Joint Working Party on Agriculture and the Environment

AGRICULTURE AND ECONOMIC ADAPTATION TO CLIMATE CHANGE

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Contact person:
Jussi LANKOSKI
E-mail: jussi.lankoski@oecd.org

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NOTE BY THE SECRETARIAT

This report on adaptation to climate change in agriculture has been prepared by Professor Robert Mendelsohn (Yale University). As climate changes, if farmers make no changes, agriculture is vulnerable to reduced productivity. Efficient adaptation means that farmers profitably change agricultural practices, which can substantially reduce the damage from climate change, and can also help by providing new opportunities for farmers to grow crops in a changing world. Governments can help by providing effective policies that increase the net benefits of the agricultural system to society and by removing policies that limit effective change.

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AGRICULTURE AND ECONOMIC ADAPTATION TO CLIMATE CHANGE

Robert Mendelsohn
Yale University

Abstract

Agronomic research has shown that crops and livestock are sensitive to both temperature and precipitation. As climate changes, if farmers make no changes, every crop and animal is vulnerable to reduced productivity. The greater the climate changes that take place, the more potential productivity will fall. Efficient adaptation concerns changing agricultural practices to maximize the net benefits of farming. Farmers can substantially reduce these potential damages from climate change by changing their behavior as climate changes. Agricultural industries can also help by providing new opportunities for farmers to grow new crops and raise animals in a changing world. Finally, governments can help by providing effective policies to manage public resources and by modifying policies that limit effective change.
Introduction

1. This paper discusses adaptation to climate change in the agriculture sector. Adaptation includes all changes that actors make to reduce the potential damage and to take advantage of new opportunities caused by climate change (Smith, 1997). Since adaptation is a reaction to climate change, we begin this introduction reviewing the basics about greenhouse gases. We then turn to a discussion of how climate change potentially could affect agriculture. This sets the background to begin to discuss how adaptation could alter these potential effects in the agricultural sector.

2. Extensive research has conclusively revealed that emissions of greenhouse gases from burning fossil fuels and land use change are causing these gases to accumulate in the earth’s atmosphere (Intergovernmental Panel on Climate Change (IPCC), 2007a). One of the most important greenhouse gases is carbon dioxide CO₂ because of the relative quantity of emissions and because it has such a long lifetime in the atmosphere (IPCC, 2007a). Carbon dioxide has a direct effect on plants through carbon fertilization and therefore has important consequences on agriculture by itself. In addition, the accumulation of carbon dioxide and other greenhouse gases in the atmosphere is trapping infrared heat on earth and raising the temperature (IPCC, 2007a). There is already substantial evidence that the global temperature has increased over the last 50 years (IPCC, 2007a). Although more uncertain, precipitation patterns may also have already changed as well. Although these historic changes may have caused small losses (Lobell and Field, 2007) or gains (Mendelsohn, 2007), the real concern is the future impacts as greenhouse gases continue to accumulate, not the historic impacts. By 2100, global temperatures could rise between 1.5° to 4.5°C above current levels (IPCC, 2007a). How much temperatures rise depends on how sensitive the climate system actually is and what happens to global emissions. Although emphasis is often placed on global temperature, it should be understood that what matters to each farm is the local climate change. The local change in climate is location and time specific. It depends on the initial climate and how much climate is expected to change in that location. Both recent experience and climate models suggest that temperatures will warm more in the north pole than in the equator, more in winter than summer, and more at night than during mid-day (IPCC, 2007a).

3. Changes in precipitation are less well understood. Although the hydrological cycle is expected to speed up with warming (leading to more evaporation and more precipitation), the climate models do not agree how precipitation will change in each locality (IPCC, 2007a). Additional rain could fall on the oceans and not land. Rainfall patterns could shift over continents causing some wet places to become dry and dry places to become wet. The intensity and timing of rain could change.

4. Other changes in climate are predicted. Sea levels will rise because of thermal expansion of the ocean. Sea levels may also rise if large land based ice sheets melt with the warmer temperatures. Of specific concern are the ice sheets on Greenland and Antarctica. Rising sea levels lead to salt water inundation and intrusion along the coast. In addition, extreme events may change. There is already growing evidence that warming will increase the intensity of tropical cyclones (Emanuel, 2005; Emanuel et al., 2008). Other extreme events such as droughts, floods, thunderstorms, and heat waves may also change (IPCC, 2007a).

5. What does climate change potentially do to agriculture? The potential effects of climate change define what adaptation must address (Tol et al., 1998). Because this essay is about the agriculture sector, we focus on the sensitivity of agriculture to the consequences of greenhouse gases. For example, experimental research in controlled settings suggests that most crops have a hill shaped relationship with both temperature and precipitation (IPCC, 2007b). It is commonly assumed that the current distribution of crops is optimized to the current climate. That is, each crop is grown in its ideal climate range. Consequently, if crops stay where they are now, any change in climate will reduce productivity. The larger the climate change, the more productivity will fall. Studies that assume no change in farm behaviour find
that climate change will cause large reductions in crop productivity (Parry and Rosenzweig, 1993; Parry et al., 2004; 2005; Rosenzweig and Parry, 1994; IFPRI, 2009). These studies suggest that if farmers continue to grow the same crops the same way for the next century, regardless of global warming, the global supply of food will fall as warming becomes more severe, leading to problems of malnutrition around the world.

6. Livestock is also sensitive to climate change. Different species tolerate different temperature and precipitation ranges. In addition to this direct effect of climate, climate can also have indirect effects on livestock through feed. For highly integrated livestock operations, the supply of grains is critical for feed. In pasture-oriented livestock systems, livestock depend on natural grasslands or forests. Changes in climate can alter the relative productivity of these grazing lands. Livestock can also be indirectly affected by climate through disease vectors that are climate sensitive.

7. Agriculture can also be affected by sea level rise, extreme events, and carbon dioxide. Farmland can be lost to rising seas. Coastal farmland is also sensitive to salt water intrusion which is likely to become more of a problem with sea level rise. Farms are vulnerable to extreme events. Severe weather that damages crops may increase with warming. Droughts have always been an issue for farmers. Floods can also cause significant damage to annual crops and farm investments. Storms can destroy cropland and animals. The changes above tend to be harmful. In contrast, the increase in carbon dioxide is expected to be beneficial. The response is expected to be logarithmic which means that one must double CO₂ concentrations to get a specific effect. Although the results across experiments vary widely, controlled experiments suggest that doubling carbon dioxide levels would increase average crop productivity for most crops (C₃) by 30% (Bazzaz and Fajer, 1992; Kimball et al., 1993; Mooney and Koch, 1994; Tubiello and Ewert, 2002). Maize, sugar cane, millet, and sorghum (C₄) crops are expected to have much smaller reactions. Higher CO₂ concentrations allow plants to reduce the opening of their stomata which may also help plants adapt to dry and hot weather. The magnitude of the carbon fertilization effect may also depend on the availability of other nutrients, including water. Open field experiments with plants limited by nutrients and other factors, such as too high temperatures, suggest limiting factors may reduce the magnitude of the carbon fertilization effect (Coll and Hughes, 2007; Long et al., 2006).

8. Efficient adaptations make the actual net damages less than the potential damages from climate change. Actual net damages are damages minus the cost of adaptation. By definition, efficient adaptations make farmers better-off by increasing net revenue. If farmers can change their behaviour to suit the new climate, the magnitude of the net damages to agriculture can be reduced. For example, laboratory studies of the productivity of crops suggest a relatively steep shaped hill for many crops with respect to temperature. In laboratory settings, specific crops do well in a narrow band of temperatures but their productivity falls rapidly with either cooler or warmer temperatures. Figure 1 illustrates this general principle. The laboratory results inform crop modelling results (e.g. Rosenzweig and Parry, 1994; IFPRI, 2009). However, cross-sectional studies of actual farm performance suggest that the hill is much flatter than the experimental evidence suggests (Mendelsohn and Dinar, 2009).

9. Impact studies of crops that incorporate adaptation predict much lower climate change impacts in developed countries (Adams et al., 1990; 1995; Mendelsohn et al., 1994; Mendelsohn and Dinar, 2003) and in developing countries (Dinar et al., 2008; Mendelsohn and Dinar, 1999; 2009; Kurukulasuriya et al., 2006; Kurukulasurya and Mendelsohn, 2008a, Sanghi and Mendelsohn, 2008; Seo and Mendelsohn, 2008a). Adaptation also helps reduce the potential damages to livestock (Seo and Mendelsohn, 2008; 2008).

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10. What happens to agriculture also depends on what happens in related sectors that compete for land and other resources. For example, agriculture must compete for land with forestry. Depending upon how climate change affects the productivity of forests, marginal land can shift back and forth between agriculture and forestry (Sohngen et al., 2002). If water runoff falls with climate change, irrigation water will become scarce. How efficiently water is reallocated after climate change has potentially big effects on agriculture (Hurd et al., 1999; Lund et al., 2006). What is done in reaction to rising sea levels can also affect agriculture (Neumann et al., 2001). If nothing is done to hold back the sea, coastal farmland can be inundated and subject to salt intrusion.

11. There are many reasons to expect that farmers and agricultural industries will adapt to climate change. First and foremost, they have a personal incentive to adapt. By changing their behaviour they can increase the net revenue they earn. Second, there is ample evidence that farmers already have adapted to climate, the climate that they currently live in. Although there may be one global average temperature, every farmer lives in a different local climate. As discussed in detail in this paper, there is ample evidence in both developed and developing countries that farmers select crops and farm practices that are suited to their local climate (Mendelsohn and Dinar, 2009). In the context of climate change, however, the challenge is to ensure that farmers can adjust in a shorter timeframe.

12. However, not all desirable adaptations will automatically be implemented. Actors may not have perfect information about either climate change or how to respond to it. Actors may not readily change their behaviour. They may consequently be slow to adapt to climate change. For farmers, adaptation options may depend on how wealthy a farmer is. Poorer farmers will not be able to choose some of the options available to wealthier farmers. Farmers who do not own their own land may not have an incentive to adapt to climate change. For example, farmers who rely on common property may have less personal interest in the long-run productivity of the land. Moreover, farming activities causes positive externalities.
(e.g. landscape maintenance and preservation of some species) and negative externalities (e.g. water and air pollution and loss of biodiversity due to land use change) strongly linked to practices and to the type of agricultural system. However, externalities are not systematically internalised to decisions by farmers who are not able to assess them fully. That is why it is national and local authorities’ responsibility to make sure that externalities and collectively managed resources are taken into account in climate change adaptation strategies. Governments must also be attentive to the timing of changes and the diversity of changes across the landscape.

13. The remainder of the paper is divided into three sections. The next section reviews the theory of adaptation: defining efficient adaptation, determining the circumstances under which adaptation will likely be efficient, and identifying important characteristics of adaptation. The paper then focuses on specific farm level and industry adaptations. The fourth section addresses the role of government: what governments should try to do and what governments should try to avoid. The paper concludes with a review of major points and policy recommendations.

Theory

14. The first important theoretical construct is to determine what the goal of adaptation should be. The purpose of adaptation is to change behaviour to maximize the net benefits to society given that climate is changing. In the context of agriculture, the purpose of adaptation is to maximise the net benefits of land and water that should be devoted to agricultural activities. Efficient adaptation increases social welfare (Mendelsohn, 2000).

15. Note that adaptation should not necessarily eliminate the impacts of climate change by “climate proofing” each economic sector. This was the objective of a recent World Bank report on adaptation (World Bank, 2009). In the executive summary, “The study assumes that countries will adapt up to the level at which they enjoy the same level of welfare in the (future) world as they would have without climate change”. The World Bank report argues funds be spent on adaptation until all climate damages are offset. Such an adaptation policy would include many actions where the cost of the adaptation would exceed the damage being eliminated. For example, the report would offset the effects of warming on agriculture by investing in research, irrigation, and rural roads (p. 57). The report imagines that a sufficient amount of these investments into infrastructure at each locality could offset any crop productivity losses from warming there. Whether any of these investments would satisfy a cost benefit analysis is not considered.

16. Under what conditions is adaptation efficient? One condition where adaptation is likely to be efficient is when the decision maker is the beneficiary, the adaptation is private (Mendelsohn, 2006). Private adaptation is defined as actions taken by an individual or firm for its own benefit. For example, the choice of which crop to grow is a private decision by a farmer. Presumably, the farmer will choose the crop that provides the highest net revenue. If the farmer continues to make that choice as climate changes, he/she will change crops efficiently. Similarly, a consumer may change what foods he/she wants to eat given the climate conditions at that moment. In these cases, the decision maker is taking into account all of the costs and benefits of the adaptations (because they are all privately borne) and so is making the efficient decision. The decision maker avoids choices that reduce welfare and makes all the choices that increase welfare, assuming that s/he knows all the ins and outs of the decision.

17. A competitive market will encourage efficient private adaptation for traditional farm choices such as choosing which crop or animal to grow. Market actors, once they have the necessary information, are going to take into account the cost and benefits of changing their behaviour and so they are going to choose efficient adaptations.
18. Public adaptations involve choices that affect the costs and or benefits of many people. The decision maker, the farmer, will often find it difficult to take into account the costs and benefits of everyone affected. For example, externalities often involve many beneficiaries. Air pollution, for instance, affects many people downwind of the source of pollution. When a farmer considers generating an emission of air pollution, there is no mechanism for the people downwind to convey to the farmer what costs the emission is imposing on them. The farmer consequently ignores the damages of his/her emissions and makes little effort to control them. The choice would not be efficient.

19. With common property, farmers do not own their own land or resources. There are many people using the land. The farmer, looking out for his/her own best interest, may not take into account the interest of the other common land owners. Adaptation on common property land is not likely to be efficient. In many circumstances, water is owned in common. The first farmer with access to the water may not take into account the interest of other farmers who also want to use the water. The first farmer may take too much of the water. Common property is generally not efficiently managed, although there are some notable exceptions to this rule (Ostrom, 1990).

20. Markets will not generally be efficient producers of public adaptation. For example, markets often cannot efficiently manage resources held in common such as many water, land, and forest resources. When there are many beneficiaries of a decision, markets tend to fail. Each actor looks out for only his own interest. Market actors will fail to take into account the impact of their choice on other people. They will consequently undervalue the costs and benefits to others. Market forces consequently have trouble making efficient decisions involving many actors.

21. Government action is generally needed to perform public adaptations. Either governments must undertake the role themselves, for example by allocating water from a public water body, or they must develop regulations to encourage private actors to behave efficiently, for example by pricing water or pollution. Providing information is another example of a public adaptation. There is little incentive for markets to fully inform everyone as many people can gain from asymmetric information. The government has a clear role to play in providing public adaptations.

22. Of course, having decided that governments are responsible for public adaptations does not guarantee that public adaptations will be efficient. Sometimes government agencies have their own personal incentives which do not align with maximizing social welfare. For example, agencies may want to maximise their own portfolio (budget) and therefore will volunteer to engage in climate adaptations that are not necessary. Special interest groups may usurp government decisions to further their own interests. For example, farmers may request subsidies for their crops or their insurance in order to cope with climate change whether or not subsidies are an effective adaptation strategy. Victims of extreme events may request free emergency relief whether or not they took any precautions to avoid being damaged in the first place. One of the most challenging tasks in climate policy is designing incentives for efficient adaptation. That includes providing incentives for government agencies to adopt efficient adaptations. Similarly, the challenge also applies to government agencies who wish to create incentives for farmers to engage in efficient adaptations.

23. Unlike mitigation which is a global problem, adaptation is inherently local. Climate change mitigation inherently involves every polluter in the world since greenhouse gases can come from anywhere. Because the benefits of mitigation are shared whereas the costs are not, there is an incentive in mitigation to shirk personal responsibility. That does not apply to adaptation because the benefits of adaptation fall largely to each private actor and each local government. Adapting my own farm to climate change, helps me. Adapting a watershed to climate change helps the people in that watershed. The benefits are local and so they can be captured by the local people. This makes adaptation a far more tractable problem than mitigation.
24. The fact that adaptation is an inherently local choice, of course, does not make it simple. If every local actor must adapt to their own local conditions efficient private adaptations will vary across the landscape. For example, with farms, efficient private adaptations depend on the initial conditions in each farm and how climate changes on that farm. This local information is something each local farmer is likely to know. However, it will be a challenge for central governments to be as informed. For central governments to know what private adaptations are efficient, they must know the local conditions and preferences of each private actor. In practice, this is a daunting task for a government agency. At best, governments are likely to choose actions that may benefit an average farmer. However, what is best for one farmer may be a disaster for another. This spatial complexity makes it inherently difficult for central governments to encourage efficient private adaptation.

25. The same principle applies to public adaptations. They too must vary across the landscape. However, in the case of public adaptations, the individual farmer will not likely take them into account at all. The government has the relative advantage here because the government is concerned with multiple beneficiaries, not just the farmer. The spatial complexity makes the task difficult to perform perfectly, but the government remains the best choice for this decision.

26. Of course, some private adaptation will need to be undertaken by poor households. Although poor households may have limited budgets, they still have a lot to gain from making efficient choices for themselves. Poor farmers do not have all the options available to rich farmers. They will not be able to apply the same level of capital and technology to their land. Governments may want to help poor households adapt for equity reasons. However, governments must be careful if they subsidize the adaptation of poor people that they do not encourage maladaptations. A maladaptation is a policy that increases climate damages rather than diminishing them. For example, subsidising farmers to grow crops in a hostile setting will encourage more farmers to get in harm’s way. This can increase the long-run damages from climate change. Programmes to help poor farmers adapt to climate change should try to avoid making the problem worse.

27. Adaptation can also be defined depending upon whether it is anticipatory or reactive (Smith, 1997). Anticipatory adaptation forecasts climate changes and acts before climate change unfolds. Reactive adaptation waits for the climate change to occur and then changes behaviour. If one can anticipate a trend in climate change, one can alter long-term decisions to take advantage of the change in advance. For example, if one anticipates that an area will become drier, one can invest in irrigation sooner. If one sees that sea levels are gradually rising, one can build a sea wall before valuable property is inundated. Alternatively, a water authority that anticipates future flooding will increase along a river, may want to build a dam before the flooding becomes a serious problem. In theory, anticipatory adaptation can substantially reduce potential damages. The dilemma with anticipatory adaptation is that it is difficult to predict local climate changes. It is reasonable to anticipate that temperatures will increase and that sea levels will rise. There are some anticipatory adaptations that can be made in agriculture in advance of both of these changes. However, it is difficult to foresee how much local temperatures will increase. Forecasting local precipitation is even more uncertain. Local precipitation may increase or fall. It is therefore likely that very little adaptation will be anticipatory.

28. Most agricultural adaptation is likely to be reactive. People will see how their local climate is changing and will react accordingly. Of course, one could be prepared to react in advance and make contingent plans but the actual changes in behaviour would wait until the climate has changed. There is much less uncertainty concerning reactive adaptation compared to anticipatory adaptation. Although we may not be able to forecast today how climate is going to change in a specific place in 2050, farmers in that place in 2050 can see for themselves how their local climate has changed.
29. Depending on reactive adaptation to climate change does not mean that one would fail to anticipate storms and other extreme events that are part of the current climate. A recent World Bank report on managing natural catastrophes argues that a great deal of the damages from weather-related extreme events can be curtailed by encouraging people to avoid high-risk locations. For example, land use planning and actuarially fair insurance encourages people to avoid high-risk locations under potential mountain landslides, near fire-prone areas, and near flooding zones. Such anticipatory plans are effective because they depend on the known climate of each region, not the unknown change in climate.

30. One adaptation promoted by insurance companies is a greater reliance on insurance. Weather insurance can spread the risk of individual weather events across a large class of clients and make everyone better-off. As climate changes, the weather next year will remain uncertain and so there is a continued need for weather insurance. Possibly with climate change, near term weather will become even more uncertain. This would increase the value of weather insurance to society. If weather becomes more hostile in a specific place, insurance companies will have to increase premiums. This will signal consumers of this insurance that it is more costly to stay in this location. The consumer can then adapt accordingly. Actuarially fair weather insurance can enhance adaptation by providing important risk information to consumers (such as farmers). Governments must be careful in designing public insurance programmes to provide these important signals to farmers to adapt. Otherwise, there is a grave danger that the insurance programme will encourage farmers to remain in hostile settings that risk analysis would suggest should be abandoned.

31. It is important to note that there is a difference between insuring against weather and insuring against climate change. For insurance to be effective against climate change, changes in long-term weather, insurance companies would have to make long-run contracts to insure against changes in the far future when weather would be quite different. This would be a departure from current insurance policies which are negotiated yearly. Most insurance contracts do not protect people against events in the far future. But, in principle, insurance companies could try to guarantee long term weather (climate). Unfortunately, such climate insurance is likely to be very expensive. It is one thing to make a payment if a single year is different from average, it is very different to have to make a stream of payments for many years because the climate has changed. Further, climate insurance would discourage farmers from making adaptations to the changing climate since they could collect the insurance payment instead. Climate insurance is likely to be a maladaptation, causing farmers to stay in harm’s way and make no effort to adapt. Climate insurance could well increase the damages from climate change.

32. Because climate change is inherently dynamic, adaptation must also be dynamic. Adaptation must be carefully timed so that it corresponds with the climate at each moment in time. For example, crops must be matched with the climate at each moment of time. It is not beneficial to grow a crop in advance of a climate change because the conditions will not be right yet. It also does little good to keep growing a crop long after the climate makes it unsuitable. Changes that might be gradual such as increasing irrigation water should also be adjusted as climate conditions change. Timing is a critical element in efficient adaptation.
Farm and industry adaptations

33. Although there is an extensive literature on the theory of adaptation, there are surprisingly few papers that specify exactly what agricultural adaptations individual farmers and industry should undertake. How should farmers change their behaviour to respond to climate change? What new products should industry explore producing? How should adaptation vary across the landscape and how should it change over time?

34. There is an extensive literature in environmental anthropology that reviews how people have historically adapted to weather and to long-run shifts in regional climate. These analyses tend to be case studies of specific places where weather has changed and people have reacted. For example, there are many studies of drought in semi-arid developing countries. Farmers have often tried to adjust seeds and timing in the face of drought. They have liquidated animal stocks to survive. Finally, they have sought income outside the farm working on nearby farms or in distant communities (Adger et al., 2002). With long run shifts in climate, there are more dramatic changes. Malthus (1798) records shifts in human populations in England with decadal shifts in weather patterns. There is growing evidence that the rise and fall of at least some ancient civilizations was concurrent with changes in local climate patterns (Weiss and Bradley, 2001).

35. Some of the first studies to look at adaptation were concerned that farmers might not adapt (Kaiser et al., 1993 and Kelly et al., 2005). They examined anticipatory adaptation and assumed farmers would have trouble predicting climate change. Their analyses suggest there would be high adjustments costs. However, if farmers follow reactive adaptation and simply adjust to the climate that they recently observe, it is not clear that there would be high adjustment costs. Farmers clearly demonstrate that they can adapt quickly to new prices. Further farm models already predict how farmers should shift from crop to crop as climate changes (Adams et al., 1999; Howitt and Pienaar, 2006).

36. Cross sectional studies have also provided useful evidence for studying long-run adaptations. By examining what farmers do in different climates, one can see how a current farm system would need to change if climate changes. By studying how people have adapted to where they live, one can learn how people currently adapt to each local climate. As climate changes from one place to another place, one can see how behaviour (choices) would have to change.

37. For example, it is well known that certain crops and livestock tend to be grown in specific regions of the world. One of the reasons that crops and animals tend to be chosen in one place rather than another is the climate. By examining the statistical relationship between choosing a particular crop or animal species and climate, one can measure the influence of climate on these choices (Kurukulasuriya and Mendelsohn, 2008b; Seo and Mendelsohn, 2008c; 2008d; Seo et al., 2010; Wang et al., 2010). A similar approach can be used to study irrigation (Kurukulasuriya et al., 2011), whether to grow crops versus livestock (Seo and Mendelsohn, 2008e), and whether to use cover or not (Dinar et al., 2011). In fact, the cross sectional method can be used to study every choice a farmer makes including which variety or breed to adopt, when to plant, when to harvest, and how much labor to apply. Of course, not all of these choices will be sensitive to climate and many other factors also influence these choices. A careful analysis would account for these other factors as well.

38. One of the dangers in using a cross sectional approach is that the analysis may not take into account important missing variables. If these missing variables are correlated with climate, the study could be biased. It is therefore critical that studies include major variables that will influence farm choice that might be correlated with climate. For example, it is helpful to include soil variables and market access variables because these are important explanatory variables for farm choices and they may be correlated with climate.
39. The cross sectional approach is a comparative static analysis. It describes long run adjustments to new conditions. It describes how farmers adjust to maximise their long-run profits in the new environment. It therefore is a model of efficient adaptation. It does not describe ineffective adaptation strategies because such policies will be rejected in the long run. The cross sectional approach also captures the indirect effects of climate. For example, it will capture the effect of diseases and pests associated with climate. It will capture how ecosystems change as climates change. This can be important to farmers of livestock in developing countries who tend to rely on the natural landscape. However, cross sectional methods cannot capture the dynamics of adjustment. Cross sectional studies cannot reveal how quickly farmers will adapt to the new equilibrium.

40. Figure 2 is an abstraction of the choice of crops against temperature. At cool temperatures, the farmer optimizes by choosing to plant wheat. As temperatures warm, however, wheat productivity falls. The farmer can choose to stay with wheat and lose substantial net revenue or switch to maize and actually earn more. Crop switching in this case turns a loss into a gain. If temperatures continue to warm, however, the farmer switches to soybean. This switch preserves the farmer’s net revenues. Finally, with more warming, the farmer switches to millet. This switch improves the farmer’s welfare but it still results in a loss compared to when the farmer could successfully grow corn and soybeans.

41. Cross sectional evidence has revealed that crop choice (Kurukulasuriya and Mendelsohn, 2008b; Seo and Mendelsohn, 2008d; Wang et al., 2010) and livestock choice (Seo and Mendelsohn, 2008b; 2008c; Seo et al., 2010) are two very important climate sensitive decisions by farmers. Figure 3 displays how farmers will gradually move from one crop to another across temperature zones in South America (Seo and Mendelsohn, 2008d). The probability of choosing each crop changes across climates. For example, wheat and potatoes are prominent in cooler climates but are much less common in warmer places. Soybeans, squash, and rice are more common in the middle range of temperatures in South America. Tropical fruits are more common in the hottest continental temperatures. Maize has the ability to grow across the entire spectrum of South American temperatures. The distribution of crops by climate provides insight into how crop choice would change if temperatures warm. Note that because each local area has a very different local climate, both the current crops chosen and the future crop choices vary across the landscape.
Figure 3. Effect of temperature on the probability of growing crops in South America

Source: Seo and Mendelsohn, 2008d.

42. Figure 4 displays the effect of precipitation on crop choice in South America (Seo and Mendelsohn, 2008c). The probability of choosing maize, soybeans and potatoes is highest in dryer climates. Wheat is chosen most often in intermediate moisture regimes. Fruits, rice, and squash are chosen more often in the wettest climates. As precipitation changes, it is likely to affect which crops are grown in each locality.
Figure 4. Effect of precipitation on the probability of growing crops in South America

![Graph showing the effect of precipitation on the probability of growing crops in South America.]

Source: Seo and Mendelsohn, 2008c.

43. Figure 5 displays the effect of temperature on livestock species choice in Africa (Seo and Mendelsohn, 2008b). Dairy cattle and cattle for meat are more prevalent in cooler temperatures but rarer in warmer climates. Chicken are present in all climates but are most common in middle temperature ranges. Sheep and goats are most common where temperatures are the highest. Again the cross sectional relationships provide an insight as to how livestock choice would change as climate changes. Because local climates vary, the graph also predicts that the choice of livestock will vary across the landscape with and without climate change.

44. Figure 6 depicts the effect of precipitation on livestock choice in Africa (Seo and Mendelsohn, 2008b). Sheep and goats are chosen most often when the climate is dry. Chicken, dairy cattle, and cattle for meat are chosen most often in average rainfall locations. The probability of each species being chosen varies significantly with precipitation. The relationship between livestock choice and precipitation can explain a great deal of the variation in livestock across space comparing the relatively drier portions of East, West, and South Africa with the wetter regions of Central Africa.
The choice of farm type (livestock-only, crop-only, or mixed farms) (Seo and Mendelsohn, 2008e) is also climate sensitive. Livestock-only is chosen in drier and hotter locations and crop-only is chosen in temperate and wet locations. The very type of farm in each location depends on climate. Further, how much land is in agriculture also varies with climate. Regions with more productive temperate climates in the United States had more farmland (Mendelsohn et al., 1996).
46. Empirical research tying other farm choices to climate has not yet been published. Good candidates for further research include the timing of planting and harvest. The division of landscapes into agro-ecological zones (FAO, 1978), for example, was based partially on the idea that certain climates permit longer growing seasons. Clearly, longer growing seasons imply that farmers would adjust to changing climates by altering planting and harvesting dates. Further longer growing seasons can sometimes accommodate double cropping within a single year. Timing planting dates to rainy seasons is also quite common in parts of the world with monsoons (distinct rainy seasons).

47. Farm inputs may also be sensitive to climate. Fertilizer, labor, and even capital may all be climate sensitive. These inputs in some cases complement climate. That is, they are used in greater quantities in more productive locations. In other circumstances, these inputs can be substitutes for climate. For example, cover and shade trees are used in hotter locations as a substitute for temperature (to compensate for the temperature being less than ideal) (Dinar et al., 2011). Irrigation is chosen in drier locations as a substitute for low precipitation (Kurukulasuriya et al., 2010).

48. One long-term adaptation that farmers may make in the future is a growing reliance on greenhouses and other climate controlled settings. Greenhouses liberate farmers from climate reliance because they create their own microclimate. Although greenhouses are expensive, they are also highly productive settings. As new designs increase energy efficiency, greenhouses could become tools that allow farmers to produce local fresh products almost year round. Controlled environments already apply to livestock management in developed countries. Chicken and pig farms and feed stock operations have largely replaced the open environment in which animals used to be raised in most developed countries. A recent study of climate sensitivity of animals in the US could find very little effects because of the reliance on such structures today (Adams et al., 1999). Similar studies in Europe reveal that the primary impact of climate change on livestock is the additional cooling costs for livestock (Valino et al., 2010). However, production systems should be assessed as a whole. Thus, it is necessary to ascertain that a recommended mode of production does not create large environmental trade-offs, including that of GHG mitigation.

49. A common assumption in the adaptation literature is that richer farmers have more technology and capital to choose from than poor farmers. They consequently have more substitutes to allow them to adapt and therefore would be able to adapt more readily. However, there is little empirical evidence that wealthier farmers will be able to adapt to climate change more readily than poorer farmers. A counter hypothesis is that wealthy farmers may have more trouble with climate change than poor farmers because they are more specialised. For example, commercial livestock farmers in Africa are much more vulnerable to warming than household livestock farmers because they specialise in high-productivity cattle that are designed for temperate climates. Poorer households have less productive animals but these local breeds are well-suited to warm climates. Further, these poor farmers have more substitute animals that are appropriate for harsh local conditions (Seo and Mendelsohn, 2008c). Commercial livestock farmers in Africa currently have much higher incomes than household farmers, but they are more vulnerable to climate change. One can also see a similar result with respect to mixed farms versus farms that have specialised in crops (Kurukulasuriya et al., 2006). The mixed farms in Africa can readily increase the amount of livestock that they own and move away from crops. The crop farmers currently earn more income but they have few substitutes if warming makes crops unsuitable. Studies of climate impacts in South America reveal that poor and rich farmers have very similar sensitivity to climate (Seo and Mendelsohn, 2008a). The empirical evidence does not suggest rich farmers have any advantage over poor farmers when it comes to climate change.
The adaptations discussed above concern what individual farmers can do. Another important set of actors in the agricultural sector include large agro-industries that supply machinery, fertilizer, and seeds. It is possible that technical change – inventing new machines, new types of fertilizer, and new types of seeds – can provide future farmers with new tools to cope with climate change. Most new crop varieties and animal breeds are climate neutral, so there are not many examples where genetic improvements have led to new opportunities to adapt to warming. However, there are a few exceptions where traditional plant breeding has led to improved crop varieties designed to grow in new places with different climates. For example, EMBRAPA has bred new soybean varieties that are now being grown in the Mato Grosso region of Brazil. Whereas this innovation was not done to adapt to climate change, it is a clear case where a crop has been developed for a warmer climate. The potential to develop new varieties more suited for warmer or drier climates has barely been tapped to date. However, it is possible that agronomic research could develop new choices for farmers more suited for a warmer world. Although part of the responsibility of technical change may well fall on government, industry is often an important player commercialising new technologies. To the extent that more farms (clients) will be located in warmer climates, it will be in the interest of these industries to find productive solutions for these farms in the future.

Governments

As argued throughout this paper, the primary adaptation role of governments is to provide public adaptation. This section reviews public adaptations related to agriculture that one would want governments to engage in. However, some government policies and activities currently lead to maladaptation. Governments should consider modifying some of their existing policies to reduce these maladaptations in the future. Finally, governments could address equity concerns if adaptation burdens fall heavily on the poor.

A good example of a desirable government activity for facilitating private and public adaptation is providing accurate forecasts of climate change. Ideally, the government can help provide more accurate updated local predictions of how climate would change in the next decade or two in every place. Unfortunately, at the moment, the accuracy of such forecasts is low. But this might change with advancing scientific capabilities. Better forecasts would help farmers make anticipatory adaptations for example by investing in long term capital that would be needed in the near term. Perhaps of even more importance, the government can help keep track of how climate is changing. That is, it can keep careful records of unfolding weather so that farmers can update what is happening in their area. This would facilitate reactive adaptation which is likely to be an important component of agricultural adaptation.

The government has historically played an important role in research and development (R&D). Specifically, governments have historically played a key role in basic research. Basic research lays the foundation for applied R&D. It is often best done by governments because it is ideal to share the new ideas that come from basic research. Private industry may spend some funds on basic research but they will tend to keep the results a secret. When governments support basic research, the wider community can benefit.

Governments have also been involved in applied research, especially in agriculture. One example of successful research done by government laboratories concerns the creation of new varieties of seed. The original hybrid corn was first developed by a government lab. Another important example is the “green revolution”, which received a lot of national and international government support. The development of a new variety of soybean capable of growing in warmer conditions was financed by EMPBRAPA in Brazil. Although the goal of the soybean research was to expand cropping into unexploited savannah areas (cerrado), new varieties such as this new soybean will have long term benefits supporting climate adaptation. It may be especially important that governments play an active role in developing new seeds to assure that the experimental approaches and the new varieties are safe. There is always a possibility that a new variety could inadvertently introduce new problems.
Although this paper focuses on the agricultural sector, there is an important link between agriculture and water management for governments. A large fraction of the value of agriculture is produced on irrigated farms. Changes in the water sector have important implications for agriculture. For example, if climate change causes runoff to fall, the supply of water will drop. Irrigation is one of the largest users of water in the water sector. Governments can help re-allocate water from low to high valued users. Farmers will see their share of the shrinking supply of water fall because the marginal value of irrigation is low compared to urban and industrial uses of water (Hurd et al., 1999). However, water reallocation does not have to be a disaster for irrigated agriculture. Within agriculture, there is a wide discrepancy in the value of water. If water is used on high valued crops and if irrigation is done efficiently, farmers can preserve most of the value of their agricultural products using much less water. A study of the California irrigation canal system revealed that by dropping low valued irrigation, the agriculture sector could preserve 94% of net production even with 24% less water (Lund et al., 2006; Howitt and Pienaar, 2006).

The government can also help with land use and land management policy. In many parts of the world, the government owns title to the land. How well the government manages public land has a big impact on agriculture. For example, in many low latitude countries, squatters regularly cut down public forestland and create temporary farms. Without land title, such transient farmers have little incentive to preserve the farmland for the future. They also would have little incentive to efficiently adapt to climate change. This could result in excessive deforestation, soil erosion problems, and insufficient investment in natural capital. Governments could privatize resources that are best developed. This would give new owners an incentive to manage for the long run. Governments could also do a better job of managing lands best left undeveloped to preserve their ecological values for society.

Farms are a source of both air and water emissions. Although it is commonly assumed that manufacturing is the primary source of pollution in the economy, agriculture is the highest polluting sector in the US economy when measured by air damages per unit of value added (Muller et al., 2011). Although their rural location often leads to lower damages per unit of emission, farms generate a large tonnage of emissions per unit of value added. The government has an important role regulating farm emissions. By reducing emissions per unit of value added, the government can help farmers make more socially efficient decisions. If water becomes scarcer with climate change, improving water quality through farm water emission reductions may become even more urgent with climate change than it is now. Warming may also enhance the formation of secondary pollutants, making emissions even more dangerous.

Not all of the current roles of government, however, lead to more efficient adaptation. For example, many governments subsidize weather insurance premiums due by farmers. The variation in weather has been a problem for farmers since agriculture first started. Weather insurance allows farmers to spread the risk of bad events across many farmers, enhancing their overall welfare. Actuarially fair insurance provides important incentives to farmers to stay out of harmful locations. The higher rates for more hazardous locations provide incentives for farmers to take into account risks. When governments get involved in insurance subsidies they may alter these signals. Governments need to modify their insurance programmes so that the incentives to avoid risky locations are maintained. Otherwise, the public insurance programmes run the risk of encouraging maladaptations – increasing the damages from weather and climate change in particular.

Emergency relief programs are safety-net programs for farmers and their first aim is to help farmers to pass through natural disasters. Beyond this legitimate objective emergency relief programmes can also lead to maladaptations. If farmers know that they will be compensated for losses from farming in hazardous locations, they will be drawn to those locations. Governments should consider how to modify emergency relief to reduce these maladaptations.
60. As regards income support governments should try to design such programmes to avoid maladaptation. For example, the support payments should be designed to discourage farming in high-risk locations. As climate changes, and makes some areas even less suitable for farming, the programme should encourage farmers to avoid these low-productivity areas.

61. One important factor helping adaptation is trade. As climate changes and makes some areas more suitable for farming and other areas less suitable for farming, society would be best off to encourage these changes. Because some of these changes will occur across national borders, climate change may alter what fraction of food can be grown within each country. Trade is an important factor contributing to adaptation to climate change as it will ensure that people will be fed regardless of where food is grown. Recent experiences with severe weather and temporary trade embargoes have revealed how sensitive food supplies can be without trade. Limitations to trade will reduce the flexibility of the global system and make people more vulnerable to malnutrition in a warmer world.

62. One final role for government is to address equity. Generally, this is interpreted as supporting a fair income distribution. Wealthier countries and wealthier people need to look out for the welfare of the very poorest countries and people. However, in climate change, there is another component to equity. The people who are emitting greenhouse gases are often not the same people who are being hurt by it. Equity also implies that those responsible for climate change do something to compensate those who are being hurt. Private donations to charities are one way that inequities can be addressed. However, it is clear that governments can also help address inequities. Can governments address equity by providing assistance with adaptation?

63. In principle governments clearly can address equity by supporting adaptation. To address equity, adaptation funds must identify an appropriate targeted population and then they must make these recipients better off. Adaptation projects and development projects consequently share a common goal. Adaptation and development programs should be designed together to serve that goal. Programmes that try to isolate adaptation apart from development will be unnecessarily restrictive. The fact that many adaptation opportunities may also help people develop should not disqualify them from being adopted.

64. However, the key to adaptation programmes, even if they are motivated by equity, is to make them effective. Making adaptation programs efficient just means that the programs will make a bigger difference to the target population’s lives given the limited funds available. Funding efficient public adaptations is one way to ensure that the adaptation funds are well spent. Funding private adaptation is another alternative but it will be more difficult for international agencies to do well. First, efficient private adaptation is likely to be done even without government support. So it is quite possible that government programs supporting private adaptation could be superfluous. Second, private adaptation must match local conditions. This requires careful attention to local climates, local climate change, local tastes and customs, and local constraints. Unfortunately, many central government programmes tend to take a blanket approach and offer a single solution to everybody. However, with climate adaptation, this will often be ineffective. For example, efficient responses to climate change may call for irrigation to increase in one place and decrease in another. In some places, farmers should switch to maize, whereas in other places, farmers should switch away from maize. Broad, sweeping programmes that simply subsidise irrigation or promote maize would not address these local conditions. In the enthusiastic push to address inequity, it is important to ask whether the resources are helping the targeted population as much as they could be.
Conclusion

65. This study reviews farm adaptation to climate change. The evidence supporting the existence of climate change and its likely magnitude is quickly reviewed. Without adaptation, climate change has the potential to do serious harm to the agriculture sector. This is an especially serious problem for farmers in low latitude countries but it is potentially an issue for farmers everywhere in the globe. Farm adaptation is therefore very important. It is critical to understand what specific actions farmers should undertake and what role governments should pursue.

66. There are several important distinctions between mitigation (reducing greenhouse gas emissions) and adaptation. Mitigation must be done by the entire planet and suffers from being a global public good. Every polluter must bear mitigation costs even though the benefits are spread across the planet. It is therefore in the interest of every polluter to shirk their responsibility to abate their emissions. Adaptation is quite different. Most agricultural adaptations are done for the benefit of each individual doing the adaptation. Adaptation is in the self interest of every farmer. Further whereas mitigation requires a global master plan to be effective, adaptation is inherently local. Adaptation should be fit to the local needs of each place. Finally, mitigation must be done in advance, in anticipation of highly uncertain future benefits. Farm adaptation can be reactive. Farmers need only change their behaviour as they observe climate changing. The huge uncertainties that plague mitigation do not necessarily apply to adaptation.

67. Not every action that farmers can take to adapt to climate change has yet been studied. Although farm adaptation has received considerable attention, the field is relatively new and there is a lot to still explore. Studies have shown that farmers should alter the amount of land in agriculture, the type of farms in each area, and the application of climate sensitive technologies such as cover and irrigation. Most important, studies have shown that crop choice and species choice are highly climate sensitive. Depending on initial conditions and how climate changes, each area needs to reconsider what crops and livestock species would be preferable in a new climate. Such changes not only can reduce damages in highly vulnerable places such as the low latitudes, but they can lead to large gains in middle to high latitude locations. In addition, there are a host of other changes that farmers may want to make in timing, fertilizer, technology, and varieties or breeds in order to adapt to climate change. More research in these areas is certainly needed.

68. The study also reviews the role of government. Although some governments may be eager to help their farmers adapt to climate change, it is not clear that this is an important function of government. The fact that farmers have a self-incentive to adapt suggests that efficient farm adaption could occur even without government help. The complex adaptation that each farmer must undertake given local conditions is not the kind of activity that governments are normally very good at doing. Concerns about equity may entice governments to try to directly support private adaptation, but governments must be careful to limit such support to efficient options.

69. In contrast, there is a whole suite of public adaptations that markets are not likely to do well. These “public adaptations” should be the primary focus of government. For example, the government should help with better weather and climate forecasting. Forecasts of future climates would help farmers anticipate local climate changes. Even providing accurate measures of current local weather is surprisingly helpful because it gives farmers up-to-date information about how the local climate is actually changing. Further, such measures are relatively inexpensive.

70. Another useful role for the government is to fund basic research into new crops and varieties. By providing basic understanding that can support future development of new crops or animals, the government can help expand the future choice set of farmers. Governments can increase the efficiency of water allocation. There are already large benefits to be gained from moving water from low to high valued
users. These gains will be larger if water in any specific basin becomes scarcer in a future climate. As a major user of water, agriculture has a lot at stake in making these changes efficiently. It turns out that agriculture is also a major polluter. Governments need to help regulate air and water emissions from farms and increase the overall performance of the agriculture sector. Again if water becomes scarce because of growth and climate change, water pollution is likely to be more important in the future.

71. The government can also help improve adaptation by modifying some of the policies and programmes currently in place. Public farm insurance programmes and emergency disaster relief could be modified to encourage farmers to stay out of harm’s way. Both programmes could be redesigned to encourage farmers not to take unnecessary risks. Governments could also modify farm subsidy programmes to encourage farmers to avoid risky and unproductive locations.

72. Finally, it is critical to note that the more free flow of goods and services across national borders contributes to climate adaptation. As some countries find it easier to grow food while others find it more difficult in a warmer world, the movement of food across borders can help ease food shortages. Assuring countries access to global markets will lead to increased food security which otherwise may be threatened by climate change.
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