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Climate change adaptation in crop production: Beware of illusions

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ABSTRACT

A primary goal of studying climate change adaptation is to estimate the net impacts of climate change. Many potential changes in agricultural management and technology, including shifts in crop phenology and improved drought and heat tolerance, would help to improve crop productivity but do not necessarily represent true adaptations. Here the importance of retaining a strict definition of adaptation – as an action that reduces negative or enhances positive impacts of climate change – is discussed, as are common ways in which studies misinterpret the adaptation benefits of various changes. These "adaptation illusions" arise from a combination of faulty logic, model errors, and management assumptions that ignore the tendency for farmers to maximize profits for a given technology. More consistent treatment of adaptation is needed to better inform synthetic assessments of climate change impacts, and to more easily identify innovations in agriculture that are truly more effective in future climates than in current or past ones. Of course, some of the best innovations in agriculture in coming decades may have no adaptation benefits, and that makes them no less worthy of attention.

1. Introduction

The potential for adaptation to reduce negative impacts or enhance positive impacts of climate change is of widespread interest. For many, this interest stems from a desire to quantify the risks that unabated climate change presents to society, in order to properly evaluate the costs and benefits of reducing greenhouse gas emissions. For others, interest in agricultural adaptation comes primarily from a desire to identify actions and investments that can help to improve the future prospects for food production and food security.

The wide and diverse interest in adaptation has inevitably resulted in many different working definitions of climate adaptation. The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities." Others have preferred much broader definitions of adaptation, which characterize adaptation as any action that improves the welfare of society enough to compensate for losses related to climate change (World Bank, 2010, Mani et al., 2008). This perspective has the obvious appeal of including activities that may not be a direct response to climate change, but nonetheless a more effective use of scarce resources to improve welfare or some other outcome of interest.

The fatal problem with broad definitions, however, is that they lose all meaning for a key purpose of defining adaptation, which is to assess the impacts of greenhouse gas emissions. Thus, in this paper I will use adaptation to mean simply an activity that is "impact-reducing," in the sense that it reduces negative (or enhances positive) impacts of climate change. I will focus on the somewhat narrow question of impacts on crop yields and crop production, rather than outcomes such as farmer or consumer welfare, partly because estimating impacts on the latter require assumptions about future wealth and discount rates that are beyond the scope of most crop impact studies.

The central thesis of this paper is that actions that are truly impact-reducing are relatively rare in agriculture, and significantly rarer than they are often presented or thought to be. To be clear, many truly adaptive actions do exist, and are likely occurring each day. Moreover, I make no attempt here to argue that impacts from climate change without adaptation represent the primary threat to global food security. However, in my experience much of the quantitative work on adaptation turns out, on further inspection, to be lacking in one or more ways to qualify as convincing evidence of adaptation. In other words, many apparent adaptations turn out to be illusions. The danger in these illusions is that the costs of climate change are undervalued, particularly by non-experts who look to the literature when compiling estimates across sectors. There is also some risk that policy makers relevant to food security are misled to think that adaptation is easier than it actually is, and thereby underestimate the challenge that climate change presents. Finally, there is a risk that truly successful adaptations get lost amid bogus claims of adaptation.

The goal in what follows is to lay out the reasons behind these illusions so that others may be quicker to recognize and avoid

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them. In the rest of the paper, I will lay out a simple conceptual model of adaptation, discuss three related causes of confusion, and finally offer some conclusions. Because direct measurements of climate change adaptations are rare, this paper largely focuses on evidence from studies that use crop simulation models to explore climate change impacts and adaptation, these studies comprising the majority of the quantitative literature on climate adaptation.

2. A schematic of adaptation

Fig. 1 presents a simple schematic of how the impacts of climate change and the moderating effects of adaptation can be calculated for two examples. In both cases, there is a shift in the climate distribution towards higher levels of stress, and at the same time there is a new technology (T_2) that replaces an older technology (T_1). For the purposes of the example, a new technology can refer to anything that affects the relationship between a given stress and yield, including simple agronomic adjustments like sowing date changes, new genetically improved crop varieties, or changes in policies that influence on-farm input use. In the first case (panel A), the technology improves yield performance equally at all levels of stress. As a result, yields at the new stress levels that occur with climate change are higher than they would have otherwise been. However, the impact of climate change, measured as the yield change from point C to point A, is unaffected by the technology since it is the same as the distance under the old technology from point D to point B.

In the second case, the new technology has little impact at the former levels of stress, but offers significant yield improvements at the new levels of stress. In this case, the new technology represents a truly impact-reducing activity. In both panels, the technology has a clear positive effect on outcomes, and both would likely be adopted by farmers. However, the distinction between the impact-neutral change in Fig. 1a and the impact-reducing change in Fig. 1b is critical from the perspective of estimating the impacts of climate change. The lack of an adaptation "label" for the technology in Fig. 1a would undoubtedly frustrate its proponents, especially since the impact on absolute yields is as large as or even larger than in Fig. 1b. The change represented in Fig. 1a might also be attractive in several other aspects, such as being affordable to the poorest farmers, reducing input use, and reducing greenhouse gas emissions. It may well be the most important innovation in agriculture in decades, but it would have been just as useful in the former climate, and therefore in our discussion does not qualify as adaptation.

3. Illusions from faulty logic

The most common way of exaggerating adaptation benefits is the failure to make the calculations illustrated in Fig. 1. That is, many studies simply count the difference between point C and D as the benefit of adaptation, without considering the difference between points A and B. Indeed, most studies never actually calculate point A, but instead start with some reference yield scenario (point B), proceed to add climate change (arriving at point D), and then test various adaptations to arrive at point C. In both panels of Fig. 1, this would result in an estimate of adaptation that is larger than the initial impact, turning the net change in yield from negative to positive. Such a scenario is commonly reported in the literature, with the estimated benefits of adaptation exceeding 10% even if initial impacts were only a few percent (Challinor et al., 2014).

The types of adaptations considered vary by study. Most frequent are simulations of shifts in sowing dates and cultivar maturity rating (Challinor et al., 2014). The former can be used to help avoid heat or drought stress occurring at particularly important development stages, whereas the latter can help to compensate for acceleration of development with warmer temperatures. Thus, there are good reasons to believe that both would be beneficial adaptations, and it is not surprising when studies find this to be the case. Many well cited studies have reported sow date and cultivar shifts to be effective at improving yields in future climates, at both regional and global scales (Müller et al., 2010; Deryng et al., 2011; Tao and Zhang, 2010). In many of these cases, the impacts without adaptation are first estimated using some estimate of current sow dates and cultivar choices, and then only after climate change is invoked do the models attempt to find the optimum sow dates and cultivars. Deryng et al. (2011) differ in that they do not base adaptation on a search for optimum sow date and cultivar length, but use an equation based on present-day relationships between temperatures and these practices.

However, longer maturing varieties and shifts in sowing dates can also often have benefits in current climate. For instance, recent yield growth in Chinese maize and rice systems is largely associated with a longer post-flowering growth period (Chen et al., 2013; Tao et al., 2013), and recent wheat yield trends in India can largely be explained by benefits of recent trends toward earlier sowing (Lobell et al., 2013b). Failure to consider the benefits of potential changes in current

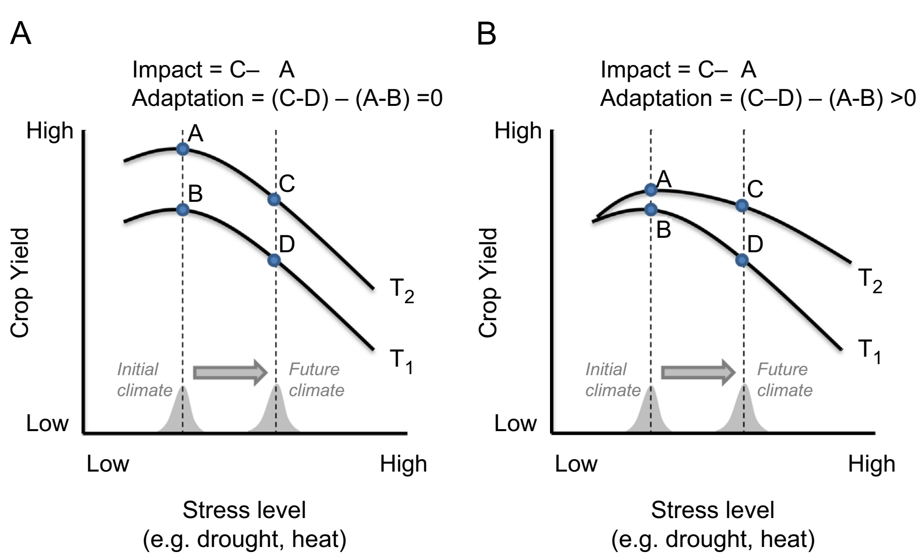

Fig. 1. A schematic of how adaptation should be calculated for new agricultural technologies.

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climate will systematically cause studies to overstate the benefits of adaptation.

Various studies of adaptation in Chinese agriculture illustrate the ease with which results can be misinterpreted as evidence for adaptation. A study of wheat and maize in North China Plain (NCP) concluded that "autonomous adoption of new crop varieties in the NCP was able to compensate the negative impact of climatic change" (Liu et al., 2009). The basis of this conclusion was a comparison of simulations using fixed varieties over the study period with others that used observed changes in varieties toward longer maturity lengths. Yield trends were more positive in the latter simulations, leading the authors to conclude a compensating effect of variety changes. However, without any tests of how these longer varieties would have helped without climate change, it is not possible to make conclusions about the adaptation benefits.

Similarly, a simulation study of the wheat–maize rotation in NCP found that total grain production was increased with delayed harvest of maize and delayed sowing of wheat (Wang et al., 2012). The authors describe this as "climate change adaptation," yet their simulations show this agronomic shift would also have been beneficial in the beginning of the study period, albeit not as beneficial as at the end. Both of these studies (and many others) equate adaptation to compensating for yield losses, but as illustrated in Fig. 1a, a technology change that leads to a net increase in yields over time (from point B to C) does not necessarily reduce the impacts of climate change.

Another commonly simulated adaptation is the development of new traits for drought or heat tolerance. Again, these changes are often invoked in the modeling process after climate change impacts for scenarios without adaptation have been estimated (Gouache et al., 2012; Challinor et al., 2010). Yet it is clear that drought and heat is a common stress in most cropping systems under current climate, so there are surely some benefits that would accrue regardless of climate change. For example, heat stress during grain filling is one of the most widely cited current causes of yield loss by wheat experts in developing countries (Kosina et al., 2007). Drought stress is similarly a major constraint on maize yields throughout the world. Improvements in drought or heat tolerance may well be more advantageous for future climates than current ones, but the difference may not be that large. Moreover, increased performance under abiotic stresses can often induce management changes, which relate to another cause of adaptation illusions (see section 5).

A recent paper on drought and heat traits in sorghum offers an excellent example, as the authors calculate benefits for both baseline (1960–1990) and future (2040–2069) climates (Singh et al., 2014). In this case the authors considered hypothetical improvements in the sensitivity of grain filling rates to temperature (heat tolerance) and higher rooting density (drought tolerance), with the simulated changes in average yields shown in Table 1. Both traits result in simulated yield gains for at least some of the sites. In the case of drought traits, gains are slightly less in future climate because of lower incidence of drought in the scenario considered. Heat tolerance offers some gains in current climate, with significant increases in benefits for future climate. The authors estimate that by 2050 the net benefits of heat tolerance will even be greater than those for drought tolerance at three of the four sites. For the purposes of the current discussion, the main point is that drought tolerance would be considered helpful for yields, but not impact-reducing as it offers no more benefit in future climate than for baseline climate (i.e. the scenario represented in Fig. 1a). In contrast, heat tolerance represents a true adaptation in that the benefits are larger in future climate (i.e. the scenario represented in Fig. 1b).

4. Illusions from model error

A second cause of illusions relates to limitations of the crop models used to study adaptation. A recent review (White et al., 2011) emphasized how nearly all of these models were originally developed for other purposes, and they are often missing key processes related to climate change impacts. For example, of 221 papers considered, only six clearly considered effects of CO_2 on canopy temperatures, and a similarly small number accounted for effects of heat stress on grain set (White et al., 2011).

Models also differ greatly in their ability to correctly simulate moisture stress. In the absence of heat or moisture stress, it should not be surprising when a model estimates that a longer season variety will have higher yields! Some studies that report benefits of longer varieties use simulations that explicitly turn off water stress (Liu et al., 2009), whereas other studies do not report whether moisture stress was considered (Cassman et al., 2010).

In reality, the appropriate length for a variety is often dictated by the prospects for severe water stress late in the season. Models that capture the dynamics of water stress, including the additional evaporative demands associated with most climate change scenarios, will nearly always infer less benefit from longer varieties than models that do not. For example, Table 2 presents estimates of the benefits of longer varieties for three sites simulated in a recent analysis of United States maize yields using the APSIM crop model, which has a well tested response to drought stress (Lobell et al., 2013a). The model suggests some recovery of yields when switching to a longer variety in a warmer scenario, but the effect is small relative to the initial yield impact. In contrast, some simulation studies indicate substantial gains from variety switches in this region (Fig. 11 in Deryng et al., 2011), which in turn drive large

Table 1
Estimated sorghum yield changes (%) at four sites associated with hypothetical drought and heat tolerance traits. Taken from (Singh et al., 2014). Note future climate includes effects of projected temperature, precipitation and CO_2 changes.

Site	Yield benefits (%) of improved drought tolerance		Yield benefits (%) of improved heat tolerance		Yield benefits (%) of drought+heat tolerance	
	Baseline climate	Future climate	Baseline climate	Future climate	Baseline climate	Future climate
Akola, India	5	2	3	11	8	14
Indore, India	7	5	0	1	7	6
Samanko, Mali	1	0	1	6	2	6
Cinzana, Mali	6	6	2	7	8	13

Table 2
Simulated response of rainfed maize yields to combinations of warming and a shift to a longer maturing variety at three sites in the United States Corn Belt, based on simulations in (Lobell et al., 2013a). Longer varieties have slight adaptive benefits in terms of average yields at the wetter sites, but not at the driest site. Yield impacts are relative to a baseline average for 1959–2004.

Site	Yield impact (%) of warming by +2 °C	Yield impact (%) of longer variety in current climate	Yield impact (%) of longer variety in +2 °C climate
Princeton, Illinois (wet)	−13.7	−1.1	1.5
Johnston, Iowa (middle)	−13.0	−1.4	0.5
York, Nebraska (dry)	−27.7	−6.4	−8.6

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global estimates of adaptation benefits because of the prominence of the United States in maize production.

Although critique of individual models' representations of water dynamics and plant water stress is beyond the scope of this paper, I suggest that researchers should be skeptical of large simulated benefits from longer varieties in rainfed systems, particularly when the benefits have not been estimated for current climates. For example, longer varieties are often expected to help moderate impacts for temperate cereals, but a recent study of oat varieties in Germany found that despite significant warming trends, farmers were actually choosing shorter varieties (Siebert and Ewert, 2012). As the authors explain “this trend is surprising because the expected adaptation to the warming trend should be in the use of cultivars with larger thermal requirements but it is in agreement with advice of the extension services encouraging the use of early developing varieties to avoid yield losses due to late season drought stress.” (Siebert and Ewert, 2012).

5. Illusions from management assumptions

The two reasons above can be viewed as technical issues with how studies are designed and interpreted. The third issue is more subtle, and relates to implicit assumptions that ignore the tendency of management to change in tandem with new agricultural technologies. In general, climate change is expected to exacerbate many of the abiotic and biotic stresses experienced by crops (though, of course, it could alleviate them in some places). A typical expectation is that adaptation efforts can help to improve performance under these stress conditions. Indeed, such efforts are greatly needed to ensure future food security and environmental quality (Connor and Mínguez, 2012, Sayer and Cassman, 2013). But will they truly reduce the impacts of climate change?

Consider the history of crop yield increases over the past half century, as discussed at length elsewhere (Evans, 1998) (Fischer et al. 2014). In wheat and rice, much of the increase was associated with greater provision of water and nutrient resources, through fertilizers and irrigation, in combination with dwarfing genes and rust resistance that allowed crops to take full advantage of these inputs. Yet in maize, the main driver of yield improvement has been increased stress tolerance of individual plants, which allowed them to be sown more densely and produce more grain per unit area (Duvick, 2005; Tollenaar and Lee, 2002).

The story of maize illustrates the importance of considering interactions between genetic progress and management systems (often called $G \times M$ interactions). As a crop's ability to withstand stress improves, the management system will respond by pushing that plant to greater limits in order to achieve higher average yields. Even in a world without climate change, much of yield progress in the next few decades would likely have to come from greater tolerance of individual plants for a variety of stresses, combined with greater exposure to those stresses. For example, more heat tolerant wheat would allow later wheat sowing and longer maturing, higher yielding rice in South Asian rice–wheat systems. Better drought tolerance in rainfed crops throughout the world would lead to a combination of denser sowing and longer season varieties to take full advantage of that water. In both of these cases, a modeling study might identify some benefits under current climate, but they would underestimate these benefits if they failed to consider the management changes that crop improvements would spur in a profit-seeking farmer.

These interactions with management are ignored in nearly all simulation studies, which typically use current management as the reference point with which to test adaptations. Yet it is critical to remember that any advances that help to moderate losses from climate change could have potentially been put to other uses. That is, greater stress tolerance could have been translated with management adjustments into higher average yields, rather than simply offsetting impacts of climate change. The most appropriate comparison is therefore with a cropping system that has fully equilibrated to the new technology.

Accounting for such management changes is a difficult task for modelers, and not one I anticipate great progress on the near term. But both producers and consumers of modeling studies should be aware that improved stress tolerance is a major driver of overall yield progress in a stable climate, and consider how these management changes could alter the conclusions. To treat stress tolerance as the sole domain of climate adaptation, and to ignore potential benefits in current climate, raises the risk of understating the impacts of climate change.

6. Conclusions

Assigning a label of “climate adaptation” to any promising innovation in agriculture is a common temptation, one that is increasingly hard to resist as funding grows for topics related to climate adaptation. Many feel justified in the use of “adaptation” if a change in technology or management helps to compensate for yield, production, or welfare losses associated with climate change. I argue that maintaining a strict definition of adaptation as an activity that reduces the impact of climate change is essential if work on agricultural adaptation is to inform broader assessments and discussions of climate impacts and policy. Of course, crop yield and production are just two of many possible impact metrics. Broader metrics that consider social or economic outcomes are also of wide interest, and in those cases any change that improves overall wealth and reduces vulnerability to income shocks could credibly be viewed as climate adaptive. But this fact does not diminish the need to quantify the value of adaptations for crop yield and production themselves, not least because yield impacts are often part of the foundation of estimates of social and economic impact.

Moving forward, it is important that studies of climate adaptation, whether using models or observations, be clear about the reference scenario, model deficiencies related to key factors, and assumptions related to management changes over time. This will help to avoid the frequent illusions that, in the author's view, cause people to underestimate the difficulty of reducing climate change impacts. At the same time, those working on global food security readily recognize that climate change is just one of many challenges in the coming decades, and many of the most successful innovations to come will be climate impact-neutral or possibly even impact-enhancing. For example, alleviating soil fertility constraints in Africa remains one of the biggest obstacles to improving global food security. Yet reducing nutrient constraints will only increase the sensitivity of production to weather, as plants are more able to take advantage of good conditions (Schlenker and Lobell, 2010). Thus, there is only a loose correlation between the value of an innovation for climate adaptation and for global food security.

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