# Adapting agriculture to climate change

**S. Mark Howden*[†], Jean-François Soussana[‡], Francesco N. Tubiello[§][¶], Netra Chhetri[‖], Michael Dunlop*, and Holger Meinke****

*Commonwealth Scientific and Industrial Research Organization, Sustainable Ecosystems, GPO Box 284, Canberra ACT 2601, Australia; [‡]Institut National de la Recherche Agronomique, UR874, 63100 Clermont-Ferrand, France; [§]Goddard Institute for Space Studies, Columbia University, 2880 Broadway, New York, NY 10025; [¶]International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria; [‖]Consortium for Science, Policy and Outcomes, Arizona State University, P.O. Box 874401, Tempe, AZ 85287-4401; and **Department of Plant Sciences, Wageningen University, P.O. Box 430, NL 6700 AK, Wageningen, The Netherlands

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**The strong trends in climate change already evident, the likelihood of further changes occurring, and the increasing scale of potential climate impacts give urgency to addressing agricultural adaptation more coherently. There are many potential adaptation options available for marginal change of existing agricultural systems, often variations of existing climate risk management. We show that implementation of these options is likely to have substantial benefits under moderate climate change for some cropping systems. However, there are limits to their effectiveness under more severe climate changes. Hence, more systemic changes in resource allocation need to be considered, such as targeted diversification of production systems and livelihoods. We argue that achieving increased adaptation action will necessitate integration of climate change-related issues with other risk factors, such as climate variability and market risk, and with other policy domains, such as sustainable development. Dealing with the many barriers to effective adaptation will require a comprehensive and dynamic policy approach covering a range of scales and issues, for example, from the understanding by farmers of change in risk profiles to the establishment of efficient markets that facilitate response strategies. Science, too, has to adapt. Multidisciplinary problems require multidisciplinary solutions, i.e., a focus on integrated rather than disciplinary science and a strengthening of the interface with decision makers. A crucial component of this approach is the implementation of adaptation assessment frameworks that are relevant, robust, and easily operated by all stakeholders, practitioners, policymakers, and scientists.**

adaptation | greenhouse | cropping | grazing | forestry

Agriculture is the major land use across the globe. Currently ≈1.2–1.5 billion hectares are under crops, with another 3.5 billion hectares being grazed. Another 4 billion hectares of forest are used by humans to differing degrees, whereas, away from land, global fisheries are used very intensively, often beyond capacity (1). To meet projected growth in human population and per capita food demand, historical increases in agricultural production will have to continue, eventually doubling current production (e.g., ref. 2). Agriculture is also a major economic, social, and cultural activity, and it provides a wide range of ecosystem services. Importantly, agriculture in its many different forms and locations remains highly sensitive to climate variations, the dominant source of the overall interannual variability of production in many regions and a continuing source of disruption to ecosystem services. For example, the El Niño Southern Oscillation phenomenon, with its associated cycles of droughts and flooding events, explains between 15% and 35% of global yield variation in wheat, oilseeds, and coarse grains (3). This existing sensitivity explains why a changing climate will have subsequent impacts on agriculture. Hence, it has become critical to identify and evaluate options for adapting to climate change in coming decades. Here we use the term "adaptation" to include the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change, as well as responses in the decision environment, such as changes in social and institutional structures or altered technical options that can affect the potential or capacity for these actions to be realized (4).

We argue there is a strong rationale for an increasing focus on adaptation of agriculture to climate change. This need arises from several considerations:

1. Past emissions of greenhouse gases have already committed the globe to further warming of ≈0.1°C per decade for several decades (5), making some level of impact, and necessary adaptation responses, already unavoidable.
2. The emissions of the major greenhouse gases are continuing to increase (6), with the resultant changes in atmospheric $CO_2$ concentration, global temperature, and sea level observed today already at the high end of those implied by the scenarios considered by the Intergovernmental Panel on Climate Change (IPCC) (7). Furthermore, some climate change impacts are happening faster than previously considered likely (5). If these trends continue, then more proactive and rapid adaptation will be needed.
3. There is currently a lack of progress in developing global emission-reduction agreements beyond the Kyoto Protocol, leading to concerns about the level of future emissions and hence climate changes and associated impacts.
4. The high end of the scenario range for climate change has increased over time (5, 8, 9), and these potentially higher global temperatures may have nonlinear and increasingly negative impacts on existing agricultural activities (1).
5. Climate changes may also provide opportunities for agricultural investment, rewarding early action taken to capitalize on these options (10).

There is an immense diversity of agricultural practices because of the range of climate and other environmental variables; cultural, institutional, and economic factors; and their interactions. This means there is a correspondingly large array of possible adaptation options. The objectives of this paper are first to outline these options for cropping and livestock systems, forestry, and fisheries, using the literature on crop yields as an example to assess the benefits of adaptation; and second, to suggest some general pathways that can help move from technical assessment of adaptation options to more practical action. Accordingly, we identify some preconditions for more effective uptake of adaptations; develop an adaptation framework to engage all decision makers (farmers, agribusiness, and policymakers) that builds on the existing substantial knowledge of

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Abbreviation: IPCC, Intergovernmental Panel on Climate Change.

[†] To whom correspondence should be addressed. E-mail: mark.howden@csiro.au.

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agricultural systems; and outline how science itself needs to adapt to remain relevant in this issue.

## Results

**Adaptation: What Is in It for Us?** The purpose of undertaking agricultural adaptation is to effectively manage potential climate risks over the coming decades as climate changes. Adaptation research undertaken now can help inform decisions by farmers, agrobusiness, and policy makers with implications over a range of timeframes from short-term tactical to long-term strategic (1). However, it is particularly important to align the scales (spatial, temporal, and sectoral) and reliability of the information with the scale and nature of the decision. For example, short-term climate adaptation by farmers may be accomplished by taking into account local climate trends if there is a strong correspondence between these trends and projected climate changes, or it may be via climate forecasting at scales from daily to interannual. However, farmers may find limited utility in long-term projections of climate, given the high uncertainties at the finer spatial and temporal scales at which their decisions are made (11). In contrast, the general trends at larger time and spatial scales able to be more reliably projected with current climate models may be quite useful for input into policy and investment analyses, provided potentially critical factors are incorporated such as changes in climate extremes (12). A significant benefit from adaptation research may be to understand how short-term response strategies may link to long-term options to ensure that, at a minimum, management and/or policy decisions implemented over the next one to three decades do not undermine the ability to cope with potentially larger impacts later in the century. In the sections below, we try to identify other key benefits from an increased focus on climate change adaptation.

**Keeping Policy Relevant.** At the current relatively early stage of the debate, it is understandable that climate change adaptation is largely being dealt with in isolation from other issues (although see ref. 13). However, over time, this situation needs to evolve so that climate change is linked with a much broader set of policies. In particular, there is a need for linkage with existing policies on climate risk such as those on drought or structural adjustment, which otherwise may become poorly targeted. Climate change will require these policies to become more dynamic, to cope with the high level of uncertainty in the timing and magnitude of potential climate changes and the rapidly evolving knowledge base. Furthermore, climate change adaptation policies will interact with, depend on, or perhaps even be just a subset of policies on sustainable development and natural resource management, such as those necessary to regulate genetically modified organisms, protect human and animal health, and foster governance and political rights, among many others. This process is often referred to as the "mainstreaming" of climate change adaptation into policies intended to enhance broad resilience to risk or to promote sustainable development (4, 14). The critical issues of how climate change and adaptation may affect food security and trade and the risk of malnourishment are dealt with in a companion paper (13).

**Informing Mitigation Targets.** Importantly, identifying and evaluating possible adaptation strategies are of fundamental value to determine a set of dynamic climate policy options that lead to the "avoidance of dangerous anthropogenic interference" component (Article 2) of the United Nations Framework Convention on Climate Change (65). This is because maximizing societal welfare under future climate risk will likely involve a mix of both mitigation and adaptation; the percentage contribution of each strategy will depend on monetary and nonmonetary cost/benefit analyses. For example, we would expect the size and cost of the adaptation task to be lower if there is effective, but perhaps costly, mitigation and higher if there is no mitigation. Similarly, the benefits of adaptation will be a function of the nature of climate change and the scale of impact. Consequently, inadequate consideration of adaptation options could result in the vulnerability to climate change being significantly overstated, giving rise to more severe mitigation targets. Additionally, mitigation policies can affect the range of adaptation options that practitioners have at their disposal (e.g., subsidizing biofuel production strongly influences the market for agricultural produce). Another perspective is that implementing effective adaptation can "buy time" until an effective mitigation response can be mounted. Hence adaptation analyses may be used to inform both the magnitude and timing of mitigation. Achievement of this complex task of effectively integrating mitigation impacts and adaptation to inform public policy development remains a significant challenge for the scientific community, although some studies are now emerging (15). This interaction of science and policy needs to evolve as the scientific knowledge base changes and may also focus attention on the importance of integrative rather than disciplinary science within the science–policy interface (16).

**Informing Investment.** Adaptation analyses can also help inform governments and industry of the investment or disinvestment decisions they need to make now or in the near future in relation to climate-sensitive aspects of their portfolios (e.g., ref. 1). In particular, this applies to long-term investments such as plant and animal breeding programs; building capacity in the scientific and user communities; developing quarantine systems; establishing perennial crops and forest plantations; purchasing or selling land; or building (or decommissioning) major infrastructure such as dams and water distribution systems, flood mitigation works, and storage and transport facilities. Climate risks are, of course, only one consideration within more complex decision-making processes (10). For example, in Western Australia, increased risk of drought under global warming was integrated with projections of population growth, economic development, and social norms in relation to water use, resulting in the construction of a major new dam and development of other new water sources (17).

**Rewarding Early Adopters.** Participatory research into climate change adaptation options can help agricultural decision makers realize that acting on the existing trends in climate now is likely to be to their advantage (e.g., ref. 18). For example, in northeast Australia, crop management that has continuously adjusted to the progressive reduction in frost risk experienced over the past several decades can almost double gross margins when compared with management based on either the long-term risk or management that does not consider frost risk (19). Participatory engagement with decision makers, by bringing their practical knowledge into the assessment, can also identify a more comprehensive range of adaptations than are typically explored by scientists, as well as being able to assess the practicality of options and contribute to more realistic assessment of the costs and benefits involved in management or policy change (19).

**Focusing on Climate Risk Management.** Finally, it should be recognized that "adaptation" is an ongoing process that is part of good risk management, whereby drivers of risk are identified, and their likely impacts on systems under alternative management are assessed. In this respect, adaptation to climate change is similar to adaptation to climate variability, changes in market forces (cost/price ratios, consumer demands, etc.), or institutional or other factors. Differences may be in the rate of realized climate change, compared with how fast we are able to implement needed solutions. Isolating climate change from other drivers of risk may be helpful, especially during the initial stages of assessment when awareness of the relative importance of this risk factor is still low. Operationally, however, translating adaptation options into adaptation actions requires consideration of a more comprehensive risk management framework. This would allow exploration of quantified scenarios dealing with all of the key sources of risk, providing more effective

**Table 1. Mean benefit of adapting wheat cropping systems to impact of temperature and rainfall changes calculated as the difference between percent yield changes with and without adaptation**

| | | Temperature change, °C | | |
|---|---|---|---|---|
| Adaptation benefit | Rainfall change | Less than 2°C | 2–4°C | Greater than 4°C |
| Yield change, % | Rainfall increase | 26.9 ± 6.0 | 18.7 ± 4.7 | 17.4 ± 4.0 |
| | Rainfall decrease | 9.0 ± 5.3 | 11.1 ± 2.6 | 15.0 (na) |

Values are means and standard errors [not applicable (na): $n = 1$]. The mean benefit of adapting was not significantly different for temperate and tropical systems (17.9% vs. 18.6%, $P = 0.86$). Data sources are listed in figure 5.2 of Easterling *et al.* (1).

decision making and learning for farmers, policymakers, and researchers: an increase in "climate knowledge" (20).

## Changing Management Unit Decisions

Changes in practices at the management unit level will be a key component in adapting agriculture to climate change (1). Consequently, we outline here a range of such adaptations for cropping, livestock, forestry, and fishery systems. However, adaptations at this level can be strongly influenced by policy decisions to establish or strengthen conditions favorable for effective adaptation activities through investment in new technologies and infrastructure (4), which are dealt with below.

**Cropping Systems.** Many management-level adaptation options are largely extensions or intensifications of existing climate risk management or production enhancement activities in response to a potential change in the climate risk profile (1). For cropping systems, there are many potential ways to alter management to deal with projected climatic and atmospheric changes (including refs. 21–26). These adaptations include:

- Altering inputs such as varieties/species to those with more appropriate thermal time and vernalization requirements and/or with increased resistance to heat shock and drought, altering fertilizer rates to maintain grain or fruit quality consistent with the prevailing climate, altering amounts and timing of irrigation and other water management.
- Wider use of technologies to "harvest" water, conserve soil moisture (e.g., crop residue retention), and use and transport water more effectively where rainfall decreases.
- Managing water to prevent water logging, erosion, and nutrient leaching where rainfall increases.
- Altering the timing or location of cropping activities.
- Diversifying income through altering integration with other farming activities such as livestock raising.
- Improving the effectiveness of pest, disease, and weed management practices through wider use of integrated pest and pathogen management, development, and use of varieties and species resistant to pests and diseases and maintaining or improving quarantine capabilities and monitoring programs.
- Using climate forecasting to reduce production risk.

If widely adopted, these adaptations singly or in combination have substantial potential to offset negative climate change impacts and to take advantage of positive ones. For example, in a modeling study for Modena, Italy (23), simple and feasible adaptations altered significant negative impacts on sorghum (−48% to −58%) to neutral to marginally positive ones (0 to +12%). In that case, the adaptations were to alter varieties and planting times to avoid drought and heat stress during the hotter and drier summer months predicted under climate change. When summarized across many adaptation studies, there is a tendency for most of the benefits of adapting the existing systems to be gained under moderate warming (<2°C) then to level off with increasing temperature changes (Table 1; ref. 27). Additionally, the yield benefits tend to be greater under scenarios of increased than decreased rainfall (Table 1), reflecting that there are many ways of more effectively using more abundant resources, whereas there are fewer and less-effective options for significantly ameliorating risks when conditions become more limiting.

The figures in Table 1 are from a synthesis of climate change impact simulations for the recent Intergovernmental Panel on Climate Change review (1), spanning the major cereal crops wheat, rice, and maize, and representing a wide range of agroclimatic zones and management options. This synthesis indicates that benefits of adaptation vary with crop (wheat vs. rice vs. maize) and with temperature and rainfall changes (Table 1; ref. 1). For wheat, the potential benefits of management adaptations are similar in temperate and tropical systems (17.9% vs. 18.6%; Table 1). The benefits for rice and maize are smaller than for wheat, with a 10% yield benefit when compared with yields when no adaptation is used (1). These improvements to yield translate to damage avoidance of up to 1–2°C in temperate regions and up to 1.5–3°C in tropical regions, potentially delaying negative impacts by up to several decades (1), providing valuable time for mitigation efforts to work.

There are several significant caveats that need to be applied in relation to the above positive results on impacts and adaptation. In particular, the simulation models used in the component studies do not yet adequately represent potential impacts of change in pest and disease effects or air pollution, and there remains uncertainty as to the effectiveness of the representations of $CO_2$ responses (2). Additionally, many of these studies changed neither the variability of the climate nor the frequency of climate extremes, both of which can significantly affect yield (2). There is also often the assumption of full capacity to implement the adaptations, whereas this may not be the case, particularly in regions where subsistence agriculture is predominantly practiced (28). Last, some of the studies were of irrigated production systems where the implications of possible reductions in irrigation water availability are not included (29). Collectively, these factors could reduce the beneficial effects, such as those associated with elevated $CO_2$, and increase the negative effects, such as those from increased temperatures and rainfall reductions. This would reduce the amount of time that adaptation would delay significant negative impacts, i.e., adaptation would "buy less time" than is indicated above. On the other hand, the adaptations assessed were only a small subset of those feasible, usually focusing on marginal change in practices to maintain the existing system such as changing varieties, planting times, and use of conservation tillage. Inclusion of a broader range of adaptations, including more significant and systemic change in resource allocations, would presumably increase the benefits, particularly if those adaptations included alternative land use and livelihood options. For instance, so-called Ricardian studies (30) that implicitly incorporate such adaptation routinely find impacts of climate change that are lower than those assessed using crop models. The balance between these opposing tendencies is currently unclear; more comprehensive analyses to identify the limits of adaptation are warranted.

**Livestock Systems.** Adaptations in field-based livestock include additional care to continuously match stock rates with pasture production, altered rotation of pastures, modification of times of grazing, and timing of reproduction, alteration of forage and animal species/breeds, altered integration within mixed livestock/crop systems including using adapted forage crops, reassessing fertilizer applications, care to ensure adequate water supplies, and use of supplementary feeds and concentrates (31–33). It is important to note, however, that there are often limitations to these adaptations; for example, more heat-tolerant livestock breeds often have lower levels of productivity.

In intensive livestock industries, there may be reduced need for winter housing and for feed concentrates in cold climates, whereas in warmer climates there might be increased need for management and infrastructure to ameliorate heat-stress-related reductions in productivity, fertility, and increased mortality. Furthermore, the capacity to implement infrastructural adaptations could be low in many tropical regions, whereas in the midlatitudes, the risk of reduction in water availability for agriculture (29) may limit adaptations that use water for cooling.

**Forestry.** A large number of adaptation strategies have been suggested for planted forests, including changes in management intensity, hardwood/softwood species mix, timber growth, harvesting patterns within and between regions, rotation periods, salvaging dead timber, shifting to species or areas more productive under the new climatic conditions, landscape planning to minimize fire and insect damage, adjusting to altered wood size and quality, and adjusting fire management systems (34–36). Adaptation strategies to control insect damage can include prescribed burning for reducing forest vulnerability to increased insect outbreaks, nonchemical insect control (e.g., baculoviruses), and adjusting harvesting schedules, so that those stands most vulnerable to insect defoliation would be harvested preferentially. Under moderate climate changes, these proactive measures may potentially reduce the negative economic consequences of climate change (37). However, as with other primary industry sectors, there is likely to be a gap between potential adaptations and realized actions. For example, large areas of forests, especially in developing countries, receive minimal direct human management (38), limiting adaptation opportunities. Even in more intensively managed forests where adaptation activities may be feasible (37), the long time lags between planting and harvesting trees will complicate decisions, because adaptation may take place at multiple times during a forestry rotation.

**Fisheries.** Marine ecosystems are, in some respects, less geographically constrained than terrestrial systems. The rates at which planktonic ecosystems have shifted their distribution have been very rapid over the past three decades, and this can be regarded as natural adaptation to a changing physical environment (39). Most fishing communities depend on stocks that fluctuate because of interannual and decadal climate variability and consequently have developed considerable coping capacity (40). With the exception of aquaculture and some freshwater fisheries, the exploitation of natural fish populations, which are common property resources, precludes the kind of management adaptations to climate change of the kind suggested for the crop, livestock, and forest sectors. Adaptation options thus center on altering catch size and effort and improving the environment where breeding occurs. Three-quarters of world marine fish stocks are currently exploited at levels close to or above their productive capacity (41). Reductions in the level of fishing are therefore required in many cases, independently of climate change stresses, to sustain yields of fish stocks. Such reductions may at the same time improve resilience of fish stocks to climate change (42). The scope for management-level adaptation is increasingly restricted as new regulations governing exploitation of fisheries and marine ecosystems come into force. Scenarios of increased level of displacement and migration are likely to put a strain on communal-level fisheries management and resource access systems and weaken local institutions and services. Despite their adaptive value for the sustainable exploitation of natural resource systems, human migrations negatively affect economic development (43).

## Changing the Decision Environment

Adaptation at the management unit level, based on current decision environments, may not fully cope with climate changes. Hence, deliberate measures, planned ahead of time at local, regional, national, and international levels, may be needed to facilitate a broader range of responses. Many options for policy-based adaptation to climate change have been identified for agriculture, forests, and fisheries (18, 44–47). These can involve adaptation activities such as developing infrastructure, capacity building in the broader user community and institutions, and in general modifications to the decision-making environment under which management-level adaptation activities typically occur (4). The process of "mainstreaming" adaptation into policy planning in the face of risk and vulnerability at large is an important component of adaptation planning (14). However, there are formidable environmental, economic, informational, social, attitudinal, and behavioral barriers to the implementation of adaptation (4). The following is a suggested approach to beginning to deal with these barriers, building adaptive capacity and changing the decision environment to promote adaptation actions (18).

1. To change their management, enterprise managers need to be convinced that projected climate changes are real and are likely to continue (48, 49). This will be facilitated by policies that maintain climate monitoring and by communicating this information effectively, including targeted support of surveillance of pests, diseases, and other factors directly affected by climate.
2. Managers need to be confident that the projected changes will significantly impact on their enterprise (50). Policies that support the research, systems analysis, extension capacity, industry, and regional networks that provide this information could thus be strengthened. This includes modeling techniques that allow scaling up knowledge from gene to cell to organisms and eventually to the management systems and national policy scales.
3. Technical and other options necessary to respond to the projected changes need to be available. Where existing technical options are inadequate, investment in new technical or management strategies may be required (e.g., improved crop, forage, livestock, forest, and fisheries germplasm), including biotechnology. In some cases, old approaches can be revived that may be suited to new climate challenges (51).
4. Where climate impacts may lead to major land use change, there may be demands to support transitions such as industry relocation and migration of people. This may be achieved through direct financial and material support, creating alternative livelihood options with reduced dependence on agriculture, supporting community partnerships in developing food and forage banks, enhancing capacity to develop social capital and share information, retraining, providing food aid and employment to the more vulnerable, and developing contingency plans (e.g., refs. 20 and 52). Effective planning for and management of such transitions may result in less habitat loss, less risk of carbon loss (e.g., ref. 53), and also lower environmental costs compared with unmanaged reactive transitions (54).
5. New infrastructure, policies, and institutions could be developed to support new management and land use arrangements. Options include addressing climate change in devel-

opment programs; enhancing investment in irrigation infrastructure and efficient water use technologies; ensuring appropriate transport and storage infrastructure; revising land tenure arrangements, including attention to property rights; and establishing accessible, efficient markets for products and inputs (seed, fertilizer, labor, etc.) and for financial services, including insurance (55).

6. Importantly, policy must maintain the capacity to make continuing adjustments and improvements in adaptation by "learning by doing" via targeted monitoring of adaptations to climate change and their costs, benefits, and effects (56).

Many adaptation-planning frameworks have been developed in the last decade, with contributions from both social and physical scientists attempting comprehensive coverage of planned adaptations, in the process describing many useful tools and methods (e.g., refs. 57 and 58). There has been significant discussion on the balance between the focus on underpinning biophysical processes or on the socioeconomic aspects critical to policy making (e.g., refs. 59 and 60). The consensus appears to be that products developed under such theoretical frameworks should be closely aligned to the needs of agricultural decision makers, and that different levels of engagement should be considered. Involving stakeholders from project inception is critical if adaptation research is to be reflected in changed decisions and altered strategies and actions (20). We suggest that a participatory approach that cycles systematically between the biophysical and the socioeconomic aspects [supporting information (SI) Fig. 1; ref. 61] could most effectively harness the substantial scientific knowledge of many agricultural systems, while retaining a focus on the values important to stakeholders, achieving relevance, credibility, and legitimacy (62). The inclusion of an adaptive loop in such frameworks is critical to developing flexible, dynamic policy and management that can accommodate climate surprises or changes in the underlying knowledge base.

## Discussion

The increasing urgency for developing effective adaptation responses to climate change suggests several research areas: enhancing existing climate risk management, more effective representation of the processes by which key climate drivers impact on agriculture, assessing the effectiveness of adaptation options, understanding likely adoption rates and how to improve these, and developing more resilient agricultural systems.

Agriculture in many regions remains sensitive to climate variability, and the capacity to manage this risk is variable (e.g., ref. 32). Given that climate change will be expressed via changes in variability at several temporal ranges, enhancing the capacity to manage climate risk is a core adaptation strategy (e.g., refs. 10 and 48). Developing this capacity involves increasing the "climate knowledge" of decision makers so they become more cognizant of climate impacts on their systems and of how to use management options to intervene, thereby reducing negative impacts and using opportunities. It also means moving the rhetorical focus from adaptation to climate change to management of climate risk, integrating climate change into a broader research domain.

There has been widespread adoption of statistical climate forecasting in agricultural management decisions, although many issues of forecast reliability, communication, and delivery remain (e.g., ref. 20). If the relationships between local weather and broad-scale climate phenomena (e.g., the Walker Circulation, regional sea surface temperatures, or the Madden–Julian Oscillation) remain largely stable, the continued use of statistical climate forecasts provides a key way for agriculture to proactively "track" climate changes (48). This also maintains coherence between the time scales of the management unit decision and of climate information. Additionally, process-based forecasts using coupled ocean-atmosphere models hold out the prospect of improved forecasts at a range of time scales that will automatically incorporate climate changes (e.g., ref. 63). These models have significantly improved their utility in recent years (64). Continued development of this modeling capability and the translation of the results to decision makers are likely to be warranted to enhance adaptation to climate risk (20). There are many region- or situation-specific climate risk management options (e.g., transhumance) that may also have adaptation value.

There is substantial room for improvement in the capacity to assess how combinations of various factors, such as $CO_2$, temperature and rainfall, pests and diseases, and air pollution, affect agricultural systems (2). Robust estimates of baseline impacts are necessary before reliable assessments of the costs and benefits of adaptations can be made. Improved knowledge is required to enable prediction of the magnitude and often even the direction of future climate change impacts on agriculture, as well as to better define risk thresholds and potential for surprises (2).

The results of adaptation will be a function of both the likely technical effectiveness of adaptations (e.g., Table 1) and their adoption rate. However, there is a paucity of studies that have assessed these two components in a thorough way, especially for higher levels of climate change and for more vulnerable systems (4). There is a particular need to expand the number of studies that engage with stakeholders in a structured way to assess adoption rates. These could focus on the acceptability of adaptation options in terms of factors important to stakeholders and their perceptions of synergies and barriers. Particular interest may be in question as to (*i*) the costs and benefits of adaptation when both market and nonmarket values are taken into account, (*ii*) the feasibility and costs of simultaneously reducing greenhouse gas emissions and adapting to climate change, (*iii*) the effect of limitations in capital and other resources such as irrigation water, energy, and fertilizer and pesticides (because of environmental concerns), and (*iv*) adoption rates in highly impacted areas if food prices decline as a result of positive climate change impacts and/or land-use intensification in temperate regions, or if demand for biofuels increases competition for land.

Finally, assessing climate risk and devising response strategies must be done in the face of many uncertainties in the underlying socioeconomic, political, and technological drivers and how these will affect climate, as well as fundamental uncertainties in characterizing the climate system (5, 11). However, uncertainty is often used as an excuse for inaction and can be inappropriately interpreted as a case of "no knowledge." Scientists need to become better at quantifying and communicating uncertainties, whereas decision makers need to accept that fuzzy knowledge is better than no knowledge at all (16). Given these circumstances, response strategies need to focus on developing more resilient agricultural systems (including socioeconomic and cultural/institutional structures), to cope with a broad range of possible changes. Enhanced resilience is likely to come with various types of costs or overheads that are often overlooked but that need evaluation. Additionally, given the above uncertainties, there is a need for directed change in management, science, and policy that in turn is monitored, analyzed, and learned from, to iteratively and effectively adjust to actual climate changes that will be experienced in coming decades. Consequently, adapting agriculture to climate change will be much more systemic than simply a farm-level activity.

## Conclusions

There is increasing urgency for a stronger focus on adapting agriculture to future climate change. There are many potential adaptation options available at the management level, often variations of existing climate risk management. However, there are as yet relatively few studies that assess both the likely effectiveness and adoption rates of possible response strategies. A synthesis of studies for cropping systems indicates first that the potential benefits of adaptation in temperate and tropical wheat-growing systems are similar and substantial (averaging 18%), even though the likely adoption rates may differ; and second, that most of the benefits of marginal adaptations within existing systems accrue with moderate climate change, and there are limits to their effectiveness under more severe climate changes. Hence, more systemic changes in resource allocation, including livelihood diversification, need to be considered. We argue that increased adaptation action will require integration of climate change risk with a more inclusive risk management framework, taking into account climate variability, market dynamics, and specific policy domains. Many barriers to adaptation exist; overcoming them will require a comprehensive and dynamic policy approach, covering a range of scales and issues, from individual farmer awareness to the establishment of more efficient markets. A crucial part of this approach is an adaptation assessment framework that can equitably engage farmers, agribusiness, and policymakers, leveraging off the substantial collective knowledge of agricultural systems, yet focusing on values of importance to stakeholders. To be effective, science must adapt, too, by continuing to review research needs and enhancing the central core integrative science in the communication and management tools developed with decision makers.

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