Risk & Sustainable Management Group

Climate Change Working Paper: C05#1

Counting the cost of climate change at an agricultural level

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THE UNIVERSITY
OF QUEENSLAND
AUSTRALIA

This version: Oct 2, 2005

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Abstract

The effects of global climate change on agriculture will be diverse and complex. Some important qualitative conclusions emerge from the literature. First, it is important to focus on the rate at which climate changes and the capacity of farmers to adjust, rather than on absolute changes in temperature. Second, given that significant warming is inevitable, it is important to focus on the marginal effects of feasible changes in the rate of warming, rather than on the aggregate rate of warming. With a convex damage function, the expected marginal cost of warming may be large even when aggregate damage, given the expected rate of warming, is close to zero. Third, uncertainty is crucial and remains poorly understood. In particular, modelling of low-probability catastrophic outcomes remains very limited. Finally, it seems likely that global climate change will enhance extremes of all kinds.

Counting the cost of climate change at an agricultural level

The problem of global climate change has, arguably, been analysed more intensively than any other environmental problem that humanity has faced. The analysis undertaken by climate scientists and summarised in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007a,b,c) leaves little doubt that human action is causing changes in the global climate, and that these changes will continue through the 21st century.

The extent and pace of these changes remains uncertain. There is considerable uncertainty about the future course of emissions of carbon dioxide (CO_2) and other human activities that affect climate, collectively referred to as anthropogenic forcings. There is also considerable uncertainty as regards the sensitivity of the global climate system to changes in forcings.

Analysis of the impact of climate change on agriculture raises yet more complexities. The effects of changes in temperature and climate will vary across different regions, so that climate change will be beneficial in some areas and harmful in others. It is necessary to take account of adaptation to climate change, and therefore to take account of both the pace of change and the impact of uncertainty on human behaviour. Finally, to reach an economic evaluation of the impact of climate change, it is necessary to aggregate changes taking place in different parts of the world, at different times ranging from the present to at least the middle of this century, and affecting different people, some of them not yet born.

This is a complex and challenging task. Nevertheless, in formulating a policy response to climate change, and determining the appropriate roles of mitigation and adaptation, this task must be undertaken. Although the literature on climate change and its effects on agriculture is too vast for a comprehensive summary, this paper will offer a survey of some of the key issues, and of the contributions of economists to analysis of those issues.

The paper is organized as follows. Section 1 is a discussion of projections of climate change, comparing 'business as usual' projections with the case where

action is taken to stabilise global CO_2 concentrations by around 2050.

In Section 2, projections of the impact of climate change on agricultural production are described. In addition to global warming, the effects of changes in rainfall, and of increased atmospheric concentrations of CO_2 are discussed.

Section 3 deals with Eeconomic evaluation of the impact of climate change on the agricultural sector. Issues addressed in this section include the choice of baseline, the effects of uncertainty, and the appropriate way to model adaptation in estimates of the likely effect of climate change.

In Section 4, the possible role of agriculture in mitigating climate change is discussed. Issues examined include biofuels, the role of the agricultural sector in absorbing CO_2 emissions, and mitigation of agricultural emissions of methane.

Finally, some concluding comments are offered.

1. Projections of climate change

In its Fourth Assessement Report, the IPCC (2007a,b,c) summarises a wide range of projections of climate change, encompassing different climatic variables, time and spatial scales, models and scenarios. Most attention is focused on projections of changes in global mean temperatures. However, analysis of the impact of climate change on agriculture requires consideration of regionally-specific changes in a range of variables including temperature, rainfall and the effects of CO_2 concentrations on crop growth.

Because the global climate adjusts to changes in greenhouse gas concentrations with a lag, some warming (about 0.6 degrees C by 2100 relative to 1980–90) is inevitable as a result of emissions that have already taken place. Even with aggressive strategies to stabilise atmospheric CO_2 concentrations at levels between 400 and 500 parts per million (ppm), it seems likely that warming over the next century will be around 2 degrees relative to 1980–90 (with a standard deviation around 1 degree).

Thus, for the purposes of policy analysis, the relevant baseline is expected warming of 2±1 degrees C under a stabilisation strategy, rather than, as in many assessments, the outcome in the absence of global warming.

The outcome under stabilisation may be compared with 'business as usual' projections, in which there is no policy response to climate change, and with a variety of mitigation strategies. The IPCC (2007a) presents a range of 'business as usual' projections, in which estimates of warming over the period to 2100 range from 2 degrees C to 6.4 degrees C. Thus, under business as usual both the expected increase in temperature and the standard deviation of change are higher.

As will be argued below, the rate of change of warming (conventionally expressed in degrees of change per decade) is at least as important as the change in temperature levels at equilibrium or over a century. Recent observed warming has been at a rate of around 0.2 degrees per decade (Hansen et al. 2006). Business as usual projections imply an increase in the rate of warming over coming decades.

Water

In addition to raising average global temperatures, climate change will affect the global water cycle. Higher global temperatures imply higher rates of evaporation, and higher atmospheric concentrations of water vapor. Since water vapor is a greenhouse gas, this increase in concentration is an important feedback effect, amplifying the initial impact on temperature of higher concentrations of CO_2.

Globally, mean precipitation (rainfall and snowfall) is expected to increase due to climate change. However, this change will not be uniform. IPCC (2007b, p. 181)

> Current climate models tend to project increasing precipitation at high latitudes and in the tropics (e.g., the south-east monsoon region and over the tropical Pacific) and decreasing precipitation in the sub-tropics.

Finally, climate change is likely to increase the frequency of extreme weather events, including cyclones and severe droughts.

In summary, climate change will increase average flows of water but the most important effect will be to increase the variability of flows over both space and time. Areas that are already wet are likely to become wetter, while those that are already dry will in many cases become drier. The increase in average precipitation will be caused mainly by more frequent events involving very high rainfall, such as monsoon rain associated with tropical cyclones. Meanwhile droughts are also likely to increase.

In Australia, for example, inflows to the Murray–Darling Basin, the location of most irrigated agriculture, are projected to decline. Severe droughts, attributed in part to climate change, have already occurred in recent years. On the other hand, areas in the wet tropics are expected to receive higher levels of rainfall (Jones et al. 2007).

2. Climate change and agricultural production

Climate change may be expected to have a range of effects on crop yields, and on the productivity of forest and pasture species. Some effects, such as increased evapotranspiration will generally be negative, while others, such as CO_2 fertilisation will generally be positive. Changes in rainfall and temperature will be beneficial in some locations and for some crops, and harmful in other cases. In general, it appears that for modest increases in temperature and CO_2 concentrations (CO_2 concentrations up to 550 ppm and temperature changes of 1 to 2 degrees C) beneficial effects will predominate. For higher levels of CO_2, the benefits of CO_2 fertilization will reach saturation. and for temperature increases above 3 degrees C negative effects will predominate.

Direct effects of higher temperatures

IPCC (2007b) summarises a large number of studies of the impact of higher temperatures on crop yields. Unsurprisingly, for small changes in

temperature, these effects are generally unfavorable at low (tropical) latitudes and favorable at high latitudes. The most important beneficial effects are on the growth of wheat in Canada, Northern Europe and Russia (Smit, Ludlow and Brklacich 1988; Parry, Rosenzweig, and Livermore 2005).

The aggregate effects of modest warming are likely to be small, but the losers are likely to be concentrated in poor countries, particularly in the tropics. As Parry, Rosenzweig, and Livermore (2005) conclude

> while one may be reasonably optimistic about the prospects of adapting the agricultural production system to the early stages of global warming, the distribution of the vulnerability among the regions and people are likely to be uneven.

Because losses are concentrated in developing countries, global warming implies a significant increase in the number of people at risk of hunger, although this risk may be mitigated by expansion of trade.

For warming of more than 2 degrees C, the marginal effects of additional warming are unambigously negative. Studies of wheat yields in mid-to-high latitudes, summarised in Figure 5.2b(c) of IPCC (2007b) show that the benefits of warming reach their maximum value for warming of 2 degrees C, while at lower latitudes, and for rice, the effects of warming greater than 2 degrees are clearly negative. For temperature increases of more than 3 degrees C, average impacts are stressful to all crops assessed and to all regions

Rainfall and evapotranspiration

Water, derived from natural precipitation, from irrigation or from groundwater, is a crucial input to agricultural production. IPCC (2007b, Chapter 3, p175) concludes, with high confidence, that the negative effects of climate change on freshwater systems outweigh its benefits. This negative finding arises from a number of features of projected climate change.

First, climate change is likely to exacerbate the spatial variation of precipitation, with average precipitation increasing in high rainfall areas such as

the wet tropics, and decreasing in most arid and semi-arid areas (Milly, Dunne and Vecchia 2005).

Second, climate change is likely to increase the variability and uncertainty of precipitation (Trenberth et al 2003). The frequency and geographical extent of severe droughts are likely to increase by multiples ranging from two to ten, depending on the measure (Burke, Brown, and Nikolaos 2006) and high intensity rainfall events are likely to become more prevalent (IPCC 2007a).

Third, higher temperatures will lead to higher rates of evaporation and evapotranspiration, and therefore to increased demand for water for given levels of crop production (Döll 2002). Water stress (the ratio of irrigation withdrawals to renewable water resources) is likely to increase in many parts of the world. Water stress may be reduced in some areas, but the benefits of increased precipitation will be offset by the fact that the increases in runoff generally occur during high flow (wet) seasons, and may not alleviate dry season problems if this extra water is not stored (Arnell 2004).

CO_2 fertilisation

Increases in atmospheric concentrations of CO_2 will, other things being equal, enhance plant growth through a range of effects including stomatal conductance and transpiration, improved water-use efficiency, higher rates of photosynthesis, and increased light-use efficiency (Drake, Gonzalez-Meler, and Long 1997).

Ainsworth and Long (2005) summarise a range of studies under conditions designed to simulate natural exposure to higher CO_2 levels. They find effects that are significant positive, but smaller than those derived from earlier experiments undertaken in controlled enclosures. The effects are greatest for trees, significant for C_3 crops including rice and wheat and least for C_4 species,

such as sugar and corn. [1] Average crop yield increases of 17 per cent were obtained for studies examining an increase in CO_2 concentrations from an initial level of around 350 ppm to elevated levels ranging from 475 to 600 ppm, with a median value of 550ppm.

The estimated relationships are curvilinear, implying that only modest increases in yields can be expected from increases in CO_2 beyond 550 ppm. For example, in open top chambers, the grain yield of wheat increased 27 per cent on when CO_2 concentrations were increased from 359 to 534 ppm, but only a further 3 per cent increase was observed when concentrations were further increased from 534 to 649 ppm (Fangmeier et al., 1996).

Temperature and precipitation changes associated with climate change will modify, and often limit, direct CO_2 effects on plants. For instance, high temperatures during flowering may lower CO_2 effects by reducing grain number, size and quality. Some of these effects may be overcome by appropriate selection of cultivars (Baker, 2004).

Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand. Xiao et al. (2005) found that, for given availability of water, the yield of wheat declined for temperature increases greater than 1.5 degrees C. Additional irrigation was needed to counterbalance these negative effects.

3. Economic evaluation of the impact of climate change on the agricultural sector

Before attempting an evaluation of the impact of climate change, it is necessary to clarify the alternatives to be evaluated and the basis of evaluation.

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[1] The distinction between C3 and C4 species refers to differs in the photosynthetic reaction. C3 plants form a pair of three carbon-atom molecules. C4 plants, on the other hand, initially form four carbon-atom molecules.

Baseline for analysis

In discussions of the impact of climate change, it is common to compare one or more 'business as usual' projections with a baseline counterfactual in which the current climate remains unchanged. Since some climate change would be inevitable even if emissions of greenhouse gases were halted immediately, such a comparison is of little value as a guide to policy.

A more appropriate basis for analysis is a comparison between 'business as usual' and a stabilisation option, in which policy responses ensure that the atmospheric concentration of greenhouse gases is stabilised at a level consistent with moderate eventual climate change. Although the latter definition is somewhat vague, a target of 550 ppm has been proposed on a number of occasions (Stern 2007). For typical estimates of climate sensitivity, this target implies temperature change of around 0.2 degrees per decade over the next century, with stabilization thereafter.

The treatment of adjustment

In early assessments of the impact of climate change on agriculture Cline (1992) and Rozenzweig and Parry (1994) used a production-function approach, in which climate was viewed as an exogenous input to agricultural production. Taking other inputs and the allocation of land to crops as given, estimates of the effects of climate change were based on the change in yields projected as a result of changes in temperature, rainfall and CO_2 concentrations. The general finding was that yields were likely to decline at low latitudes (tropical and subtropical regions) and to increase at high latitudes where cold weather is an important limiting factor in agriculture. In most studies taking this approach it was concluded that the net impact of climate change would be moderate, but negative.

The production function approach took no account of the potential for adjustment, and was criticised by Mendelsohn, Nordhaus and Shaw (1994) as representing a 'dumb-farmer scenario'. Indeed, it may be argued that, except in regions where heat or cold is a limiting factor, the production-function approach

approach is likely to generate negative estimates of the impact of climate change in either direction. This is because existing agricultural activities in any given area have been selected to maximise returns in the current climate and are likely to produce lower returns if climate changes.

Mendelsohn, Nordhaus and Shaw (1994) proposed, as an alternative, a 'Ricardian' approach based on treating climate as one of the characteristics affecting the valuation of agricultural land. The effects of a change in climate in any given area, considered as a capitalised flow, may then be estimated by the change in the predicted value of land. This approach produces zero or moderately positive estimates of the impact of climate change on US agriculture.

Quiggin and Horowitz (1999) reject both the production function function approach and the Ricardian approach, arguing that comparative static equilibrium analyses are not relevant to the evaluation of a dynamic process of climate change. Quiggin and Horowitz conclude that the main costs of climate change will be costs of adjustment. Stocks of both natural capital and long-lived physical capital will be reduced in value as a result of climate change.

An analysis focused on adjustment costs is appropriate both in relation to human activity and to the effects of climate change on natural ecosystems. As temperatures increase, climate in any given location becomes more like that previously observed at a point closer to the equator. Conversely, biozones suitable for particular ecological or agricultural systems tend to migrate away from the equator and towards the pole. Hansen et al. (2006) estimate that the average isotherm migration rate of 40 km per decade in the Northern Hemisphere for 1975–2005 yields an average, exceeding known paleoclimate rates of change.

Such a rapid rate of adjustment imposes significant stress on natural ecosystems. As Hansen et al (2006) observe:

> Some species are less mobile than others, and ecosystems involve interactions among species, so such rates of climate change, along with habitat loss and fragmentation, new invasive species, and other stresses are expected to have severe impact on species survival

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Parmesan and Yohe (2003) found that 1,700 plant, animal and insect species moved poleward at an average rate of about 6.1 km per decade in the last half of the 20th century, a rate considerably less rapid than that required to match the change in climate.

Human activities are more adaptable than natural ecosystems. Nevertheless, adjusting to a shift of 40 km per decade will involve substantial continuing costs. For example, Quiggin and Horowitz (1999) note that the optimal service radius for grain handling facilities in Australia is around 25 km. Hence a facility initially located near the margin of grain production might be outside the zone or production within a decade of construction.

Uncertainty and variability

The treatment of uncertainty and variability is crucial in evaluating the effects of climate change. Most obviously, the discussion above shows that damage to agriculture is a convex function of the rate of warming. At rates of warming below 0.2 degrees per decade, aggregate damage over the period to 2100 is likely to be small, with gains offsetting losses. At higher rates of warming, damages increase and benefits decline so that aggregate damages grow rapidly.

Convexity implies, by Jensen's inequality, that the expected cost of warming is greater than the cost of warming at the expected rate. More importantly for policy purposes, the expected marginal cost of additional emissions is greater than the marginal cost of emissions in the case where the rate of warming is equal to its expected value. Most of the expected loss to agriculture from warming arises in the right-hand tail of the distribution. The importance of considering the tails of the distribution has been stressed by Weitzman (2007).

Uncertainty also affects estimates of the cost of adaptation. Most studies assume adaptation to a known change in climate. In reality, however, farmers must adjust to changing climate without being able to make a reliable distinction

between permanent changes associated with global climate change and temporary local fluctuations. Thus the cost of adaptation may be underestimated and the benefits overestimated.

In general, then, uncertainty about climate change raises the likely cost of change. However, arguments based on option value may support delaying costly and irreversible mitigation actions. The argument, put forward by Nordhaus and Boyer (2000) is that, if such actions are delayed, more information about the likely cost of warming will be obtained. If the rate turns out to be slow, and the mitigation actions are unnecessary, the option has yielded a positive return. This option value must be set against the likelihood that, the more rapid the rate at which mitigation must be undertaken, the greater the cost.

Aggregate economic impact

In assessing the aggregate impact of climate change on agriculture it is necessary to take account of the interaction between production systems and markets. In general, demand for agricultural products is inelastic. Conversely, the elasticity of equilibrium prices with respect to exogenous shifts in aggregate supply is typically greater than 1. That is, a reduction in global agricultural output caused by an exogenous shock such as climate change will increase the aggregate revenue of the agricultural sector.

This general result must be qualified, however, by the observation that global markets are not frictionless. If, as most projections suggest, moderate warming will increase output in temperate-zone developed countries while reducing output in (mainly tropical) developing countries, the net impact is ambiguous.

A number of studies have attempted to estimate the impact of global warming on agricultural output and on aggregate returns to the agricultural sector. Fischer et al. (2002) estimate that, under a 'business as usual' projection, global output of cereals will decline by between 0.7 per cent and 2.0 per cent, relative to the case of no change in climate, while the estimated change in agricultural GDP ranges from -1.5 per cent to +2.6 per cent.

As noted above, comparisons in which the baseline simulation involves no climate change are not particularly useful. It is more appropriate to compare feasible outcomes under stabilisation with those under 'business as usual'. Darwin (1999) estimates that world welfare may increase if the average surface land temperature does not increase by more than 1.0 or 2.0 C, as is likely under stabilisation If the average surface land temperature increases by 3.0 C or more, however, world welfare may decline. Similarly, Parry, Rosenzweig, and Livermore (2005) find that stabilisation at 550 ppm avoids most of the risk of increased global hunger associated with a 'business as usual' projection.

4. Agriculture and mitigation

Agriculture is likely to play an important role in mitigating emissions of greenhouse gases. Cole et al (1997) estimate that the agricultural sector accounts for between one fifth and one third of anthropogenic climate change, and that changes in agricultural practices could reduce anthropogenic impact by an amount equivalent to between 1.15 and 3.3 Gt of carbon equivalents per year. Of the total potential reduction, approximately 32 per cent could result from reduction in CO_2 emissions, 42 per cent of carbon offsets by biofuel production on 15 per cent of existing croplands, 16 per cent from reduced methane emissions and 10 per cent from reduced emissions of nitrous oxide.

Conversely, efforts to mitigate global warming, by reducing emissions of CO_2 and other greenhouse gases, or through the expansion of offsetting sinks, may have a significant effect on agricultural production

Biofuels

Policies aimed at reducing CO_2 emissions are likely to encourage increased use of fuels derived from agricultural sources, collectively referred to as biofuels, either through direct policy mandates (such as that embodied in the US *Energy Policy Act* 2005) or through the market incentives associated with carbon taxes or cap-and-trade systems of emissions permits. The most important

single instance is likely to be the use of ethanol, derived either from food crops or from energy crops such as switchgrass, as a substitute for gasoline.

In 2004, around 4 billion gallons of ethanol (16 billion litres), mainly derived from corn and sorghum, was produced in the United States, accounting for around 11.3 per cent of US corn output and 11.7 per cent of sorghum output and replacing around 3 per cent of US gasoline consumption. These proportions are expected to grow steadily (Eidman 2006). Other possible biofuels include biodiesel, derived from soybean oil, bagasse and other crop residues used as fuel in electricity generation and methane derived from manure (Gallagher 2006).

Eidman claims that, even in the absence of continued subsidies or carbon taxes, bio-ethanol production will be a viable competitor at plausible prices for natural gas and corn (the inputs) and gasoline (the competing option). By contrast, Pimentel and Patzek (2005) claim that producing ethanol uses more energy than the resulting fuel generates. Assuming that all energy inputs must be purchased and that the value of energy inputs is proportional to their energy content, one obvious implication of this claim is that subsidy-free ethanol production can never be economically viable.

Assuming that biofuels are economically competitive with fuels derived from fossil sources, the expansion projected by Eidman (2006) and others would imply the creation of a substantial new source of demand for agricultural output, in addition to existing demands for food. If existing processes were used to replace 20 per cent of fuel consumption, the input required would be equal to more than 50 per cent of the current US output of corn and sorghum.

Such an increased demand would have to be met either by an expansion of supply or by reductions in food consumption. In either case, the increase in demand implies an increase in prices, which will be beneficial to agricultural producers and harmful to food consumers.

The feasibility of large-scale expansion of biofuel production depends on complex interactions of markets for carbon credits, biofuels and, potentially, emissions credits for mitigation. Schneider and McCarl (2004) suggest that,

relative to a baseline estimate of potential mitigation, alternative economic assumptions could reduc3e the estimated by as much as 55 per cent or increase it by as much as 85 per cent. That is, the minimum and maximum estimates differ by a factor of four.

Land clearing and tree planting

The clearing of forested land for agriculture, mainly in the tropics, has been a significant contributor to net emissions of CO_2, partly offset by regrowth in boreal forests in Europe and North America. Conversely, expansion of the area of forested land is currently one of the most cost-effective methods of offsetting CO_2 emissions (IPCC 2007c), and is likely to play an important role in the future.

The treatment of land use in international agreements on climate change has been controversial. Under the Kyoto Protocol, Australia which had adopted policies restricting land clearance on environmental grounds, was permitted to count the estimated reductions in emissions, relative to the 1990 level, towards its emissions target. However, the Australian government subsequently decided not to ratify the Protocol.

Discussion of the potential role of forestry in mitigating emissions of CO_2 is beyond the scope of the present paper. However, it is important to note that forestry competes with agriculture for land, and that a substantial increase in the area allocated to forestry will, other things being equal, increase the price of agricultural land. These effects must be considered in combination with the possible effects of increasing agricultural production of biofuels.

Soil carbon

Poor cultivation practices generate large, and potentially avoidable, losses of carbon from the soil. Between 30 billion and 55 billion tonnes of organic carbon have been lost from soil as a result of cultivation, compared to a current stock of 167 billion tonnes. Management practices to increase soil carbon stocks include reduced tillage, crop residue return, perennial crops (including

agroforestry), and reduced bare fallow frequency. Cole at al (1997) estimate that total potential carbon sequestration of 40 billion tonnes over a fifty year period is equivalent to 7 per cent of projected fossil fuel carbon emissions over the same period.

Agricultural emissions of methane

In addition to its role in the carbon cycle, agriculture is a major source of emissions of methane. The largest agricultural sources of methane are ruminant animals and rice production. Emissions of methane from rice production arise primarily from the use of flood irrigation (Yan, Ohara and Akimoto 2003).

As Cole et al (1997) observe, methane lost from anaerobic digestion of livestock manure constitutes a wasted energy source, which implies that reductions in emissions can, potentially at least, yield net benefits. Emissions can be reduced either by changes in livestock diet, so that nutrients promote additional growth instead of being excreted, or by using manure as an energy source. There are also a range of options for reducing methane emissions from rice production.

To assess the role of such measures in a mitigation strategy, it is necessary to compare the benefits of reducing emissions of different greenhouse gases. This is commonly done using measurements of global warming potentials, which use the accumulated radiative forcing of each gas by a set time horizon to establish emission equivalence.

However, as Manne and Richels (2001) point out, because the atmospheric lifetime of gases differ, such an approach depends critically on the arbitrary choice of time horizon. In particular, because methane is relatively shortlived (an atmospheric lifetime of 10 to 15 years, compared to an effectively infinite lifetime for CO_2), the longer the time horizon the greater the implied warming potential of methane. The problem can be overcome, to a significant extent, by focusing on rates of change of temperature, rather than on the temperature change that is predicted to occur by an arbitrary target date.

Concluding comments

The effects of global climate change on agriculture will be diverse and complex. Much remains to be done before reliable estimates of the net impact on the value of global agricultural production, and its distribution, can be obtained. Nevertheless, some important qualitative conclusions emerge from the literature.

First, it is important to focus on the rate at which climate changes and the capacity of farmers to adjust, rather than on absolute changes in temperature. As long as the rate of global warming remains comparable with that of the recent past, that is, 0.1 and 0.2 degrees per decade, it seems likely that the aggregate impact of climate change on global agricultural production will be small. Adverse impacts will be mitigated by adjustment, and offset by beneficial effects such as CO_2 fertilisation and longer growing seasons in high latitudes.

Second, given that significant warming is inevitable, it is important to focus on the marginal effects of feasible changes in the rate of warming, rather than on the aggregate rate of warming. With a convex damage function, the expected marginal cost of warming may be large even when aggregate damage, given the expected rate of warming, is close to zero.

Third, uncertainty is crucial and remains poorly understood. In particular, modelling of low-probability catastrophic outcomes remains very limited.

Finally, it seems likely that global climate change will enhance extremes of all kinds. Dry areas will generally become drier, and wet areas wetter. Farmers in poor countries will lose, while those in rich countries will, for the most part, be little affected. So, although the phenomenon is global, analysis of the effects of climate change must be undertaken at the local level.

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