Climate Impacts on Agriculture: A Challenge to Complacency?

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Abstract

Unduly optimistic views of the impacts of climate change on agriculture, drawing on the research of the 1990s, have helped to justify relatively complacent approaches to climate policy. In the last decade, newer research has identified more ominous climate threats to agriculture - which should call for a revised perspective on climate policy.

We review three categories of climate impacts on agriculture. Carbon fertilization, while still seen as a benefit to most crops, is now estimated to be smaller than in earlier research. The effect of temperature increases on crops is now recognized to involve thresholds, beyond which yields per hectare will rapidly decline. Finally, changes in precipitation can be crucial - not only in cases of drought, but also in subtler shifts in timing and intensity of rainfall.

Response to the climate crisis in agriculture will require adaptation to inescapable near-term trends, via the creation of heat-resistant and drought-resistant crops and cultivars whenever possible. Yet unchecked climate change would quickly reach levels at which adaption is no longer possible; it is also urgent to reduce greenhouse gas emissions as rapidly as possible, to limit future climate-related damages.

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A new paradigm is emerging in recent research on climate and agriculture. Its findings are not yet well known outside of specialized academic journals – but they deserve much wider attention. Taken seriously, this new standard constitutes a challenge to the complacency of most countries' climate policies. A warming world may experience food crises in the not-so-distant future, a threat that should inspire immediate responses.

This article draws on our forthcoming book, *Climate Economics: The State of the Art* (Ackerman and Stanton 2013) and on our ongoing research, including a major study of climate impacts on the U.S. Southwest (Ackerman and Stanton 2011), to attempt a synthesis of recent findings on climate and agriculture and their implications for public policy.

Background: the foundations of inaction

Climate policies rely, explicitly or implicitly, on estimates of the damages that will be caused by climate change. This dependence is explicit when policy recommendations draw on the results of formal economic models. Such models typically weigh the costs of policy initiatives against the benefits. The costs of emission reduction are the incremental expenditures for renewable electricity generation, low-emission vehicles, and the like, compared to more conventional investments in the same industries. The benefits are the future climate damages that can be avoided by emission reduction. The greater the expected damages, the more it is "worth" spending to avoid them. As explained below, many of the best-known and most widely used models are significantly out of date in their damage estimates, in agriculture among other areas.

Often, of course, policy decisions are not based on formal models or explicit economic analysis. Yet even when politicians and voters decide that climate action is simply too expensive, they may be relying on implicit estimates of damages. Declaring something to be too expensive is not solely a statement of objective fact; it is also a judgment that a proposed expenditure is not particularly urgent. Protection against threats of incalculable magnitude – such as military defense of a nation's borders, or airport screening to keep terrorists off of planes – is rarely described as "too expensive."

The conclusion that climate policy is too expensive thus implies that it is an option we can do without, rather than a response to an existential threat to our way of life. Can we muddle along without expensive climate initiatives, and go on living – and eating – in the same way as in the past? Not for long, according to some of the new research on climate and agriculture.

What we used to know about agriculture

Agriculture is one of the most climate-sensitive industries, with outdoor production processes that depend on particular levels of temperature and precipitation. Although only a small part of the world economy, it has always played a large role in estimates of overall economic impacts of climate change. In monetary terms, agriculture represents less than 2 percent of GDP in high-income countries, and 2.9 percent for the world as a whole.[3] It is more important to the economies of low-income countries, amounting to almost one-fourth of GDP in the least developed countries. And its product is an absolute necessity of life, with virtually no substitutes.[4]

In the 1990s, it was common to project that the initial stages of climate change would bring net benefits to global agriculture (e.g., Mendelsohn et al. 1994). As late as 2001, the U.S. Global Change Research Program still anticipated that U.S. agriculture would experience yield increases due to climate change throughout this century (Reilly et al. 2001).Warmer weather was expected to bring longer growing seasons in northern areas, and plants everywhere were expected to benefit from carbon fertilization. Since plants grow by absorbing carbon dioxide (CO_2) from the air, higher CO_2 concentrations might act as a fertilizer, speeding the growth process.

Simple and dated interpretations of climate impacts on agriculture continue to shape relatively recent economic assessments of climate damages. Widely used integrated assessment models such as DICE and FUND are still calibrated to relatively old and optimistic agricultural analyses.[5] Even the more sophisticated and detailed PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) project, analyzing climate impacts throughout Europe, assumed linear relationships between average temperatures and crop yields.[6] It projected that temperature changes through the end of this century would cause yield declines in Mediterranean and southern Atlantic Europe, and yield increases elsewhere (Iglesias et al. 2011). For Europe as a whole, PESETA estimated little change in crop yields for average European temperature increases up to 4.1°C, with a 10 percent yield decline at 5.4°C, the highest temperature analyzed in the study (Ciscar et al. 2011).

Such estimates have fallen well behind the state of the art in the research literature. There are three major areas in which recent results and models suggest a more complex relationship between climate and agriculture: the revised understanding of carbon fertilization; the threshold model of temperature effects on crop yields; and the emerging analyses of climate and regional precipitation changes.

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[3] World Bank data on agricultural value added as a share of GDP in 2008, http://data.worldbank.org.

[4] In economic terms, the fact that food is a necessity means that it has a very low price elasticity of demand, implying that it has a very large consumer surplus. If contributions to well-being are measured by consumer surplus rather than shares of GDP, as economic theory suggests, then agriculture looms much larger in importance.

[5] For the damage estimates used in DICE, including a projection of virtually no net global losses in agriculture from the first few degrees of warming, see Nordhaus and Boyer (2000); this earlier analysis is still a principal source for damages estimates in the latest version of DICE (Nordhaus 2008; Nordhaus 2007). On the dated and problematical treatment of agricultural impacts in FUND, see Ackerman and Munitz (2012); the 2010 release of FUND relies on agricultural research published in 1996 and earlier.

[6] Using historical data from 1961-90, PESETA modeled yields at nine locations, as linear functions of annual and monthly average temperatures (as well as precipitation). In three locations, there was a negative coefficient on a summer month's temperature as well as positive coefficients on springtime and/or annual average temperatures – perhaps a rough approximation of the threshold model discussed below (Iglesias et al. 2011).

Reduced estimates of carbon fertilization

The best-known of the new areas of research is the empirical evidence that carbon fertilization benefits are smaller than previously believed. Plants grow by photosynthesis, a process that absorbs CO_2 from the air and converts it into organic compounds such as sugars. If the limiting factor in this process is the amount of CO_2 available to the plant, then an increase in the atmospheric concentration of CO_2 could act as a fertilizer, providing additional nutrients and allowing faster growth.

Almost all plants use one of two styles of photosynthesis.[7] The majority of food crops and other plants are C_3 plants (so named because a crucial molecule contains three carbon atoms), in which growth is limited by the availability of CO_2, so that carbon fertilization could be beneficial to them. In contrast, C_4 plants have evolved a different photosynthetic pathway that uses atmospheric CO_2 more efficiently. C_4 plants, which include maize, sugarcane, sorghum, and millet (as well as switchgrass, a potentially important biofuel feedstock), do not benefit from increased CO_2 concentrations except in drought conditions (Leakey 2009).

Initial experimental studies conducted in greenhouses or other enclosures found substantial carbon fertilization effects. The 2001 U.S. National Assessment summarized the experimental evidence available at that time as implying yield gains of 30 percent in C_3 crops and 7 percent in C_4 crops from a doubling of CO_2 concentrations (Reilly et al. 2001). More recently, Free-Air CO_2 Enrichment (FACE) experiments have allowed crops to be grown in outdoor environments with a greater resemblance to the actual conditions of production. According to a widely cited summary, the effects of CO_2 on yields for major grain crops are roughly 50 percent lower in FACE experiments than in enclosure studies (Long et al. 2004).[8] Another literature review reaches similar conclusions, offering “important lessons from FACE,” one of which is that “the [CO_2] ‘fertilization’ effect in FACE studies on crop plants is less than expected” (Leakey 2009).

One summary of the results of FACE experiments reports that an increase in atmospheric CO_2 from 385 ppm (the actual level a few years ago) to 550 ppm would increase yields of the leading C_3 crops, wheat, soybeans, and rice, by 13 percent and would have no effect on yields of maize and sorghum, the leading C_4 grains (Ainsworth and McGrath 2010). Cline (2007) develops a similar estimate; because C_4 crops represent about one-fourth of world agricultural output, he projects a weighted average of 9 percent increase in global yields from 550 ppm.

While research on carbon fertilization has advanced in recent years, there are at least three unanswered questions in this area that are important for economic analysis. First, there is little information about the effects of very high CO_2 concentrations; many studies have only examined yields up to 550 ppm, and few have gone above 700 ppm. Long-term projections of business-as-usual emissions scenarios, however, frequently reach even higher concentrations. Does CO_2 fertilization continue to raise yields indefinitely, or does it reach an upper bound?

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[7] A third photosynthetic pathway exists in some plants subject to extreme water stress, such as cacti and succulents; it is not important in agriculture.

[8] This article has been criticized by Tubiello et al. (2007); the original authors respond in Ainsworth et al. (2008).

Second, most studies to date have focused on the leading grains and cotton; other plants may have different responses to increases in CO_2. For at least one important food crop, the response is negative: Cassava (manioc), a dietary staple for 750 million people in developing countries, shows sharply reduced yields at elevated CO_2 levels, with tuber mass reduced by an order of magnitude when CO_2 concentrations rise from 360 ppm to 710 ppm (Gleadow et al. 2009; Ghini et al. 2011). This result appears to be based on the unique biochemistry of cassava, and does not directly generalize to other plants. It is, nonetheless, a cautionary tale about extrapolation from studies of a few plants to food crops as a whole.

Third, carbon fertilization may interact with other environmental influences. Fossil fuel combustion, the principal source of atmospheric CO_2, also produces tropospheric (ground-level) ozone, which reduces yields of many plants (Ainsworth and McGrath 2010). The net effect of carbon fertilization plus increased ozone is uncertain, but it is very likely to be less than the experimental estimates for carbon fertilization alone.

Temperature thresholds for crop yields

Describing climate change by the increase in average temperatures is inescapably useful, but at the same time often misleading. Increases in global average temperature of only a few degrees, comparable to normal month-to-month changes in many parts of the world, will have drastic and disruptive effects. A recent study suggests that it may be easier for people to perceive climate change as reflected in temperature extremes, such as the marked increase in the frequency of temperatures more than three standard deviations above historical summer averages (Hansen et al. 2012).

An important new wave of research shows that crops, too, are often more sensitive to temperature extremes than to averages. In many cases, yields rise gradually up to a temperature threshold, then collapse rapidly as temperatures increase above the threshold. This threshold model often fits the empirical data better than the earlier models of temperature effects on yields.

It is obvious that most crops have an optimum temperature, at which their yields per hectare are greater than at either higher or lower temperatures. A simple and widely used model of this effect assumes that yields are a quadratic function of average temperatures.[9] The quadratic model, however, imposes symmetry and gradualism on the temperature-yield relationship: yields rise smoothly on the way up to the optimum temperature, and then decline at the same smooth rate as temperatures rise beyond the optimum.

The threshold model makes two innovations: it allows different relationships between temperature and yield above and below the optimum; and it measures temperatures above the optimum in terms of the growing-season total of degree-days above a threshold, rather than average seasonal or annual temperatures.[10] Perhaps the first use of this model in recent

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[9] That is, the equation for yields has both temperature (with a positive coefficient) and temperature squared (with a negative coefficient) on the right-hand side.

[10] Degree-days are the product of the number of days and the number of degrees above a threshold. Relative to a 32°C threshold, one day at 35°C and three days at 33°C would each represent three degree-days.

agricultural economics was Schlenker et al. (2006), drawing on earlier agronomic literature. This approach has a solid grounding in plant biology: many crops are known to have temperature thresholds, in some cases at varying temperatures for different stages of development (Luo 2011).

The threshold model has been widely used in the last few years. For instance, temperature effects on maize, soybean, and cotton yields in the United States are strongly asymmetric, with optimum temperatures of 29 - 32°C and rapid drops in yields for degree-days beyond the optimum. For maize, replacing 24 hours of the growing season at 29°C with 24 hours at 40°C would cause a 7 percent decline in yields (Schlenker and Roberts 2009).

A very similar pattern was found in a study of temperature effects on maize yields in Africa, with a threshold of 30°C (Lobell et al. 2011). Under ordinary conditions, the effects on yields of temperatures above the threshold were similar to those found in the United States; under drought conditions, yields declined even faster with temperature increases. Limited data on wheat in northern India also suggest that temperature increases above 34°C are more harmful than similar increases at lower levels (Lobell et al. 2012).

A study of five leading food crops in sub-Saharan Africa found strong relationships of yields to temperatures (Schlenker and Lobell 2010). By mid-century, under the A1B climate scenario, yields are projected to drop by 17 to 22 percent for maize, sorghum, millet, and groundnuts (peanuts) and by 8 percent for cassava. These estimates exclude carbon fertilization, but maize, sorghum, and millet are C_4 crops, while cassava has a negative response to increased CO_2, as noted above. Negative impacts are expected for a number of crops in developing countries by 2030. Among the crops most vulnerable to temperature increases are millet, groundnut, and rapeseed in South Asia; sorghum in the Sahel; and maize in Southern Africa (Lobell et al. 2008).

Other crops exhibit different, but related, patterns of temperature dependence; some perennials require a certain amount of “chill time,” or annual hours below a low temperature threshold such as 7°C. In a study of the projected loss of winter chilling conditions in California, Germany, and Oman, fruit and nut trees showed large decreases in yield due to climate change (Luedeling et al. 2011). In this case, as with high-temperature yield losses, the relevant temperature variable is measured in terms of threshold effects, not year-round or even seasonal averages. Small changes in averages can imply large changes in the hours above or below thresholds, and hence large agricultural impacts.

Studies of temperatures and yields based on recent experience, including those described here, are limited in their ability to project the extent of adaptation to changing temperatures. Such adaptation has been important in the past: as North American wheat production expanded into colder, drier regions, farmers adapted by selecting different cultivars that could thrive in the new conditions; most of the adaptation occurred before 1930 (Olmstead and Rhode 2010). On the other hand, regions of the United States that are well above the optimum temperatures for maize, soybeans, and other major crops have grown these crops for many years, without any evidence of a large-scale shift to more heat-resistant crops or cultivars; temperature-yield relationships are quite similar in northern and southern states (Schlenker and Roberts 2009). Thus adaptation is an important possibility, but far from automatic.

Climate change, water and agriculture

A third area of research on climate and agriculture has reached less definite global conclusions, but it will be of increasing local importance. As the world warms, precipitation patterns will change, with some areas becoming wetter, but some leading agricultural areas becoming drier. These patterns are difficult to forecast; climate model predictions are more uncertain for precipitation than for temperature, and "downscaling" global models to yield regional projections is only beginning to be feasible. Yet recent droughts in many parts of the world underscore the crucial role of changes in rainfall. Even if total annual precipitation is unchanged, agriculture may be harmed by changes in the seasonality or intensity of rainfall.

Overall, warming is increasing the atmosphere's capacity to hold water, resulting in increases in extreme precipitation events (Min et al. 2011). Both observational data and modeling projections show that with climate change, wet regions will generally (but not universally) become wetter, and dry regions will become drier (Sanderson et al. 2011; John et al. 2009). Perceptible changes in annual precipitation are likely to appear in many areas within this century. While different climate models disagree about some parts of the world, there is general agreement that boreal (far-northern) areas will become wetter, and the Mediterranean will become drier (Mahlstein et al. 2012).

With 2°C of warming, dry-season precipitation is expected to decrease by 20 percent in northern Africa, southern Europe, and western Australia, and by 10 percent in the southwestern United States and Mexico, eastern South America, and northern Africa by 2100 (Giorgi and Bi 2009).[11] In the Sahel area of Africa, the timing of critical rains will shift, shortening the growing season (Biasutti and Sobel 2009), and more extensive periods of drought may result as temperatures rise (Lu 2009).[12] In the Haihe River basin of northern China, projections call for less total rainfall but more extreme weather events (Chu et al. 2009). Indian monsoon rainfall has already become less frequent but more intense, part of a pattern of climate change that is reducing wet-season rice yields (Auffhammer et al. 2011).

The relationship of crop yields to precipitation is markedly different in irrigated areas than in rain-fed farming; it has even been suggested that mistakes in analysis of irrigation may have accounted for some of the optimism about climate and agriculture in the 1990s literature (Schlenker et al. 2005). In California, by far the leading agricultural state in the United States, the availability of water for irrigation is crucial to yields; variations in temperature and precipitation are much less important, as long as access to irrigation can be assumed (Schlenker et al. 2007). Yet there is a growing scarcity of water and competition over available supplies in the state, leading some researchers to project a drop in irrigated acreage and a shift toward higher-value, less water-intensive crops (Howitt et al. 2009). An analysis of potential water scarcity due to climate change in California estimates that there will be substantial costs in dry years, in the form of both higher water prices and supply shortfalls, to California's Central Valley agriculture (Hanemann et al. 2006).

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[11] End-of-century (2081-2100) precipitation under A1B relative to 1981-2000.

[12] Lu (2009) notes that there is significant uncertainty regarding future Sahel drying, because it is influenced by 1) sea-surface temperature changes over all the world's oceans; and 2) the radiative effects of greenhouse gas forcing on increased land warming, which can lead to monsoon-like conditions.

In our study of climate change and water in the southwestern U.S., we found that climate change is worsening the already unsustainable pattern of water use in agriculture (Ackerman and Stanton 2011).[13] Nearly four-fifths of the region's water is used for agriculture, often to grow surprisingly water-intensive, low-value crops; a tangled system of legal restrictions and entitlements prevents operation of a market in water. If there were a market for water in the Southwest, municipal water systems and power plants would easily outbid many agricultural users. Yet one-fifth of U.S. agricultural output comes from this region, virtually all of it dependent on irrigation.

More than half of the water used in the region is drawn from the Colorado River and from groundwater, neither of which can meet projected demand. The Colorado River is infamously oversubscribed, and is the subject of frequent, contentious negotiations over the allocation of its water. Climate change is projected to cause a decrease in precipitation, runoff, and streamflow in the Colorado River basin, leading to frequent water shortages and decreases in energy production (Christensen and Lettenmaier 2007).[14]

Groundwater supplies are difficult to measure, and there are two very different estimates of California's groundwater reserves. Even assuming the higher estimate, the state's current patterns of water use are unsustainable, leading to massive shortfalls of groundwater within a few decades.

In California, projections of changes in annual precipitation are not consistent across climate models. Even if annual precipitation remains constant, however, climate change can worsen the state's water crisis in at least two ways. On the demand side, higher temperatures increase the need for water for irrigation, and for municipal and other uses. On the supply side, rising temperatures mean that winter snows will be replaced by rain, or will melt earlier in the year – which can have the effect of reducing the available quantity of water.

The mountain regions of the western United States are experiencing reduced snowpack, warmer winters, and stream flows coming earlier in the calendar year. Since the mid-1980s, these trends have been outside the past range of natural variation, but consistent with the expected effects of anthropogenic (human-caused) climate change (Barnett et al. 2008). In the past, snowmelt gradually released the previous winter's precipitation, with significant flows in the summer when demand is highest. The climate-related shift means that water arrives, in large volume, earlier in the year than it is needed – and the peak runoff may overflow existing reservoir capacity, leading some of it to flow directly to the ocean without opportunity for human use (Barnett et al. 2005).

We developed a model of the interactions of climate, water, and agriculture in California and in the five-state region, assuming constant annual precipitation but modeling temperature-driven increases in demand as well as changes in seasonal streamflows (Stanton and Fitzgerald 2011). We found that climate change makes a bad situation much worse, intensifying the expected gap between water supply and demand. Under one estimate of the cost of supplying water, we found that climate change is transforming the region's $4 trillion water deficit over the next century

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[13] We studied a five-state region: California, Nevada, Utah, Arizona and New Mexico. California accounts for most of the population, agriculture, and water use of the region.

[14] The Colorado River basin includes most of the four inland states in our study region, but only a small part of California. Nonetheless, California is legally entitled to, and uses, a significant quantity of Colorado River water. Other rivers are also important to water supply in California, but much less so in the inland states.

into a $5 trillion shortfall (Ackerman and Stanton 2011). If we had also modeled a decline in annual precipitation, of course, the problem would have been even worse.

To those unfamiliar with the southwestern United States, this may sound like an excursion into hydrology and water management rather than an analysis of agriculture. No one who lives there could miss the connection: most of the region's water is used for agriculture; virtually all of the region's agriculture is completely dependent on a reliable flow of water for irrigation. As climate change presses down on western water, it will start to squeeze a crucial sector of the U.S. food supply. This is a far cry from the optimism of earlier decades about what climate change will mean for agriculture.

Conclusion

The extraordinary proliferation of recent research on climate change has moved far beyond an earlier complacency about agricultural impacts. With better empirical studies, estimates of carbon fertilization benefits have shrunk for C_3 crops (most of the world's food) in general – as well as being roughly zero for maize and other C_4 crops, and negative for cassava. With a better explanatory framework, focused on temperature extremes rather than averages, judgments about temperature impacts on crop yields have become more ominous. With more detailed local research, the regionally specific interactions of climate, water, and agriculture are beginning to be understood, often implying additional grounds for concern.

It should not be surprising that even a little climate change is bad for agriculture. The standard models and intuition of economic theory emphasize options for substitution in production – less steel can be used in making cars, if it is replaced by aluminum or plastic – but agriculture is fundamentally different. It involves natural processes that frequently require fixed proportions of nutrients, temperatures, precipitation, and other conditions. Ecosystems don't make bargains with their suppliers, and don't generally switch to making the same plants out of different inputs.

Around the world, agriculture has been optimized to the local climate through decades of trial and error. The conditions needed to allow crops to flourish include not only their preferred ranges of average temperature and precipitation, but also more fine-grained details of timing and extreme values. This is true for temperatures, as shown by the existence of thresholds and the sensitivity of yields to brief periods of extreme temperatures beyond the thresholds. It is also true for precipitation, as shown by the harm to Indian rice yields from less frequent but more intense monsoon rains, or by the sensitivity of California agriculture to the delicate timing of snowmelt.

Global warming is now causing an unprecedented pace of change in the climate conditions that affect agriculture – much faster than crops can evolve on their own, and probably too fast for the traditional processes of trial-and-error adaptation by farmers. At the same time, the world's population will likely continue to grow through mid-century or later, increasing the demand for food just as climate change begins to depress yields. To adapt to the inescapable early states of climate change, it is essential to apply the rapidly developing resources of plant genetics and biotechnology to the creation of new heat-resistant, and perhaps drought-resistant, crops and cultivars.

Adaptation to climate change is necessary but not sufficient. If warming continues unabated, it will, in a matter of decades, reach levels at which adaptation is no longer possible. Any long-run solution must involve rapid reduction of emissions, to limit the future extent of climate change. The arguments against active climate policies, based on formal or informal economic reasoning, have been propped up by a dated and inaccurate picture of climate impacts on agriculture, which lives on in the background of recent models and studies. Updating that picture, recognizing and accepting the implications of new research on climate threats to agriculture, is part of the process of creating climate policies that rest soundly on the latest scientific research.

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