds, may be decreasing in North America and Europe because of pollution control measures, they are increasing in other regions of the world, especially Asia. Additionally, as global ozone exposures increase over this century, direct and indirect interactions with climate change and elevated CO_2 will further modify plant dynamics (72, 73). Although several studies confirm previous findings that elevated CO_2 may ameliorate otherwise negative impacts from ozone, the essence of the matter should be viewed the other way around: increasing ozone concentrations in future decades, with or without CO_2, with or without climate change, will negatively impact plant production, possibly increasing exposure to pest damage (74, 75). Current risk assessment tools do not sufficiently consider these key interactions. Improved modeling approaches linking the effects of ozone, climate change, and nutrient and water availability on individual plants, species interactions, and ecosystem function are needed, and some efforts are under way (76, 77). Although UV-B exposure is in general negative to plant growth, knowledge on the interactions of UV-B exposure with elevated CO_2 is still incomplete, with some experimental findings suggesting amelioration of negative UV-B effects on plant growth by elevated CO_2, whereas others show no effect (12).

Vulnerability of Carbon Pools. Impacts of climate change on managed systems, because of the large land area that is under human management for food and livestock, have the potential to significantly affect the global terrestrial C sink and further perturb atmospheric CO_2 concentrations (53, 78). Furthermore, vulnerability of organic carbon pools to climate change has important repercussions for land sustainability and climate mitigation actions. Future changes in carbon stocks and net fluxes would critically depend on land use planning (set aside policies, afforestation/reforestation, etc.) and management practices such as N fertilization, irrigation, and tillage, in addition to plant response to elevated CO_2 (14). Recent experimental research confirms that carbon storage in soil organic matter pools is often increased under elevated CO_2, at least in the short term (e.g., ref. 79); yet the total soil C sink may become saturated at elevated CO_2 concentrations, especially when nutrient inputs are low (80).

Uncertainty remains with respect to several key issues, such as the impacts of increased frequency of extremes on the stability of carbon and soil organic matter pools; for instance, the recent European heat wave of 2003 led to significant ecosystem carbon losses (53). In addition, the effects of air pollution on plant function may indirectly affect carbon storage; recent research showed that tropospheric ozone resulted in significantly less enhancement of C sequestration rates under elevated CO_2 (81), because of negative effects of ozone on biomass productivity and changes to litter chemistry (73). Increases were projected in carbon storage on croplands globally under climate change up to 2100, yet ozone damage to crops could significantly offset these gains (77).

Finally, recent studies show the importance of identifying potential synergies between land-based adaptation and mitigation strategies, linking issues of carbon sequestration, emissions of greenhouse gases, land-use change, and long-term sustainability of production systems within coherent climate policy frameworks (e.g., ref. 82).

Impact Assessments

Simulation results of crop models and integrated assessments performed over the last 15–20 years indicate rather consistently that impacts on food systems at the global scale may be small overall in the first half of the 21st century, but progressively negative after that, as mean temperatures increase regionally and globally >2.5–3°C (12, 14). Uncertainties capable of significantly altering these conclusions, for instance, by increasing the magnitude of projected impacts and anticipating projected damages to earlier decades, were identified in several areas, including: the true strength and saturation point of the elevated CO_2 response of crops grown in real fields; water relations and water availability; irrigation; crop interactions with air pollutants and with weeds, pathogens and disease; importance of changes in the frequency of climate extremes versus changes in mean climate; implementation of CO_2 effects in models, and other scale/validation issues; interactions of socio-economic and climate scenarios within integrated assessments, and their validation; and timing and implementation of adaptation strategies. In addition, new studies are starting to also consider impacts of climate change under mitigation scenarios and analyze the interactions of adaptation and mitigation strategies.

Discussion: Recent Advances in Impact Assessment Studies

Although globally aggregated impacts on world food production are projected to be small by current models, with large negative impacts in developing regions, but only small changes in developed regions, (3, 4, 10), there is significant possibility of negative surprises as discussed below.

Increases in Frequency of Climate Extremes May Lower Crop Yields Beyond the Impacts of Mean Climate Change. More frequent extreme events may lower long-term yields by directly damaging crops at specific developmental stages, such as temperature thresholds during flowering, or by making the timing of field applications more difficult, thus reducing the efficiency of farm inputs (e.g., refs. 49 and 83). A number of simulation studies have investigated specific aspects of increased climate variability within climate-change scenarios. It was computed that, under scenarios of increased heavy precipitation, production losses caused by excessive soil moisture, already significant today, would double in the United States to $3 billion per year in 2030 (84). Others have focused on the consequences of higher temperatures on the frequency of heat stress during growing seasons and the frequency of frost occurrence during critical growth stages (12).

Impacts of Climate Change on Irrigation Water Requirement May Be Large. A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO_2 on crop water use efficiency. Considering direct impacts of climate change on crops evaporative demand, but no CO_2 effects, Döll (85) estimated an increase of net crop irrigation requirements, i.e., net of transpiration losses, of +5% to +8% globally by 2070, with larger regional signals, e.g., +15% in southeast Asia. In another study, including positive CO_2 effects on crop water use efficiency, increases in global net irrigation requirements of +20% by 2080 were projected, with larger impacts in developed vs. developing regions, due to both increased evaporative demands and longer growing seasons under climate change (86). New studies (86, 87) also projected increases in water stress (the ratio of irrigation withdrawals to renewable water resources) in the Middle East and southeast Asia. Recent regional studies (12) have likewise underlined critical climate change/water dynamics in key irrigated areas, such as North Africa (increased irrigation requirements) and China (decreased requirements).

Stabilization of CO_2 Concentrations Reduces Damage to Crop Production in the Long Term. Recent work further investigated the effects on regional and global crop production of mitigation leading to stabilization of atmospheric CO_2. Compared with business-as-usual scenarios, under which, however, the overall impacts were already small, by 2100 impacts of climate change on global crop production were only slightly less under 750 ppm CO_2 stabilization, but significantly reduced (−70% to −100%), with lower risk of hunger (−60% to −85%), under 550 ppm CO_2 stabilization (87, 88). These same studies suggested that climate mitigation may alter the regional and temporal mix of winners and losers with respect to business-as-usual scenarios, but that specific projections are highly uncertain. In particular, in the first decades of this century and possibly up to 2050, some regions may be worse off with mitigation than without, because of lower CO_2 levels, thus reduced stimulation of crop yields, but the same magnitude of climate change, compared with the unmitigated scenarios (88). Finally, a growing body of work has started to analyze potential synergies and incompatibilities between mitigation and adaptation strategies (12).

Conclusions

Understanding the key dynamics that characterize the interactions of elevated CO_2 with changes in climate variables, including extremes, soil and water quality, pest weed and disease, and ecosystem vulnerability, remains a priority for better quantifying future impacts of climate change on managed-land systems.

In terms of experimentation, there is still a lack of knowledge of CO_2 and climate responses for many crops other than cereals, including many of importance to the rural poor. Finally, the last 15 years have produced a wealth of experimental data on the effects of elevated CO_2 on crops under both optimal and limiting conditions. However, scaling this knowledge to farmers' fields and even further to regional scales, including predicting the CO_2 levels beyond which saturation may occur, remain a critical challenge.

In terms of simulation studies, there is a need to enhance comparisons of different crop models; such activity is not performed often and should be enhanced. It is important that uncertainties related to crop model simulations of key process related to climate change (e.g., temperature and water stress), including their spatial-temporal resolution, be better evaluated and understood, or findings of integrated studies will remain too dependent on the particular crop model used. Importantly, it is still unclear how implementation of plot-level experimental data on CO_2 responses compares across models, especially when simulations of several key limiting factors such as soil and water quality, pests weeds and disease, and the like, remain either unresolved experimentally or untested in models.

In general, greater collaboration between experimentalists and modelers, and across disciplines, is necessary to bridge some of the existing knowledge gaps and better understand related uncertainties.

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