Climate change: a crop protection challenge for the twenty-first century

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Abstract

Convincing data now show that temperatures are increasing, and that changing precipitation patterns are already affecting agriculture. Predicted future impacts vary by region, but all are projected to suffer productivity declines by the late twenty-first century unless successful mitigation measures are implemented soon. Exacerbating the climate change challenge, doubling of overall crop productivity will be required by mid-century. Clearly, crop protection will become increasingly difficult as higher-yielding varieties present a larger and more tempting target to all pests, and the pests themselves extend their ranges poleward and into other new geographies owing to reduced winterkill and longer growing seasons. Fortunately, good progress on enhancing crop protection technology to meet these challenges is already being made, but the scope of this climatic provocation is such that complacency is not an option. Increased investment into new technologies and adoption of new agricultural practices with improved adaptive and mitigation potential are both essential.

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1 INTRODUCTION

Farming has made enormous productivity gains over the twentieth century, but continuing this rapid pace of growth through the twenty-first century may prove challenging. On a global basis, much of the enhanced productivity achieved to date has come through the widespread adoption of inorganic nitrogen fertilizers, but some have questioned the long-term wisdom of this practice. The name of Malthus is often invoked, the notorious nineteenth-century philosopher who forecast unavoidable future food shortages. Indeed, the production and use of inorganic nitrogen fertilizers results in significant greenhouse gas (GHG) emissions, thereby allegedly contributing to the very climate change that may threaten the future productivity of cropping systems. Such issues have raised concerns over the long-term sustainability of modern agricultural techniques.

But farming has never been easy. Weed control, in particular, has plagued our ancestors from the very beginning. Indeed, the first few pages of the Bible describe this problem as a direct consequence of mankind’s disobedience: ‘cursed is the ground because of you . . . both thorns and thistles it shall grow for you’. In addition to unwanted weedy plants, there are numerous insect and fungal pests that plague farmers. But now, according to many environmental scientists, an even larger threat of biblical or even apocalyptic proportions looms over agriculture – global climate change.

It was against this backdrop in late 2006 that Monsanto, a company wholly dedicated to agriculture, called upon its leading scientists to form the Monsanto Fellows Climate Change Panel, which evaluated the current science behind the theory of man-made global warming and assessed its likely impact on agriculture in the early portion of the twenty-first century. This paper contains an updated summary of the Panel’s report, originally compiled in June 2007.

2 CLIMATE SCIENCE

Monsanto does not have its own climate scientists, so the Panel established contact with external experts and collected extensive information on the development of this area of science, and the origins of the theory of man-made global warming. The Panel found unequivocal and convincing data that temperatures are now increasing and precipitation patterns are changing in a manner largely consistent with that theory. Further details on each of these findings are presented below.

2.1 Overview of climate science

The possibility that climate might be affected by man-made GHG emissions, particularly those related to the combustion of coal and other fossil fuels, appears to have first been proposed in 1896 by Arrhenius. He reasoned that gas molecules like carbon dioxide (CO2), which absorb infrared radiation, must be having a net warming effect on the planet by trapping heat that would...
scientists are still debating the extent to which CO2 contributed to double the amount of CO2 in the air (560 ppm), they were not particularly alarmed by their calculations, because higher than the median of current model projections. However, this prehistoric climate record.

Climate glaciation (the ‘Ice Ages’) were shown by Milankovitch to be related to seemingly infinitesimal wobbling of the Earth’s orbit. Climate isotopic analysis of air bubbles trapped in ice cores collected from Antarctica and elsewhere (see Fig. 2). However, the wide temperature swings seen in these data were not directly caused by changes in atmospheric CO2. Instead, these periods of cyclical glaciation (the ‘Ice Ages’) were shown by Milankovitch to be related to seemingly infinitesimal wobbling of the Earth’s orbit. Climate scientists are still debating the extent to which CO2 contributed to an apparent amplification of the temperature swings present in this prehistoric climate record.

One of the other complexities and sources of misunderstanding of climate science is the following apparent contradiction: climate modelers claim an ability to predict long-term (decadal) trends in climate, whereas short-term (more than a few days) weather remains stubbornly unpredictable. But this apparent inconsistency is a simple consequence of (admittedly higher) mathematics. The inability to predict near-term weather has been linked, by mathematical proof, to the fact that weather is governed by a system of coupled non-linear differential equations. As such, it is subject to the so-called ‘butterfly effect’ first discovered and described by Lorenz, which states that such initial value problems are numerically unstable to vanishingly small perturbations in the initial conditions. Stated in non-mathematical terms, a butterfly flapping its wings one way in Walla Walla on Wednesday can affect the weather in Timbuktu on Tuesday. However, climate (the long-term trend in weather) is a boundary value problem, and therefore not beset by the vagaries of the butterfly effect.

Although climate models do not have this issue, their accuracy is plagued by at least two other critical questions: Is there a positive warming feedback process governing the climate? If so, how strong is it? There are several possible feedback processes that have been proposed, and a likely candidate is atmospheric water vapor. As the warming induced by man-made GHGs causes the world’s oceans to warm, more water evaporates, increasing the amount of water in the atmosphere. Because water vapor is itself the most important GHG, this should lead to accelerated warming. Eventually, of course, such a warming feedback loop should stop, as cloud cover increases and reflects a higher fraction of the incoming sunlight. But a stable climate at much higher temperatures is possible and is present within the paleoclimate record (see Fig. 3).

James Hansen, a scientist with NASA, has argued for such strong positive feedback, based on his analysis of climate over the past 65 million years. Fig. 3 contains a reploting of both Hansen’s paleoclimatic data and more recent data as a ‘phase–space’ diagram. Global mean temperatures are plotted as a function of the direct radiative forcing of carbon dioxide. These results are consistent with strong positive feedback, and also show that temperatures far higher than those observed at present are possible in the earth’s climate system. Recent temperatures are on a warming trajectory not seen in the paleoclimate record. The fact that current temperatures are still much lower than past temperatures at the current level of CO2 is likely due to the large thermal inertia of the Earth’s climate system, primarily within the oceans (a type of climate ‘hysteresis’). The higher radiative forcing caused by increased CO2 has come too quickly for global temperatures to respond fully. But the graph clearly implies much warmer temperatures are inevitable if CO2 levels continue to escalate. On the basis of analyses such as these,
Hansen has asserted that 350 ppm would be the highest tolerable concentration for atmospheric CO\(_2\) in order to avoid global warming of more than 2 °C.\(^6\) As shown previously in Fig. 1, the current CO\(_2\) concentration is nearly 390 ppm, and still accelerating upward.

By the late 1980s, global concerns over the potential threat represented by man-made global warming resulted in the formation of the Intergovernmental Panel on Climate Change (IPCC), which has issued a series of four detailed assessment reports, most recently in 2007.\(^7\) These reports discuss the considerable progress that has been made in climate science, based on large amounts of new and much more comprehensive data, improvements in the understanding of the underlying processes and more sophisticated analyses of the model results. All of these factors enable better characterization of the uncertainties in climate predictions, although it is not clear whether the public or policymakers have been able fully to appreciate the implications of this considerable uncertainty in our future climate trajectory.

The 2007 IPCC report was the first to discuss another serious consequence of CO\(_2\) emissions: ocean acidification.\(^12\) Approximately half of the excess CO\(_2\) has been absorbed by seawater, which has lowered the surface pH of the ocean and increased the solubility of calcium carbonate, a key component of many marine organisms. Those most at risk to this phenomenon include coral, mollusks and a number of microscopic species. In addition to overfishing, this represents a growing threat to marine food webs, and may help explain documented declines in the global catch of certain fish.\(^12\) More recently, it has been reported that the concentration of marine phytoplankton has decreased 40% since the middle part of the twentieth century,\(^13\) which was attributed primarily to the warming of the sea surface (by density-driven slowing of nutrient upwelling). If true, this would represent a strong warming feedback process, because such phytoplankton carry out a substantial proportion of global carbon fixation.

### 2.2 Warming is now accelerating

The Panel found convincing evidence that global temperatures are increasing, consistent with the basic tenets behind the theory of man-made global warming.\(^10\) All temperature records, whether based on ground or satellite observations, agree that warming has been steadily accelerating since the late 1960s,\(^14\) \(-17\) especially on the land surfaces of the Northern Hemisphere, where most of the world’s crop production takes place (Fig. 4).

A 7 year moving average (centered) has been added to Fig. 4 in order to see the overall trend a little more easily. The striking thing is that the temperature trend has been accelerating in a continuous manner for about the past 40 years. A variety of possible explanations could be offered to explain the recent dominance of the warming trend, but it seems likely that the man-made GHG warming effect has now overwhelmed the mix of other man-made activities that have a net cooling effect (such as cooling due to airborne particulate matter). The upward curvature is consistent with positive warming feedback in the climate system.

The accelerating warming curve is fit extremely well by the following equation, which was obtained by simple least-squares regression to the 7 year moving average of the observed data from January 1968 to January 2007, when the Panel was conducting its investigations:

\[
T = \left[ a(Y - 1968)^2 \right] + \left[ b(Y - 1968) \right]
\]  
(1)

where \(T\) is the Northern Hemisphere land surface warming relative to the year 1968 (°F), \(Y\) is the year (conventional Gregorian calendar), \(a\) is 0.0008338 °F year\(^{-1}\) (see Ref. 2) and \(b\) is 0.024337 °F year\(^{-1}\).

As shown in Fig. 4, this quadratic fit predicts faster warming than the IPCC model predictions for the decade of the 2020s. A closer look at how well equation (1) fits the observed warming since 1968 is shown in Fig. 5. The degree of fit is excellent, and the monthly temperature anomalies observed since it was first fit to the data (January 2007) continue to hover around the curve (lower right inset of Fig. 5). It is unknown whether temperatures will continue to follow this quadratic, but if they did (see upper left inset of Fig. 5) it would result in significant Northern Hemisphere land warming (16 °F by the year 2100).

As for the hypothesis that man-made GHG emissions are largely responsible for the observed warming, there is considerable evidence that it is true. As shown in Fig. 6, the rapidly rising concentrations of CO\(_2\), N\(_2\)O and CH\(_4\) closely parallel recent increases in world population. Although CO\(_2\) is the most important of these three gases and is mainly a result of burning coal and other fossil fuels as fuel and a source of electricity, agriculture is responsible for the majority of the N\(_2\)O and CH\(_4\) emissions. Combined with the impact of land use change (the carbon released
reduce GHG emissions. However, regardless of the particular scenario, which subsequent generations will adopt new technologies to mitigate changes is unclear. Projections of future warming are heavily dependent on the rate of continuing economic development and the degree to which climate change is controlled.

2.3 Expected course of climate change

Projections of future warming are heavily dependent on the rate of continuing economic development and the degree to which subsequent generations will adopt new technologies to reduce GHG emissions. However, regardless of the particular development scenario, the pattern of global warming will be non-uniform, both in terms of temperature rise and in terms of changes in precipitation. The following general statements characterize the expected pattern of future climate change:

1. Warming is predicted to occur mainly...
   - over land areas rather than over the oceans;
   - near the poles rather than in the tropics;
   - at night rather than during mid-day;
   - in winters rather than in summers.

2. Precipitation changes are less certain, but...
   - an overall increase is certain, especially near the poles;
   - decreases will occur in certain areas (mainly subtropical);
   - extreme precipitation events will increase in frequency;
   - current deserts are likely to expand.

3 IMPACT ON AGRICULTURE

The Panel found that the impacts of climate change on agriculture would be highly regional in nature, as detailed further below. Crop yields in certain areas are likely to benefit from the predicted changes through the mid-twenty-first century, but productivity is expected to be hampered in all regions by the end of the century unless mitigation occurs. The Panel found that modern agriculture is well positioned to deal with the expected pace of climate change, and possesses significant untapped potential to contribute to adaptation and mitigation of GHG emissions.

3.1 Expected effects of climate on agriculture

Considering all of the potential impacts, there is little doubt that water, either too much of it or too little, is the biggest climate threat to agriculture. By the middle of the twenty-first century, average annual river runoff and water availability should increase by 10–40% in high latitudes and in typically wet tropical regions, but available water will decrease by 10–30% over currently drier areas. Thus, current deserts and drought-stricken areas will likely increase in frequency, which are often a source of crop damage. Water availability will be severely impacted in those regions dependent on fresh water sourced by snow cover and glaciers, because both of these fresh water resources will become severely limited during the course of the twenty-first century.

Crop productivity is projected to increase slightly owing to climatic factors at mid to high latitudes until mid-century, when the excess heat will begin to harm yield. At lower latitudes, which are dominated by developing countries of lower adaptive ability, crop yields are likely to be negatively impacted by climate factors, and this trend will worsen as the warming proceeds. After mid-century, crops in all world areas are expected to be negatively impacted by changes in rainfall patterns, not only in terms of drought but also in terms of heavy precipitation events and the increased frequency of severe storms. Aquaculture and fisheries will be adversely affected owing to the combination of warming, acidification and other stressors (such as hypoxia).

In addition to the obvious effects of higher temperature and increased moisture stresses (both too much and too little rainfall), pest pressure is expected to intensify. Weeds will experience changes in their range, and some will become more productive and prolific owing to the natural fertilization of higher CO2 levels and potentially lengthened growing seasons. These changes in weed populations have implications for both pathogens and the insects that utilize such hosts.

As with weeds, insect pests are expected to increase their ranges, especially toward the poles. As already discussed, crop yields are increasing around the world, which means the coming century will see crops becoming larger and even more tempting targets for such pests. Insects are also hosts to other organisms,
including some that have both agricultural and human health implications. Many plant diseases are made worse by warmer temperatures, so this represents yet another potential threat to crops. Finally, the phenomenon of resistance among all categories of pests is expected to become a greater concern, as the number of annual generations increases, especially for those regions that no longer experience wintertime temperatures cold enough to kill off potentially resistant survivors.

Drought is expected to become an increasing threat to agriculture, but it will be highly regionalized.25 It is expected to be most intense in southern Africa, the Mediterranean, southwestern North America, eastern Brazil, western Australia and southeast Asia. Given the importance of each of these areas to crop production, this highlights the importance of developing new crop varieties with drought tolerance, whether via biotechnology or via advanced breeding techniques.

3.2 Adaptation and mitigation using modern agricultural technology

Fortunately, there is strong evidence that recent advances in agricultural technology are keeping pace with the rate of climate change, with strong potential for continued adaptation to warmer temperatures and even mitigation of GHG emissions.18,20,26 The primary mitigating effect of modern agricultural technology is its potential to boost crop yield, which Burney and coauthors18 found has resulted in the avoidance of major GHG emissions, in the range of 85–161 gigatons of carbon (GtC). The upper end of this range represents one-third of all human GHG emissions since 1850.19

Extension of Burney's analysis to a future case in which global crop yields are doubled over the period 2000–2030 results in avoided GHG emissions of 93–173 GtC (see Fig. 8). This extension was performed by observing that Burney's historical analysis implies a simple linear relationship between GHG emission avoidance and the rate of yield gain:

$$\text{GHG} = -\int_{t_1}^{t_2} \alpha \frac{dY}{dt} \, dt$$

(2)

where $GHG$ represents the cumulative GHG emissions (GtC) avoided over the time interval $t_1$ to $t_2$ (years), $dY/dt$ is the rate of gain in global crop yields (kg ha$^{-1}$ year$^{-1}$) and $\alpha$ is an empirically derived conversion factor with units of GtC kg$^{-1}$ ha$^{-1}$. According to data available from the analysis of Burney et al.,18 $\alpha$ ranges from 0.041 to 0.076 GtC kg$^{-1}$ ha$^{-1}$ for global crop yields. The analysis for the doubling of global crop yields by 2030 (shown in Fig. 8) is based on a comparison relative to a case in which global crop yields continue to follow the observed yield trend line (1961–2005).

In addition to advances in yield, today’s crops have become more efficient in terms of their conversion of inputs (nitrogen, water, energy) into harvestable material.20 The advent of new traits introduced through biotechnology has further accelerated these benefits and holds the potential for step changes in both yield and input efficiency. Crops engineered to produce their own insecticide (Bt) use solar energy, rather than fossil fuels, to power crop protection, which results in a reduction in GHG emissions. Conventional crop chemical production is associated with emissions of approximately 20 kg CO2e per kg of crop chemical produced.27 While this is a relatively modest amount of GHG emissions relative to the much larger amounts associated with other aspects of the overall agricultural production system (especially tillage), it does represent the single largest source of emissions for Monsanto. Monsanto has been self-reporting its emissions for more than 20 years and has been actively managing production processes in order to lower the amount released per unit of crop chemical produced.28

Another widely used biotechnology trait is herbicide tolerance technology. The simplicity and agronomic advantages of herbicide tolerance crops have resulted in them now being widely grown in North America and several other world areas.29 Such crops facilitate the use of conservation tillage, which provides further GHG reductions by incremental sequestration of carbon in the soil and the avoidance of fuel consumption during the tillage operation.30 In a reduced tillage system, the farmer also conserves soil, with the large decrease in CO2 emissions sufficient to outweigh potential increases in N2O emissions associated with higher soil moisture and less aeration.31

New traits in development offer the promise of further improvements in the GHG profile of crop production. These include both nitrogen use efficiency traits, which could reduce N2O emissions, and drought tolerance traits, which could reduce crop irrigation requirements, thereby resulting in lower use of fuel or electricity to pump groundwater. Reducing the nutrient and water requirements of crops would also have clear sustainability advantages beyond the GHG reductions, especially in areas where access to such inputs is limited (as in sub-Saharan Africa).

The Panel also found that today’s advanced breeding techniques are continuously adapting the germplasm of today’s crops to ongoing climate change by testing them in a range of higher stress environments around the world. Assuming the rate of warming continues to be fairly gradual, this would suggest that advanced breeding techniques will continue to be able to keep pace, at least through the middle of the twenty-first century. As mentioned previously, current modeling suggests that conditions by that time may begin to become harmful to crop productivity, making it that much more critical to utilize all available technology to meet the world’s growing food needs.

In closing this discussion on the adaptation and mitigation possible through the use of advanced breeding and biotechnology, it is important to highlight the essential role that improved agronomic practices have also played. Today’s higher yields would not have been possible without the use of modern planters, sprayers, harvest equipment, conservation tillage and all of the other tools utilized in precision agriculture.32 As climate change stresses intensify, it will become increasingly critical not only to utilize these improved agronomic practices more fully throughout the developed world but also to adopt the best of these approaches within the developing world as those countries work to boost agricultural productivity through mechanization. Improved systems of production will be needed everywhere crops are grown in order to meet the crop protection challenge posed by climate change, fully utilizing all aspects of modern agriculture: optimized biotech traits, the most advanced germplasm and the best agronomic practices.
4 CONCLUSIONS
The Monsanto Fellows Climate Change Panel found that climate change is already under way, and that rising global temperatures and changing precipitation patterns will increasingly impact agriculture. The changes will be non-uniform and are likely to increase the relative crop productivity advantages already enjoyed throughout much of the Americas and parts of Asia. Severe drought is likely to become a major concern in many important regions, especially those with Mediterranean (already semi-arid) climates.

In spite of these stresses and the enormity of the future challenge, the Panel found that today’s agricultural production systems are secure and sufficient to meet the forecast pace of climate change, at least through mid-century. Beyond that time, modeling suggests that crop productivity in all regions could begin to be harmed by the higher temperatures predicted for that period, unless successful GHG mitigation measures are implemented soon. By boosting yields and improving the overall sustainability profile of cropping systems, the use of modern agricultural technology has already made tremendous contributions to help reduce the overall carbon footprint of agriculture. However, there is enormous untapped potential to make further progress in this area, limited primarily by unfavorable policy toward some of those technologies, especially biotechnology. Thus, there is a pressing challenge for all of those engaged in production agriculture to educate others on how modern agricultural technology and new practices will be needed to help adapt to ongoing climate change, and to help mitigate its overall impact.

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